Energy systems and climate policy: Long-term scenarios for an uncertain future

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Long-term scenarios for an uncertain future.

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lange-termijn scenario's voor een onzekere toekomst
(met een samenvatting in het Nederlands)

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1. INTRODUCTION

1.1 Energy and sustainable development

Energy plays a crucial role in sustainable development of people and their economies. On the one hand, the consumption of energy is a necessary condition for human activities, and thus economic welfare, while on the other, the way energy is currently produced and consumed also causes various sustainability problems in terms of environmental impacts and energy security. First of all, fossil fuel combustion is the single most important cause of anthropogenic climate change. Climate change is currently regarded as one of the greatest problems in human-environment relationships, being a direct threat to both ecosystems and human development (MA, 2005). Reducing the greenhouse gas emissions in the energy system is regarded by the International Energy Agency as ranking among the greatest challenges facing the energy system today (IEA, 2006a). A second sustainability problem is the significant contribution of the energy system to air pollution on various scales: regional (e.g. emissions of ozone precursors of acidifying compounds), urban (contributing to smog and particulate matter) and household (mostly particulate matter emissions from traditional bio-energy). Various other environmental problems are also associated with the production of energy, such as landscape disturbance, generation of waste and the risks of nuclear accidents (Goldemberg, 2000).

With respect to energy security, it is highly questionable if the current energy consumption levels can be maintained in the long term. Energy resources are limited and their distribution across the earth is uneven. The latter creates an additional uncertainty for importing regions.

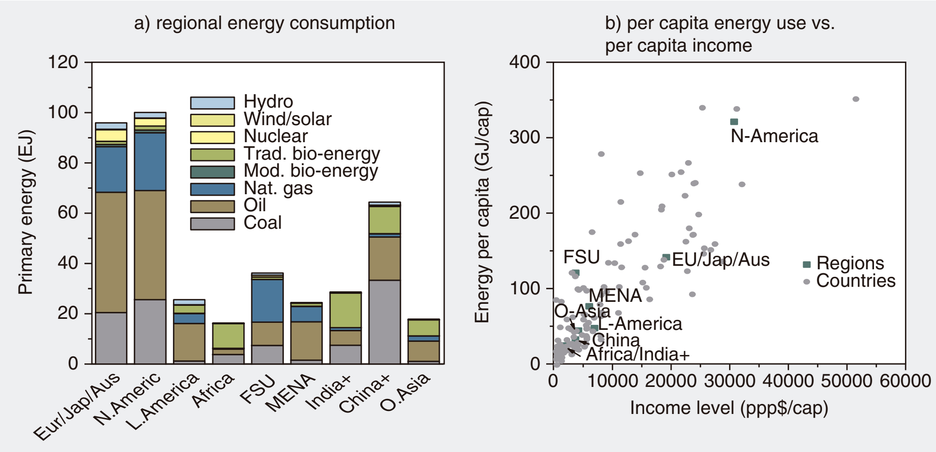

Figure 1.1 Regional differentiation in primary energy use. Primary energy use by energy carrier (a) and the relationship between per capita income and per capita energy use (b). (IEA, 2003b; WorldBank, 2006) (FSU = Former Soviet Union; MENA = Middle East and North Africa).

Finally, it should be noted that at the moment about 1.6 billion people have no access to electricity and nearly 2.4 billion people (in Africa, Asia and Latin America) consume mainly traditional bio-energy (Modi et al., 2006). Figure 1.1b illustrates the large differences in energy consumption patterns across the world, with high-income regions consuming, on average, more than 100 GJ per capita per year (OECD regions and the Former Soviet Union) and low-income regions consuming less than 40 GJ (Other Asia, China, Africa and India). Providing sufficient energy supply forms, on the one hand, an essential condition for economic growth in these regions, but, on the other, is likely to contribute further to the global environmental problems and energy security issues. Again, this is illustrated in Figure 1.1b, which shows the strong correlation between income levels and energy consumption when looking at the overall trend. However, it should also be noted that the relationship is not universal: individual countries may diverge sharply from the general trend.

Given the situation described above, *the challenge for sustainable development* in the energy system can be translated into the following goals (MNP, 2005b; EC, 2006; G8, 2006):

- providing consumers with access to affordable energy services and, in particular, to the more than 2 billion people who have no access to sufficient, modern forms of energy today.
- reducing the environmental impacts and safety risks of the energy system to sustainable levels.
- ensuring long-term energy security.

The energy system today and its relationship to sustainable development is a consequence of long-term developments that can be characterized by a series of transitions (Smil, 1994; Grübler et al., 1995; Grübler, 1998; de Vries and Goudsblom, 2002) (Figure 1.2). The first transition took place in the pre-industrial times, when humans learned how to control fire. Over time, new energy sources were introduced such as wind power, small-scale hydro power and the use of animals; however, energy use remained at relatively low levels. A very important step in the late 18th and early 19th centuries was the transition in industrializing countries from a mainly wood-fired system to an increasingly coal-based system, initiated by the steam engine. The use of coal, which was more easily transported and stored, allowed higher power densities than the wood-fired systems. By the turn of the 20th century, coal had become the major fuel source at global level; at the same time, global average per capita energy consumption increased from around 10 GJ in 1850 to 30 GJ in 1900.

A second transition occurred with the introduction of oil, which was an even more convenient energy source. Oil was particularly attractive in fuelling transport. With the growth of transport, the use of oil steadily increased and by the 1970s oil had superseded coal as the most important energy carrier. Another transition in the 20th century was the introduction of electric power. Electricity is an energy carrier that can be easily converted to light, heat or work at the endpoint. Electricity also allows for a large diversification of supply side technologies (fossil fuels, hydropower, nuclear and renewables). Natural gas, used in buildings, industry and power production, started to penetrate the energy system in some regions (e.g. the USA) from 1920-1930 onwards, but only in the second half of the 20th century did it become an important factor in the global energy system. Again, convenience in handling formed a significant driving factor for the growth of natural gas use, next to its high conversion efficiency and low pollution levels.

Interestingly, while energy carriers seem to subsequently replace each other as the most dominant fuel, no energy carrier really declined in terms of absolute consumption levels. It seems that each new fuel has only helped in supplying an ever-growing energy demand. Over the 1850-2005 period, global energy demand grew by about 2.2% annually. If we look at the long-term growth rates, it would seem that energy and economic development are closely related. However, this is somewhat misleading: in reality the relationship varies over time and from region to region. For example, the

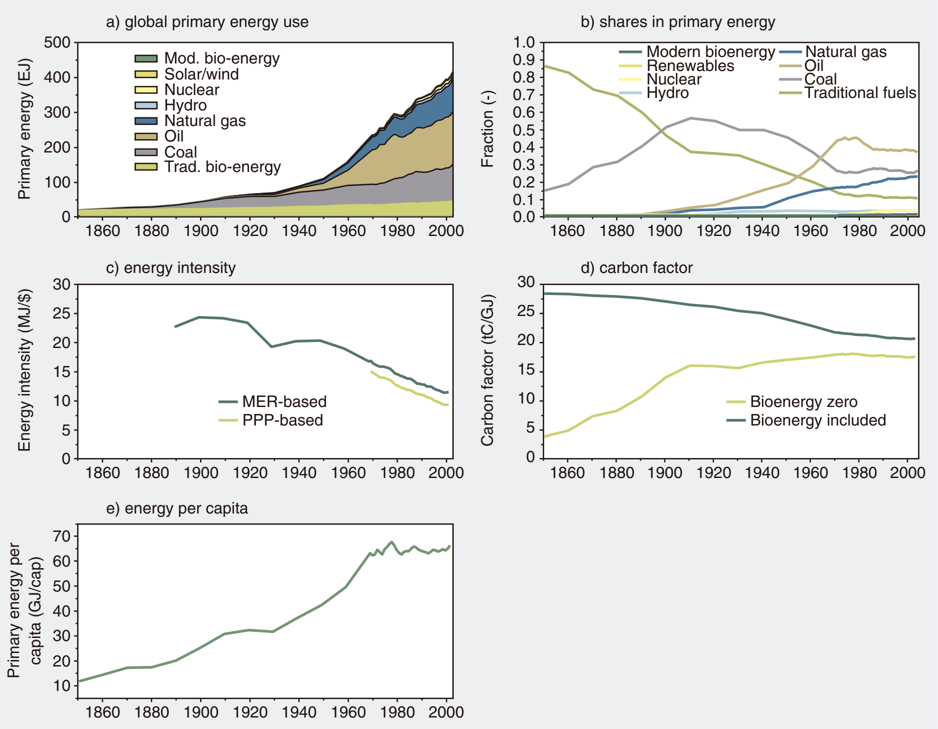

Figure 1.2 Long-term trends in the global energy system (1850-2005). Primary energy consumption by energy carrier (a), fraction of energy carriers in total consumption (b), energy intensity and per capita consumption (c) the carbon content of fuels and (d) (Grübler et al., 1995; IEA, 2006b).

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[i] If bio-energy is accounted for on the basis of the carbon included in the combusted fuel itself, a trend of decreasing carbon content becomes obvious that is sustained over a very long time period. For bio-energy, however, this carbon has been absorbed from the atmosphere during the growth phase of the tree or crop. The carbon therefore does not necessarily lead to increasing atmospheric CO_2 concentrations. If instead, a zero carbon factor is assigned a very different trend becomes apparent, which first shows a rapid increase (as a result of penetration of fossil fuels) followed by a more-or-less constant carbon factor.

increasing efficiency levels in OECD countries in response to high oil prices during the 1970s and 1980s have shown that at least over short periods, economic growth can occur without any increase in energy use (Goldemberg, 2000). These energy efficiency improvements led to a more-or-less constant per capita energy consumption on a global scale after 1970 and constant shares of oil and gas in the total energy mix. Finally, Figure 1.2 also shows hydro, nuclear, solar and wind power, which all represent only a small fraction of the total energy system.

The long-term trends can also be seen in more aggregated indicators such as the energy intensity (energy per unit of GDP) and the carbon factor (carbon content of fuels per unit of energy). Here, the historical trends can be characterized in terms of a steadily decreasing energy intensity (as a result of increasing efficiency and changes in the type of economic activities), an increasing per capita energy use (however, there are some forms of saturation in some sectors in industrialized countries) and a decreasing carbon content of fuels (going from wood to coal to oil and gas)[i] (Figure 1.2). Such trends have been used to derive insights into universal characteristics of the energy system (Marchetti and Nakicenovic, 1979; Grübler et al., 1995).

The future of the energy system (associated with the sustainable development goals introduced earlier) will be partly dependent on similar long-term trends and universal characteristics. At the same time, however, there will be many unknowns. For instance, at what rate will technology development occur? What new technologies will be introduced? What emphasis will human societies give to economic objectives vis-à-vis social and environmental objectives?

Energy models have been designed to provide insight into the (possible) future interplay of economic growth, energy use and supply, technological change, environmental problems and societal goals. In recent years, such models have been used specifically in the context of climate change (e.g. Weyant et al., 2006). Model-supported scenario analysis provides a common method for exploring both potential baseline developments and strategies to mitigate greenhouse gas emissions.

In this thesis, we will look into energy-climate modeling, with the aim of increasing insight into three fundamental areas:

1. *What are possible development pathways for the global energy system and associated emissions in the absence of climate policy?*
2. *What types of uncertainties are associated with energy scenarios, and what are promising ways of handling those?*
3. *Is it possible to stabilize greenhouse gas concentrations at low levels - and if so, what kind of strategies might contribute to this?*

We will explore these areas mainly by looking at a series of analyses performed with one energy model, TIMER, developed at the Netherlands Environmental Assessment Agency (see Chapter 2). In the subsequent sections of this chapter, we will fill in further elaborate relevant concepts and focus on the leading issues for this thesis.

1.2 The energy system and its relation to climate change

1.2.1 Defining the energy system

The energy system can be represented in different ways, but one of the most universal is mapping the chain from energy service back to primary energy carriers. Energy analysts refer to an energy system as the “combined processes of acquiring and using energy in a given society or economy” (Jaccard, 2006). Such a system includes therefore sources of *primary energy*, the conversion process, different forms of *secondary energy* that can be readily applied and the final *energy services* such as lighting, mobility, space heating and cooling (also known as *energy end uses* or *useful energy*).

Primary energy describes the original source of the energy that is consumed by humans (it should be noted that only deliberate energy consumption is included; passive solar heating is, for instance, not included). Before the industrial revolution, there was little processing of primary energy to secondary energy. Nowadays, the majority of primary energy is converted. The most notable form of conversion is the generation of electric power from primary energy carriers. Electric power can be generated from fossil fuels (with typical efficiencies of 30-50%), bio-energy, uranium and renewable sources. Most other fuels are also converted. Crude oil, for instance, is transformed at an oil refinery into a range of refined petroleum products, including gasoline, diesel and heating oil. Natural gas is processed in order to extract sulfur, liquids and other gases. The total efficiency of converting primary energy into secondary energy carriers is about 70%: Worldwide primary energy use amounts to 400 EJ in 2000; while secondary energy amounts to around 280 EJ. The difference is mostly caused by the losses in electric power conversion.

In terms of *secondary energy carriers*, a clear trend can be noted along with development (both in time and between rich and poor countries) from the use of readily available, but relatively inconvenient fuels (such as wood) to fuels that have a high degree of convenience (no handling, easy to convert and negligible environmental and health impacts in use). This transition is sometimes referred to as the energy ladder. Among the most convenient and cleanest energy forms (at end-use) are electricity and, possibly relevant in the longer term, hydrogen (both need to be produced from primary sources). From the perspective of society, energy is not an end in itself. The energy system is designed to meet demands for a variety of *services*. While focus is usually on obtaining sufficient secondary energy for an energy service, increasing the efficiency of the final conversion process (known as energy conservation) can also be an important way to enhance supply of energy services; in such a way the same service can be produced using less primary energy. Estimates of efficiency in final energy conversion depend strongly on the system boundaries. These estimates nevertheless show that this efficiency is relatively low. One estimate indicates a global average of 40% (Gilli et al., 1995), but very different numbers can also be found.

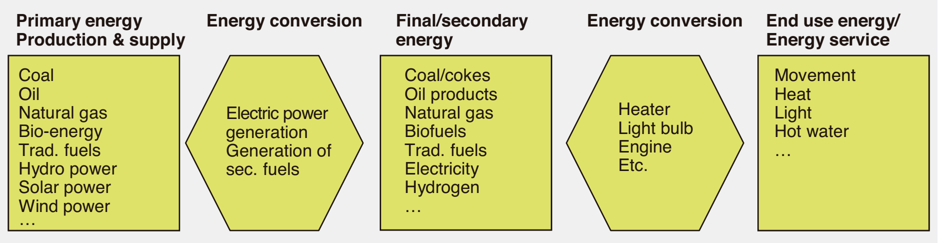

Figure 1.3 Representation of the energy system, moving from primary energy production to end-use energy.

The overall performance and efficiency of an energy system depends on individual process efficiencies, the structure of energy supply and conversion, and energy end use patterns. As the system is relatively complex, improving the overall performance and minimizing its side-effects can best be studied using models that capture the most relevant causalities in the system.

1.2.2 Climate Change

Environmental impacts of energy use are not new. For centuries, wood burning has contributed to deforestation and indoor air pollution. After the industrial revolution uncontrolled combustion of fossil fuels (mainly coal) too, led to alarmingly high levels of urban air pollution. More recent, however, are the links between energy use, and continental and global environmental problems. Of these problems, climate change is one of the most important.

The term “climate change” refers to relatively rapid changes in the earth’s climate observed over the last century, attributed to the so-called “enhanced greenhouse effect”. This enhanced greenhouse effect describes the process in which the absorption of infrared radiation by so-called greenhouse gases in the atmosphere warms a planet. Such gases include water, CO_2 and CH_4. The existence of the natural greenhouse effect is undisputed and without this effect, it is estimated that the earth’s surface would be up to 30°C cooler. The greenhouse effect itself was described as early as the 19th century by, for example, Fourier in 1824 and Arrhenius in 1896 (Arrhenius, 1896; Doeoes, 1997). A logical hypothesis is that adding more greenhouse gases to the earth’s atmosphere, for example, through release of $CO_{2,}$ combustion of fossil fuels and deforestation, is likely to make the planet’s surface warmer (the so-called enhanced greenhouse effect). Since the late 19th century knowledge on the climate system has significantly increased. Nowadays, the main question is not so much whether anthropogenic enhanced climate change exists, but to what degree the increase in radiative forcing by greenhouse gases will lead to changes in the earth’s climate, given the complex and indirect changes in the atmosphere. The Intergovernmental Panel on Climate Change (IPCC), a UN forum of scientists established to collect and summarize information on climate change, has indicated in its latest report that most of the observed increase in globally averaged temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic greenhouse gas concentrations (IPCC, 2007). IPCC also indicates that a further increase of 1.1-6.4°C could occur in the absence of climate policies (IPCC, 2007).

The main greenhouse gases (and other compounds) contributing to anthropogenic climate change include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), different groups of halogenated gases (CFCs, HFCs, PFCs, SF_6), ozone (O_3) and some forms of aerosols (so-called black and organic carbon). Fossil fuel combustion produces more greenhouse gases than any other human activity, as indicated in Figure 1.4 (about 65%)[ii]. Without climate policy, the share of the energy sector is even likely to increase (as land use-related emissions are likely to grow less rapidly or even decline). Current CO_2 emission trends from the energy system, if not controlled, could lead to more than a doubling of atmospheric CO_2 concentrations before 2070, relative to pre-industrial levels (IMAGE-team, 2001).

What might be the consequences of climate change? A large body of studies reports that the consequences of climate change are likely to increase with a further rise in temperature. MNP_5 based on earlier IPCC figure, summarized the potential impacts in Figure 1.5 (IPCC, 2001). The figure identifies various concern categories: I) risks to unique systems, II) risks from extreme climate events (such as floods or hurricanes), III)

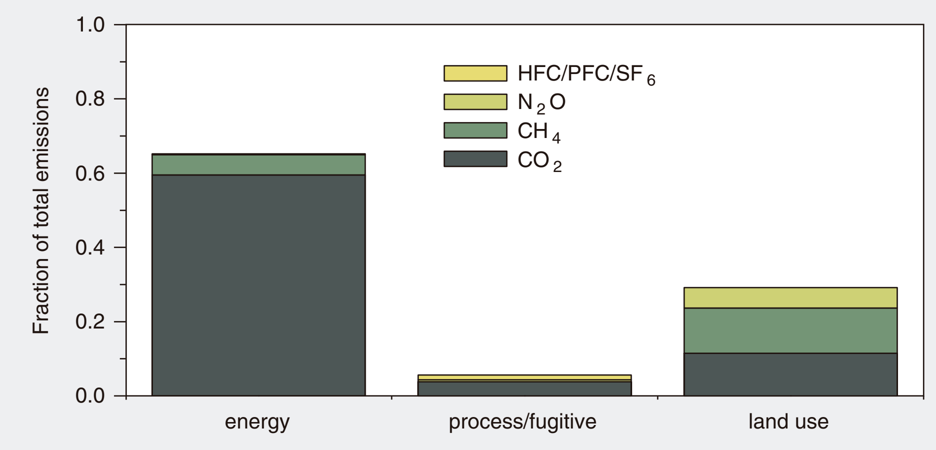

Figure 1.4 Contribution to greenhouse gas emissions (measured as CO_2-equivalents using 100-year GWPs) in 2000 (IMAGE-team, 2001) (the category of process and fugitive emission include, for instance, CO_2 emissions from cement production, CH_4 emissions from steel production and emissions of halogenated gases).

[ii] The CO_2 emissions per unit of energy are the largest for coal (around 25.5 tC/GJ), followed by oil (around 19.3 tC) and natural gas (15.3 tC). Direct emissions from wood combustion are even higher than those from coal, but as the carbon has been recently absorbed during the growth phase of the tree, these emissions are generally assumed not to contribute to climate change – unless they lead to net deforestation (these emissions are categorized under land use).

Box 1.1 CO$_2$ and CO$_2$-equivalents.

Carbon dioxide (CO$_2$) is an important waste product of combustion, and is also the most important gas contributing to increased global warming. But it is not the only gas: other greenhouse gases and radioactive substances too account significantly for an increase in so-called "radiative forcing". The latter refers to the change in the radiation energy entering or leaving the climate system. These other greenhouse gases include, for example, methane (CH$_4$), laughing gas (N$_2$O), halogenated gases such as CFCs, HFCs, PFCs, and SF$_6$ and different kinds of aerosols. Some of these gases are only found in the atmosphere in low concentrations, but their impact per weight unit on increasing the greenhouse effect is sometimes thousands of times greater than CO$_2$.

The concept of CO$_2$-equivalents – used in this thesis – has been introduced to bring all gases together under one common denominator. The CO$_2$-equivalent concept is aimed at converting the effects of other greenhouse gases to the equivalent of CO$_2$. For emissions, this is done by expressing them in tonnes CO$_2$-eq., converted on the basis of so-called Global Warming Potentials (GWPs). Unfortunately, GWPs cannot capture all aspects of weighting the different gases – and therefore CO$_2$-eq emissions remain only as a rough indicator (see also Chapter 6 of this thesis). For concentrations, the concept of total radiative forcing can be used, expressed in W/m^2 or converted into parts per million CO$_2$-eq. (ppm, the number of molecules of CO$_2$ per million parts of air). The concept of CO$_2$-eq concentrations does not suffer the same limitations as equivalent emissions.

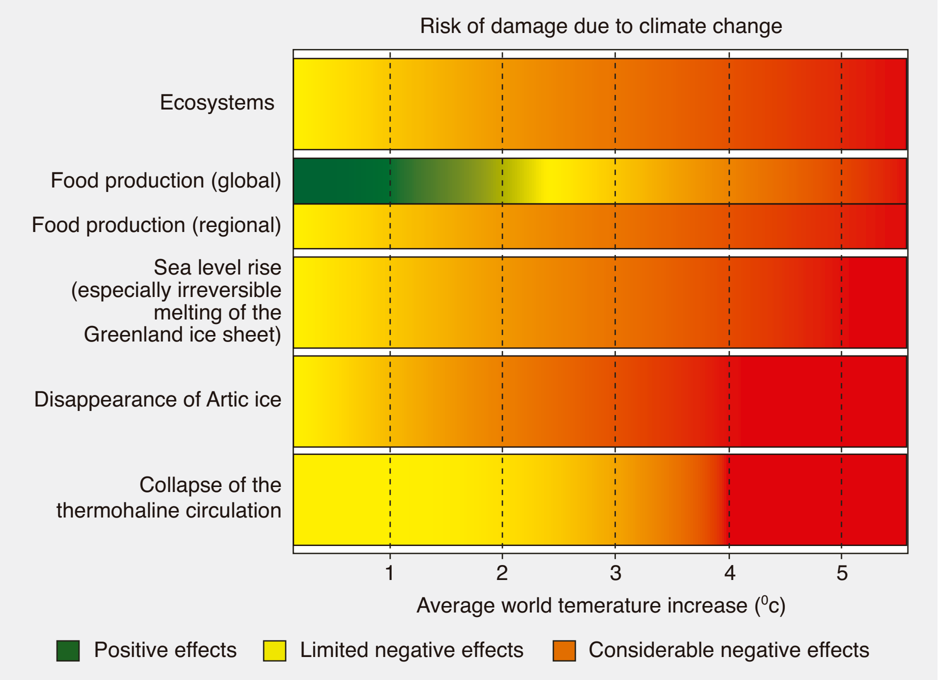

Figure 1.5 Potential impacts of climate change as a function of the increase in global mean temperature compared to pre-industrial levels according to MNP, as based on an earlier assessment in IPCC's Third Assessment Report (IPCC, 2001; MNP, 2005a).

impacts, including agriculture in specific regions but not globally, IV) impacts as in III but now global aggregate, and V) risks of global climate system disturbance. Although there are still considerable uncertainties, the expectation is that for moderate levels of temperature increase, sensitive ecosystems (such as coral reefs) or local systems (food supply) could be negatively affected. Further temperature increase is likely to lead to larger impacts, including sea level rise as a consequence of thermal expansion of water, negative influences on the overall global food production, changes and possible increases in extreme weather events, the melting of Arctic sea ice and parts of the Greenland ice sheet. The latter could add to the sea level rise. Finally, climate change could also lead to large-scale discontinuities such as the weakening of the thermohaline circulation.

The comparison of projected increase under different projections (1.1 to 6.4°C) and the possible impacts (Figure 1.5) show that all of the impacts discussed above could occur if climate policies are not implemented. On the basis of such insights, the EU has chosen to aim at limiting global average temperature increase to a maximum of 2°C compared to the pre-industrial level (EU, 1996; EU, 2005). This objective should be seen as a political decision based on the risks of climate change, and the opportunities and associated costs of preventing climate change.

While there is agreement that the climate is changing, the exact relationship between greenhouse gas emissions, their concentrations in the atmosphere, and the resulting temperature is far from clearly defined. There are a number of uncertain variables, such as the sensitivity of the climate system to increased concentrations of greenhouse gases (climate sensitivity), the relationship between emissions and atmospheric concentrations, and the contribution of the different gases and other radiative agents. Figure 1.6 summarizes current insights into the relationship between atmospheric greenhouse gas concentration levels and the likely temperature increase at equilibrium. The figure

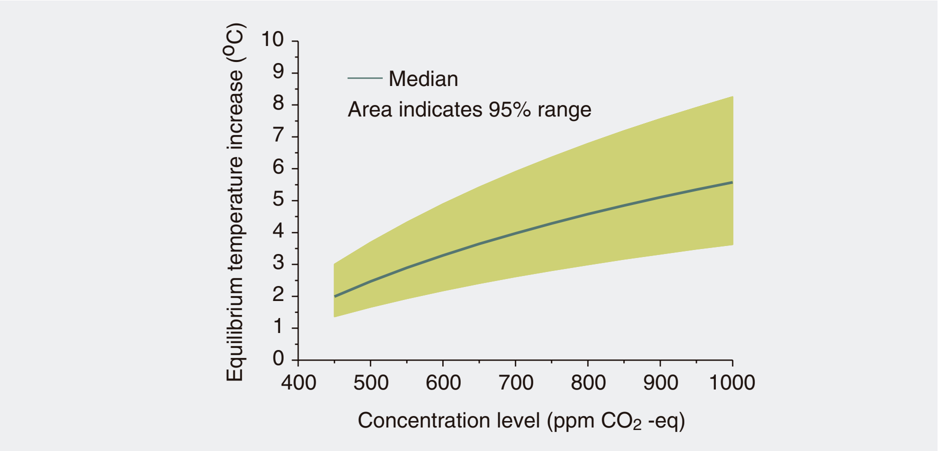

Figure 1.6 Relationship between greenhouse gas concentrations and temperature change at equilibrium (IPCC, 2007) The ranges indicate the 95% probability interval.

indicates that keeping the temperature increase below 2°C (the above-mentioned EU target) would at the very least require concentration levels in the order of 550 ppm CO_2-eq or less. At a stabilization level of 550 ppm CO_2-eq., the probability of achieving the 2ºC target is currently estimated at around 20% (with a most likely outcome of 2.9ºC). At a concentration level of 450 ppm CO_2-eq. or below, there is a reasonable chance (over 50%) of achieving the 2°C objective. In order to reach such low stabilization levels, emissions would need to remain in the order of 700-1100 GtC-eq (550 ppm) or 300-750 GtC-eq. (450 ppm) (den Elzen and Meinshausen, 2005); this implies at least a 50-75% reduction in emissions in the absence of climate policy throughout the century. This obviously would represent an enormous change in the energy system.

1.3 Knowledge on the future

1.3.1 Introduction to the scenario approach

From the two previous sections, we can ascertain that it is relevant to assess future long-term trends in the energy system. Two of the crucial issues in sustainable development of the energy system – energy security and climate change – require long-term planning, since current decisions on the energy system will influence the energy and climate system for several decades (system inertia). There are several factors contributing to this:

- Important parts of the energy infrastructure have very long lifetimes. For instance, the lifetime of an electric power plant could easily span 40-50 years. Retirement of capital before it has reached the end of its lifetime is costly.
- Lock-in effects (in infrastructure, technology and product design) further slow down the rate of change in the energy system (e.g. Unruh, 2002). Such effects arise from the fact that once a system establishes itself, it may be difficult and/or costly to change course again (underlying factors may include habits, invested interests, interconnected systems etc.).
- Climate change is a slow process. Current emissions will continue to influence the world's climate system over the next century.

Unfortunately, assessing the future of the energy system is not easy: the evolution of the energy system and its underlying driving forces is highly uncertain. Complex dynamic processes such as demographic and economic development, technological change, energy policies, and resource availability and environmental policies (such as climate policy) all interact as determinants of future energy use. Diverging development patterns for each of these factors could introduce very different futures (Nakicenovic and Swart, 2000). An additional complication is that these factors are partly determined by human decisions. People generally make decisions based on their current knowledge and their expectations for the future. This reflexivity of human behavior further constrains the reliability of predictions (Funtowicz and Ravetz, 1993). Many examples of failure in statements on future trends are available. Among notorious examples are statements on the phasing-out of fossil fuels by nuclear power in the early 1970s and the overestimation of primary energy demand by most studies during the 1970s and 1980s (DeCanio, 2003; Smil, 2003).

Different methods can be used for developing an understanding of the future (see also Alcamo et al., 2006; de Vries, 2006a) [iii]. These methods are mainly distinguished from each other by the degree of knowledge that is available (see also Figure 1.2). One situation is that of s*trong knowledge.* This can be created for systems that can be well described and allow for reproducible (controlled) experiments to test hypotheses on the functioning of the system. On the basis of experiment and theory, it is here possible to *predict* system behavior (e.g. weather). Such a situation is normally impossible in energy–climate modeling. Here, knowledge can be characterized more as *weak knowledge* with complex systems, indirect observations that are usually uncertain and poorly understood interactions among key parameters. In such a situation, it is not possible to "predict" system behavior, but statements can be made on possible system functioning under clearly defined assumptions. This method is generally referred to as (model-based) scenario analysis.

The term *scenarios* – as used in this thesis –is defined as a plausible description of how the future might develop, as 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) (Nakicenovic and Swart, 2000). The rationale of the scenario approach is that instead of estimating the most likely future, the situation moves into an assessment of possible pathways of events ("what if"?) (see also Chapter 5).

Scenarios exist in very different forms:

- One aspect relates to the tools that are applied. Scenarios may use *qualitative* approaches (using a narrative text), *quantitative scenarios* (using modeling tools), or *both,* to develop internally consistent storylines assessed through quantification and models. In the last approach, qualitative elements add to the modeling by focusing on non-quantifiable factors (Swart et al., 2004; Alcamo et al., 2006). Most of the work in this thesis conforms to the last approach.
- Another important difference in types of scenarios occurs between primarily *descriptive / explorative scenarios*, i.e. scenarios that are constructed to explore the future under a set of "what-if" assumptions and *normative scenarios*, i.e. scenarios that lead to a future that is pre-defined on the basis of a set of goals. Within the first group, studies usually look at a set of contrasting scenarios, but also "*business-as-usual*" or "*best-guess*" scenarios can be seen as part of this group. Despite the fact that the latter are usually less clear about their assumptions, they still aim at identifying the most likely outcomes under a defined set of assumptions (e.g. continuation of current trends for driving forces). For *normative scenarios*, one needs to take into account that these scenarios do not intend to show what will happen, but

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[iii] It should be noted that these terms are often not strictly separated in the literature. Moreover, despite the fact that scenario analysis has been used for a few decades, the field has not yet been codified into a common set of definitions and procedures.

what could or should happen. This part is often misunderstood in the evaluation of these scenarios in cases where they are discredited on the basis of actual historical trends (de Vries, 1989).

- *Probabilistic scenarios* represent a different approach to uncertainties than the normal descriptive scenarios. Probabilistic scenarios are based on estimates 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.

The most important characterization of scenarios for this thesis is formed by *baseline* and *mitigation* scenarios[iv] (these are simply a special form of descriptive and normative scenarios). *Baseline scenarios* explore possible development without climate policies – while *mitigation scenarios*, in general, aim at a pre-specified GHG reduction pathway. Most *mitigation scenarios* belong to the subgroup of *stabilization scenarios,* aiming to stabilize GHG concentrations in the atmosphere. Some scenarios in the literature are difficult to classify as either mitigation or baseline scenarios, such as those developed to assess sustainable development paths. Moreover, with the current development of climate policies, the distinction between baseline and mitigation scenarios becomes more difficult to make.

It should be noted that the design of a scenario exercise is obviously strongly related to its purpose. For relatively new, complex and long-term problems the use of scenarios to frame the problem will automatically lead to an approach with multiple, diverging storylines. Such scenarios can help to frame discussion between policy makers, scientists and stakeholders. On the other hand, if the problem is already more structured and

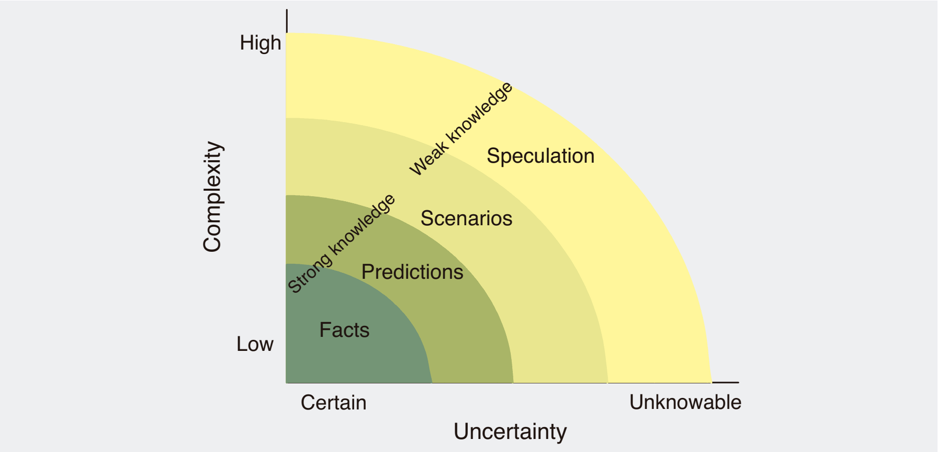

Figure 1.7 Different methods to assess the future in relation to uncertainty and system complexity (based on (Zurek and Henrichs, 2006)).

[iv] Alternative terms for baseline scenarios used in literature are reference scenarios and non-intervention scenarios. Mitigation scenarios are sometimes referred to as intervention scenarios.

focused less on problem framing and more on problem solving, this might be a reason to use only one central scenario as a basis for deriving a set of policy scenarios.

Scenarios play a central role in this thesis as a tool for exploring long-term pathways of energy systems. In the thesis, scenarios have the following characteristics:

- The long-term assessments are not meant as predictions of the future, and will almost certainly be proven (partly) wrong in time. Nevertheless, they should comprise the best available information currently available to make them relevant to intended users – including an assessment of the uncertainties.
- Scenarios still need to be plausible.
- Scenarios should not become too complex: if they are to be relevant for today's decisions, there needs to be an understandable relationship (for users, i.e. decision makers) between the decision and the actual chain of events.
- The use of qualitative information (narratives) next to quantitative information can strengthen scenarios in areas of weak knowledge and in making information more accessible.

1.3.2 Current status in the field of energy—climate scenarios

As explained in the previous section, there are two main categories of scenarios in energy—climate modeling: 1) baseline scenarios that explore alternative development pathways, and 2) mitigation scenarios that explore options for emission reduction (climate policy).

Baseline scenarios

The most prominent application of the alternative scenario approach in energy—climate modeling is formed by the IPCC SRES scenarios (Nakicenovic and Swart, 2000). These scenarios map out a range of possible emission trajectories based on the wide variation in assumptions structured around four main storylines. These four storylines can be characterized along two main axes:

- the degree of globalization (1) versus regionalization (2)
- the focus on economic objectives alone (A), vis-à-vis the focus on social and environmental objectives (B).

This leads to four characteristic scenarios: A1, a scenario dominated by rapid economic growth, globalization and rapid technology development; A2, a scenario characterized by a strong regional focus, a lack of international trade and slow technology development; B1, a scenario strongly focusing on finding global solutions to social and environmental problems and B2, a scenario that again focuses on regional development, but now including an environmental focus. In reality, the storyline of the B2 scenario is often ignored in energy-climate modeling, and instead, the scenario is characterized by medium assumptions for all parameters. Interestingly, the IPCC SRES scenarios map well to the scenarios of other major scenario exercises. An indication of the main assumption of the IPCC SRES scenarios (and the main archetypes found in the literature) is provided in Table 1.1.

Table 1.1 Key assumptions in different scenario "archetypes"

	Economic optimism	Reformed markets	Global sustainable development	Regional competition	Regional sustainable development	Business as Usual
	A1		B1	A2	B2	B2*
Economic development	very rapid	rapid	ranging from slow to rapid	slow	ranging from mid to rapid	medium (globalization)
Population growth	low	low	low	high	medium	medium
Technology development (general)	rapid	rapid	ranging from mid to rapid	slow	ranging from slow to rapid	medium
Technology development (environment)	rapid	rapid	rapid	slow	medium to rapid	medium
Main objectives	economic growth	various goals	global sustainability	security	local sustainability	not defined
Environmental protection	reactive	both reactive and proactive	proactive	reactive	proactive	both reactive and proactive
Trade	globalization	globalization	globalization	trade barriers	trade barriers	weak globalization
Policies and institutions	policies create open markets	policies reduce market failures	strong global governance	strong national governments	local steering; local actors	mixed

Note: B2 indicates the position of the IPCC B2 scenario on the basis of its original storyline. B2* indicates position on the basis of how it is often applied.

A crucial debate in scenario development over the last few years has centred on the way uncertainties are handled, with two prominent approaches being the *alternative scenario approach* and *fully probabilistic approach*. While the first aims to capture uncertainty by exploring different possible storylines, the latter does so by estimating probability distribution functions for main input parameters. A lively debate has been held on the need for and appropriateness of dealing with probabilistic assignments (Grübler and Nakicenovic, 2001; Schneider, 2002; Webster et al., 2002). Uncertainty analysis will most likely continue to be a key issue in scenario analysis in the coming years. The quest is for a balanced use of different analytical tools, each of which addresses different forms of uncertainty.

Mitigation scenarios

Climate change intervention, control or mitigation scenarios capture measures and policies for reducing GHG emissions with respect to some baseline (or reference) scenario. A large number of such scenarios have been produced over the years. In the analysis, there are a number of recurring themes (a more extended overview is given in Chapter 7). These include:

- the issue of stabilization targets and overshoot
- the identification of overall cost levels of stabilization
- the issue of timing (early action or delayed response)
- the role of technological development.

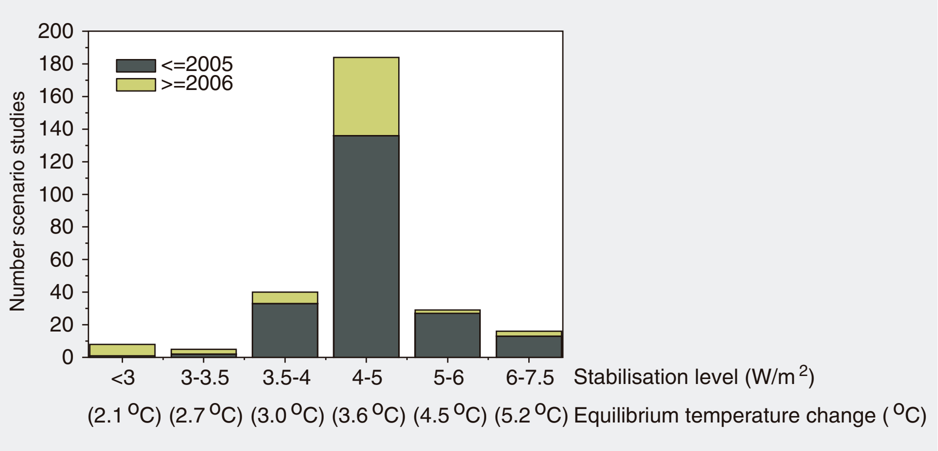

Figure 1.8 Distribution of long-term stabilization scenarios in the literature included in the emissions database (Hanaoka et al., 2006; Nakicenovic et al., 2006). The red column indicates the situation before 2006, and the purple column points to publications in 2006 where two major model intercomparison studies were published (see also Chapter 6 of this thesis), and several low-concentration stabilization scenarios, including the studies described in Chapter 7 of this thesis. The indicative equilibrium temperature change is based on the mean value for climate sensitivity.

A recent database of mitigation scenarios shows that the vast majority of mitigation scenarios focus on only a limited set of stabilization levels (Figure 1.8; the figure distinguishes between scenarios up to 2005 and scenarios published in the last year. The latter category includes the scenarios described in Chapter 7 of this thesis). In Section 1.2, we have shown that for limiting global mean temperature increase to 2°C (the objective of EU climate policy) with a probability higher than 50%, stabilization of greenhouse gases at a concentration below 450 ppm CO_2-eq (or 3 W/m^2) is needed. The great majority of current mitigation scenarios, however, focus on stabilization at around 650 ppm CO_2-eq. (or 4.5 W/m^2). As a result (certainly before 2006; the database includes, in fact, only one single scenario before 2006 in the lowest category) no evidence was provided from scenario analysis on whether the EU climate objective was feasible, and if so, how it could be obtained. This implies that in addition to the further elaboration of the themes mentioned above, exploration of low-stabilization scenarios represents a key issue in mitigation scenario analysis.

1.4 Energy models

In this thesis we concentrate on the application of an energy model (TIMER) in the context of climate change. This section provides a brief overview of the type of energy models in existence, and places the model used in this thesis within this larger context.

1.4.1 Categories of different models

A large number of energy models have been developed in the last few decades, partly supported by expanding computer possibilities. These models vary considerably, with several attempts made to classify energy models (e.g. Grubb, 1993; Hourcade, 1996; Zhang and Folmer, 1998; Van Beek, 1999; Weyant, 1999; Löschel, 2002; Jebaraja and Iniyan, 2006; van Vuuren et al., 2006c). However, the problem with classifying energy models is that there are many ways to characterize them, while the existing diversity implies that no single system fits all individual models. Van Beek (1999) identifies a large number of ways in which models can be characterized (purpose, model structure, analytical approach, methodological and mathematical approach, geographical coverage, sectoral coverage, time horizon and data requirements).

For the purpose of this thesis, we will be much less comprehensive and only point out a few important elements. All models share the characteristic of being abstractions of the real world and, so, by definition, have shortcomings. Their performance, therefore, needs to be assessed against the goals for which they are designed. In the field of energy–climate modeling, the main goals of using modeling tools include (based on Dowd and Newman, 1999):

- Defining possible pathways of greenhouse gas emissions under different assumptions;
- Defining target levels of greenhouse gas (GHG) emission reductions and/or least-cost responses to GHG reduction targets;
- Identifying the best technology opportunities for action;
- Identifying and assessing the effects and costs of proposed policies;
- Assessing the ancillary benefits of different energy policies;
- Estimating (or at least defining more clearly) sectoral costs;
- Assessing the interactive effects of various policies.

1.4.2 Modeling approach

A classic distinction is made in energy modeling between the so-called top-down versus bottom-up approach. The distinction, however, is not clear-cut. Within each approach, subgroups exist and the difference can therefore be better interpreted as a continuum, with more extreme forms on either side. Characteristic differences include:

1) the level of detail in the description of technology, and
2) the positioning of the energy sector in the larger economic context.

The *bottom-up approach* focuses on the energy system alone and describes a large number of single energy technologies to capture important dynamics such as the substitution of energy carriers, process innovations and energy savings (Löschel, 2002). A large group of bottom-up models (but not all) are used to determine the least-cost solution to meet a final energy demand subject to various system constraints such as emission reduction targets. The current energy system, however, is not necessarily assumed to be optimal. In contrast, by focusing on technologies, analysts tend to find a large number of technologies that would be cost-optimal to use but are currently not chosen due to all kinds of implementation barriers. The simples bottom-up models consists of technology databases with a relatively simple set of implementation rules, while more elaborate forms include the MARKAL models (see overview provided by Worrell at all. (2004).

The *top-down approach* emphasizes the relationship of the energy system to the general economy. The energy system is described in a highly aggregated way using economic production functions that capture factors like capital, labor and energy that can be substituted on the basis of elasticities (Löschel, 2002). Within the group of top-down models, different categories exist such as macro-econometric models (consisting of econometrically-determined relationships without equilibrium assumptions) and Computable General Equilibrium (CGE) models. The latter have become the most prominent tool among the different top-down models and is widely applied to estimate macro-economic impacts of greenhouse gas abatement policies. The substitution elasticities included in these models are determined on the basis of past trends, where response is assumed to be optimal and in full equilibrium. Examples of CGE models used in the field of energy-climate modeling include EPPA (Reilly and Paltsev, 2006) and WorldScan (Bollen et al., 2004; Lejour et al., 2006).

Historically, the categories of bottom-up and top-down models are not only characterized by different approaches but also show radically different outcomes (Smil, 2003). An important cause of this is the different assumption of the optimality of past and future energy systems as indicated in the description above (Grubb, 1993). In recent years, the distinction between the approaches has been gradually reduced – and the strengths and weaknesses of both approaches are recognized (Hourcade and Shukla, 2001; Hourcade et al., 2006). Bottom-up models bring in more energy-system detail and insights into technology development; top-down models add the larger economic context and a fuller concept of cost, but suffer from less detail and a lack of insight "physical" developments. Hybrid models have also been developed (Hourcade et al., 2006). Nevertheless, many models can still be classified on the basis of these two approaches.

Another important distinction in energy modeling is the difference between *optimization* and *simulation* models. These categories exist within both the approaches discussed above. The first aims to describe least-cost energy systems under a set of constraints (e.g. using linear programming or recursive dynamic techniques). Systems are thus in "equilibrium" (i.e. operated at the lowest over-all costs) from a centralized perspective. The strength of the approach is transparency and the ability to provide policy advice. The weakness is that for a real energy system such a "central optimizer" does not exist – and system behavior is determined by decisions of many decentralized actors. Simulation models, in contrast, describe the development of the energy systems with a pre-defined set of rules that do not necessarily require optimality. While the approach may describe real world systems better, it may be at the cost of reduced transparency.

In Chapter 6, we will compare a large set of currently used energy–climate models with respect to modeling of non-CO_2 gases. This overview includes a description of the main modeling approaches.

1.4.3 Environmental Integrated Assessment Models

A special group of so-called integrated assessment models (IAMs) has been developed in response to the environmental challenges facing human society today. These consist of energy/economy models in combination with environmental models. The focus of IAMs is on integration, either vertically (describing the full causal link of one particular problem) or horizontally (connecting various problems). As for energy models, subsets of IAM models may also be identified (e.g. Tol, 1996). Two typical approaches within the IAM community are the policy optimization models and the process-based IAM. The first approach, rooted in economics, combines simplified economic and climate change models in order to perform cost-benefit analysis of both mitigation costs and climate damages, such as the DICE model (Nordhaus, 1993) and the FUND model (Tol, 1996). These models typically have a high level of integration and focus on overall messages. The alternative, process-based approach focuses more on the physical processes that cause climate change and describes these with a high degree of detail. This approach is rooted more in system-dynamics. Examples include MiniCAM, AIM and IMAGE (descriptions and references of these models are provided by Nakicenovic and Swart (2000)). The first category of IAM models connects better to the top-down approach in energy modeling, while the second has stronger connections to the bottom-up approach.

1.4.4 Trends in model development

Without the pretention of being complete, some crucial challenges in energy-climate modeling can be identified:

- Uncertainty management is the key to any modeling attempt. Nevertheless, further attention needs to be paid to this (Lempert et al., 2004; de Vries, 2006b).
- Attempts have been made to develop top-down/bottom-up hybrid models. Such models can provide technical detail and include other measures than pricing measures (see further), while still ensuring economic consistency in their assumptions (Hourcade et al., 2006).
- More attention is paid to the role of technology change, both in energy system models and in economic models (endogenous technology change) (Edenhofer et al., 2006).
- Model results have been mostly analyzed at the level of the world as a whole. More explicit modeling of spatial issues and bringing existing regional detail forward might be important topics: for instance, considering that developing countries are becoming more and more important (e.g. China) (de Vries, 2006b).
- At the moment, most models focus on more-or-less optimal (least-cost) solutions induced by price measures. Future modeling efforts may pay more attention to different types of policies (Worrell et al., 2004).

1.4.5 The position of the TIMER model

The TIMER model used in this thesis is an energy system model. It is relatively rich in technological detail, although not as detailed as real bottom-up models. The model uses a simulation approach (Chapter 2 provides an extensive description of the model). Its relative strength compared to some of the other models is the integration within the IMAGE-integrated assessment model, the connection to the FAIR climate policy modeling framework, the relatively well-advanced description of technology change, emissions of greenhouse gases and air pollution and its applications in the field of renewable energy. IMAGE (Integrated Model to Assess the Global Environment) is a process-based Integrated Assessment Model that consists of several coupled submodels (Bouwman et al., 2006) (see also Chapter 2). Together, they describe elements of global environmental change, in particular, climate change and land use. FAIR (Framework to Assess International Regimes for differentiation of future commitments) is a policy-support model that deals with international climate policy, including burden-sharing issues and evaluation of emission pathways (den Elzen and Lucas, 2005). In recent years, the TIMER model has contributed to advancing the state of science in energy modeling in some of the fields mentioned above. This includes, for instance, the progress in assessing uncertainties (Chapter 5), modeling technology dynamics (Chapter 8 of this thesis), the provision of regional detail (see Chapter 4 of this thesis), introduction of alternative policy instruments (Chapter 4 and Chapter 9) and the study of low concentration stabilization levels (Chapter 7).

1.5 Aim and outline of the thesis

1.5.1 Aim

In the previous sections, an overview was given of some relevant issues related to long-term development of the energy system. Climate change was shown to represent one of the most important challenges for the energy system in the current century. Development of the energy system in relation to climate change and socio-economic changes can be studied using scenario analysis and energy modeling. Within this context, this thesis concentrates on the analysis of long-term energy–climate scenarios, addressing three crucial questions:

1. *What are possible development pathways for the global energy system and associated emissions in the absence of climate policy?*
2. *What types of uncertainties are associated with energy scenarios, and what are promising ways of handling those?*
3. *Is it possible to stabilize greenhouse gas concentrations at low levels – and if so, what kind of strategies might contribute to this?*

The first two questions are clearly interlinked and will be dealt with in Part 2 of this thesis. The third question forms Part 3 of this thesis (Part 1 of the thesis includes the introduction sections).

Baseline emission paths and uncertainties (part 2)

Exploring the development of the energy system and related greenhouse gas emissions in the absence of climate policy is not only useful for identifying the possible impact of climate change, but baseline emissions also represent a major factor determining the costs of climate policy.

Uncertainties in emission scenarios have various causes and can be classified in different ways (Moss and Schneider, 2000; Dessai and Hulme, 2001; Van der Sluijs et al., 2003; Patt and Dessai, 2005). Chapter 5 provides a discussion of the uncertainty categories. Further exploring uncertainties in relation to long-term scenarios is a relevant exercise (de Vries, 2006b). Methods that have been applied in the past include: 1) alternative scenario method, 2) fully probabilistic method, 3) model comparison, 4) validation of scenario results against real trends and 5) the NUSAP method. In the literature, a lively debate has been held with respect to the first two methods, revealing their strengths and weaknesses. While the strength of the alternative scenario method is that it is able to make consistent assumptions for domains characterized by weak knowledge, critics argue that the lack of probability assignments imply that usefulness of the information for decision-makers is limited. In contrast, the strength of probabilistic methods is that they provide a formalized method to deal with uncertainty in relatively well-defined systems. Critics, however, indicate that the attempts of the method to assign subjective probabilities in a situation of ignorance form a dismissal of uncertainty in favor of spuriously constructed expert opinion.

In Part 2 of the thesis, we discuss four studies that analyze possible greenhouse gas emission pathways in relation to the issue of uncertainties using :1) comparison of scenarios with historical trends and short-term projections, 2) alternative scenarios, 3) model comparison and 4) conditional probabilistic analysis. The last method represents an attempt to combine the strength of the scenario approach in providing consistent descriptions of various uncertainties, and dealing with ignorance of the strengths of the formal uncertainty approach in making/using explicit probability statements. The rationale is that the reduction of the uncertainty space, with help of divergent storylines, will make uncertainties more suitable for a formal uncertainty method.

Collectively, the studies provide insight into potential developments in the energy system and associated emissions globally and regionally, with China as regional example.

Mitigation analysis (part 3)

Limiting global mean temperature increase to 2°C (the target of EU climate policy) is likely to require stabilization at low greenhouse gas concentration levels (a 20% probability is obtained at 550 ppm CO_2-eq; a 50% probability at 450 ppm CO_2-eq). In Section 1.3, however, we have shown that scenarios aiming for such low GHG concentrations levels hardly exist. In Chapter 7, we have, therefore, analyzed whether stabilization of low GHG concentration could be achieved and what kind of strategies would be required. Chapter 7 uses a comprehensive integrated assessment approach, combining energy modeling (TIMER), land-use modeling (IMAGE), climate modeling (IMAGE & FAIR) and climate policy (FAIR). The study also pays considerable attention to the associated uncertainties.

Next, we analyze two crucial issues in more depth: 1) technology development and 2) co-benefits. Analysis of mitigation strategies shows technology assumptions to be crucial for the feasibility of low concentration levels, for costs and for the timing of action. In this context, we explore the impact of different assumptions in technology change. Finally, we look into co-benefits by analyzing the relationship between climate policy and air pollution control using a coupled integrated assessment modeling approach, TIMER and RAINS.

1.5.2 Outline

Chapter 2 first provides a description of the TIMER model and its main subcomponents. The TIMER model, an energy system model, is used in most of the remaining chapters of this thesis.

In part 2, Chapter 3 presents "a reality check" of one of most influential emission scenario projects of the last decade, i.e. IPCC's Special Report on Emission Scenarios (SRES). The scenarios cover a very long time period, from 1990 to 2100, on the basis of analysis performed mainly in the 1996-1998 period. Comparing these scenarios to information on actual trends between 1990 and 2000, more recent medium- and long-term scenarios can be used to highlight the level of uncertainty involved in long-term energy and climate projections and to see how these projections stand the test of time[v]. Constant validation of the SRES scenarios is important as these scenarios still form an important basis of climate modeling.

In Chapter 4, we apply the scenario approach as a method of dealing with fundamental uncertainties with respect to future developments in the energy system of China. We use the scenario approach (based on the IPCC SRES storylines), not only to develop long-term baseline scenarios together, but also to evaluate different options for mitigating the growth of greenhouse gas emissions. Given China's large population and rapidly growing economy, different development pathways for China's energy system will not only have important consequences for China itself, but also for the rest of the world. The chapter also provides insight into how uncertainties can be handled in the scenario analysis.

In Chapter 5, we go beyond the classic alternative scenario approach that is applied in Chapter 4, by proposing a conditional probabilistic approach as a novel method of dealing with uncertainty in long-term energy scenarios. This method has been applied earlier to population scenarios (O'Neill, 2004). The method consists of formal proba-

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[v] The TIMER model was one of the models used in the SRES report.

bilistic uncertainty analysis using the TIMER model conditional upon the IPCC SRES storylines. The central issue of this chapter is how global emissions in the 21st century could develop, realizing the role of different type of uncertainties? In addition, we also identify the most important parameters contributing to uncertainty in these TIMER scenarios.

Chapter 6 uses model comparison as a method to deal with a more fundamental form of uncertainty, i.e. uncertainty related to the modeling approach. The chapter focuses on a set of multi-gas scenarios developed in the context of Stanford University's Energy Modeling Forum (EMF-21) by a large number of models. In the chapter, we compare the results of these models to identify robust messages – mainly with respect to development of CO_2 and non-CO_2 emissions, the advantages of a multi-gas approach compared to strategies focusing on CO_2 alone and different ways to deal with the substitution across different gases. The chapter can be used to compare the uncertainty range of one model (identified in the previous chapter) against those in a whole set of models.

As the main chapter in part 3 (on mitigation scenarios), Chapter 7 discusses the application of TIMER (in the larger context of the IMAGE modeling framework) in developing low greenhouse gas concentration stabilization scenarios. These scenarios assess a wide range of mitigation options, and discuss different scenarios aiming at 450, 550 and 650 ppm CO_2-eq. The central issue in this chapter is whether stabilization at such low greenhouse gas is possible – and if so, what would be the consequences for the energy system. In the chapter, we also identify important uncertainties influencing results.

In Chapters 5 and 7, we show the crucial importance of technology development assumptions for baseline emissions and mitigation costs. In the TIMER model, technology development is mostly modeled in the form of "learning-by-doing". In Chapter 8, this concept leads to both learning under baseline conditions and policy-induced learning. The relative strength of these two processes is very important for the timing of climate policy. In the chapter, a set of experiments is performed (varying the timing of policy) to identify the importance of learning assumptions on the model response to different carbon tax levels.

In Chapter 9, we further elaborate the issue of co-benefits by discussing results of TIMER and RAINS models in taking an integrated approach to climate change and air pollution in Europe under the Kyoto Protocol. The central issue is to identify the possible extent of co-benefits of the Kyoto Protocol (based on different ways this Protocol is implemented). It should be noted that such co-benefits could actually form an important leverage in the implementation of climate policies, given the fact that the former are much earlier in time than the latter.

Finally, Chapter 10 brings together the highlights of the preceding chapters in a summary.

2. TIMER MODEL DESCRIPTION

Abstract. The TIMER model describes long-term development pathways in the energy system in the broader context of impacts on climate change, air pollution and sustainable development. TIMER is integrated into the integrated assessment modeling framework IMAGE via energy-related emissions of greenhouse gases and air pollutants, the use of bio-energy, and the role of the energy system in mitigation scenarios. In dynamic terms, the models describe the evolution of a set of energy technologies in different energy markets (most notably five end use sectors, electric power, hydrogen production) that compete for market shares on the basis of their relative costs and preferences. In time the costs of these technologies are driven by both technology development and depletion dynamics. The coupled TIMER-IMAGE-FAIR framework can be used to study different mitigation scenarios.

This chapter is based on: Van Vuuren, D.P, van Ruijven, B., Hoogwijk, M., Isaac, M., de Vries, B. (2006). TIMER 2.0: Model description and Application. In: Bouwman, L., Kram T. and Klein-Goldewijk, K. (2006). IMAGE 2.4: An overview, Netherlands Environmental Assessment Agency, Bilthoven.

2.1 Introduction

Energy forms a central component of discussions on sustainable development. The use of energy supports economic development; furthermore, securing affordable energy supply is an important element in the economic and energy policies of many countries. Fossil fuel resources, which currently account for more than three-quarters of the world energy use, are slowly being depleted. Especially oil and gas resources are becoming more and more concentrated in a limited number of supply regions. At the same time, renewable energy sources have limitations too. Secondly, fuel combustion is the single most important cause of both air pollution and greenhouse gas emissions. The future of global energy use is highly uncertain and depends on such uncertain factors as technological innovation and breakthroughs, as well as socio-economic development, resource availability and societal choices. Exploring different scenarios for the future energy system can thus provide crucial information to decision-makers.

The IMage Energy Regional model (TIMER) is an energy model that has been developed to explore different scenarios for the energy system in the broader context of the IMAGE environmental assessment framework (Integrated Model to Assess the Global Environment) (Alcamo et al., 1996, Bouwman et al., 2006). TIMER is an energy-system simulation model, describing the demand and supply of 12 different energy carriers for a set of world regions. Its main objective is to analyze the long-term trends in energy demand and efficiency and the possible transition towards renewable energy sources. Within the context of IMAGE, the model describes energy-related greenhouse gas and air pollution emissions, along with land-use demand for energy crops. The TIMER model focuses particularly on several dynamic relationships within the energy system, such as inertia, learning-by-doing, depletion and trade among the different regions. The TIMER model is a simulation model, which means that the results depend on a single set of deterministic algorithms instead of being the result of an optimization procedure. As such, it can be compared to other energy system simulation models such as POLES (Criqui and Kouvaritakis, 2000). A description of the different types of energy models, and the position of the TIMER model within this field, can be found in Chapter 1 of this thesis.

The TIMER model was originally developed as a one-world model (TIME) for the TARGETS sustainable development model (Rotmans and de Vries, 1997). Between 1997 and 2000, a model version with 17 world regions was developed (TIMER 1.0) (de Vries et al., 2001). The TIMER 1.0 model was applied, amongst others, for the development of some of the IPCC SRES scenarios (de Vries et al., 2000), exploration of climate policies (van Vuuren and de Vries, 2001; Van Vuuren et al., 2003b), country-level scenario assessment and, together with IMAGE, global environmental scenario studies (UNEP, 2002; Carpenter and Pingali, 2006). The TIMER 1.0 model is used in Chapters 4, 8 and 9 of this thesis.

More recently, improved modeling of renewable energy sources, revision of the electricity model and the development of a hydrogen sub-model has led to the TIMER 2.0 model[i]. This model version was used to explore different stabilization strategies, as discussed in Chapter 7 of this thesis. The model is also used in the uncertainty analysis described in Chapter 5. While some interesting elements have been added to the model, the differences between TIMER 1.0 and TIMER 2.0 are not relevant for the main conclusions of the chapters where TIMER 1.0 has been applied.

In this chapter we present an overview of the TIMER model, including the most recent developments. Full documentation on the TIMER 1.0 model is available (de Vries et al., 2001). Section 2.2 overviews the model and discusses the sub-models on energy demand, conversion and supply. Section 2.3 discusses some crucial model elements, including technology development, and depletion and substitution. Section 2.4 indicates how the TIMER model can be used in combination with FAIR and IMAGE.

2.2 Model Outline and Structure

The TIMER model describes the chain from demand for energy services (useful energy) to the supply of energy by different primary energy sources and related emissions (Figure 2.1). The steps are connected by demand for energy (from left to right) and by feedbacks, mainly in the form of energy prices (from right to left). The TIMER model has three types of submodels: (i) the energy demand model; (ii) models for energy conversion (electricity and hydrogen production), and (iii) models for primary energy supply. Some of the main assumptions for the different sources and technologies are listed in Table 2.1.

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[i] Even more recently, the TIMER 2.0 model has been recalibrated for 26 regions.

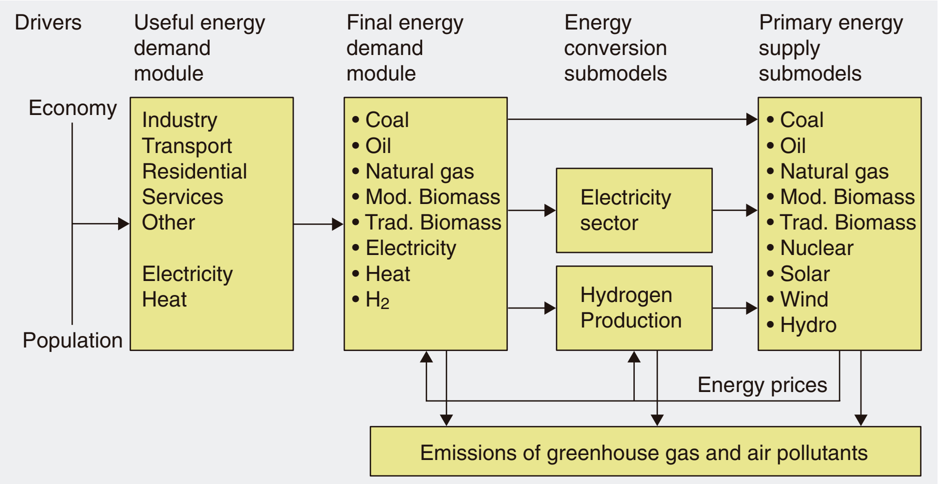

Figure 2.1 Overview of the TIMER model.

2.2.1 The Energy Demand submodel

Final energy demand (for five sectors and eight energy carriers) is modelled as a function of changes in population, in economic activity and in energy intensity (Figure 2.2). The model distinguishes four dynamic factors: structural change, autonomous energy efficiency improvement, price-induced energy efficiency improvement and price-based fuel substitution, which are discussed below.

First, demand for useful energy (or energy services) is calculated according to:

$$UE_{R,S,EF} = Pop_R {}^* \; ACTpc_{R,S} {}^* \; SC_{R,S,EF} {}^* \; AEEI_{R,S,EF} {}^* \; PIEEI_{R,S,EF} \tag{2.1}$$

in which Pop represents population, ACT pc the sectoral economic activity indicator (see Table 2.2), SC a factor capturing sub-sectoral structural change, AEEI the autonomous energy efficiency improvement and PIEEI efficiency improvement in response to prices. The indices R,S, and EF indicate region, sector and energy form (heat or electricity), respectively. Both population and economic activity levels are exogenous assumptions to the model.

The energy-intensity development for each sector as a result of sub-sectoral structural change only (i.e. energy units per monetary unit in absence of efficiency improvement) is assumed to be a bell-shaped function of the per capita activity level (i.e. sectoral value added or GDP) (see equation 2.2):

$$SC_{R,S,EF} = UEIbase_{R,S,EF} + 1/(\alpha + \beta {}^* \; DFpc_{R,S} + \gamma {}^* \; DFpc_{R,S}{}^{\delta}) \tag{2.2}$$

in which UEIbase indicates a base intensity level, DFpc the per capita driving force indicator (see Table 2.2) and α, β, γ and δ calibration parameters. The SC formulation can be

Table 2.1 Some main assumptions in the TIMER model

Option	Assumptions	References
Fossil fuels	Regional resources and production costs for various qualities; the ultimate coal, oil and natural gas resources equal 300, 45, and 117 ZJ, respectively. In time, depletion leads to price increases, while technology change reduces prices. Under a medium scenario (B2) global average crude energy prices in 2050 are around 1.4, 5.1 and 4.4 1995US$ / GJ for coal, oil and natural gas, respectively. In 2000, these prices are 1.1, 3.0 and 2.3 1995US$ / GJ.	Rogner (1997), TNO (2006)
Carbon capture and storage (CCS)	Regional reservoir availability and storage costs for various options (different categories of empty oil and natural gas reservoirs, coal reservoirs, coal-bed methane recovery, aquifers). Total capacity equals 1500 GtC. Transport and storage costs range, depending on category and region, from 10-150 US$/tC.	Hendriks et al. (2002a)
Power plant efficiency and investment costs	Power plant efficiency and investment costs for 20 types of thermal power plants (coal, oil, natural gas, biomass) including carbon capture and storage defined over time.	Hendriks et al. (2004)
Energy crops	Potential and costs for energy crops defined by region on the basis of IMAGE 2 maps (including abandoned agricultural land, natural grasslands and savannah). Primary biomass can be converted into liquid biofuels (for transport) and solid bio-energy (for electricity). Technology development is based on learning-by-doing. Under a medium (B2) scenario, maximum potential equals 230 EJ in 2050 and 600 EJ in 2100. Production costs for liquid fuels varies from 12-16 US$/GJ in 2000 to around 8-12US $/GJ in 2050 (depending on scenario). Production costs for solid fuels varies around 4 US$/GJ.	Hoogwijk (2004)
Solar / wind power	Solar and wind power based on studies that assess global potential on the basis of 0.5 x 0.5 degree maps. Costs change over time as a result of depletion, learning-by-doing and grid penetration (declining capacity credit and excess electricity production).	Hoogwijk (2004)
Nuclear power	Investment costs of nuclear power based on available information in the literature (most important references indicated). Investment costs are assumed to decrease over time. Fuel costs increase over time as a result of depletion.	MIT (2003); Sims et al. (2003)
Hydrogen	Hydrogen modelled on the basis of production from fossil fuels, bio-energy, electricity and solar power (including carbon capture and storage).	Van Ruijven et al. (in press)
Energy demand	Parameters for autonomous and price-induced efficiency improvement, and structural change, are mostly based on model calibration.	De Vries et al. (2001)

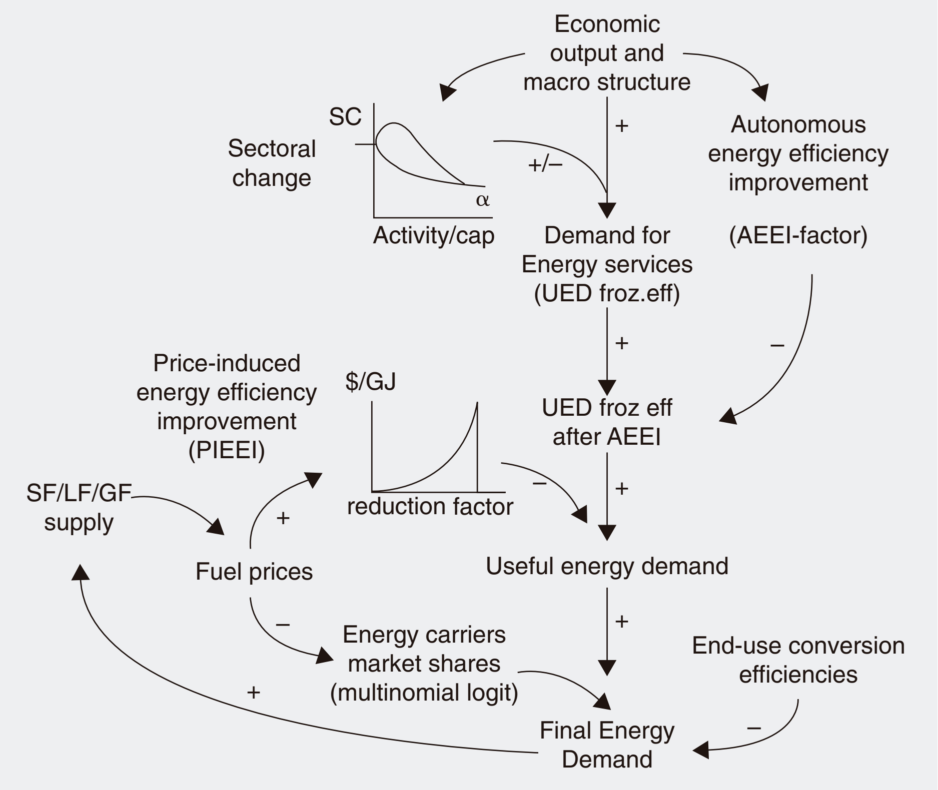

Figure 2.2 System dynamics representation of the Energy Demand submodel. UED is Useful Energy Demand, i.e. the energy services delivered; SF/LF/GF indicate Solid Fuel, Liquid Fuel and Gaseous Fuel respectively (+/- signs indicate positive/ negative coupling between parameters).

interpreted as the income elasticity that is included in most energy-economics models (increase in energy demand for an increase in income levels), although the value of income elasticity in equation 2.2 is far from constant.

The form of this equation is indicated on the left-hand side of Figure 2.3, while the right-hand side indicates the resulting trajectory for per capita energy use. The form reflects an empirical observation that a changing mix of activities with rising activity within a sector could first lead to an increase and then to a decrease in energy intensity (structural change). Evidence of this trend is more convincing in some sectors (e.g. industry) than in others (e.g. transport) (de Vries et al., 2001). The assumed formulation assumes saturation at a constant per capita useful energy use per sector – although the choice of parameters can actually imply that this occurs at activity levels that are unlikely to be reached during the scenario period. In any case, the actual shape of this function (defined by sector and region) has a large influence on the demand for energy services in the model. The activity indicator and the assumed drivers of structural change trends are indicated in Table 2.2.

Table 2.2 Sectors, activity indicators and driving forces of structural change, where the economic activity levels (activity and driving force) are both exogenous assumptions to the model

	Activity	Driving force	Intensification	Extensification	Heat/power
Industry	Industry VA pc	GDP pc	Growth of heavy industry	Shifts to high value-added industries	Eq. 2.2 for total demand; % electricity set externally
Transport	GDP pc	GDP pc	Rapid growth of freight and person transport	Saturation of transport	Eq. 2.2 for total demand; % electricity set externally
Residential	Priv. Cons pc	Priv. Cons pc	Rapid increase in heating/cooling demand + appliance use	Saturation	Eq. 2.2 applied to heat and power separately
Services	Service VA pc	Service VA pc	Rapid increase in heating/cooling demand + appliance use	Shifts to high value-added sectors	Eq. 2.2 applied to heat and power separately
Other	GDP pc	GDP pc	Intensification of energy use in agriculture	Saturation of agriculture energy demand	Eq. 2.2 for total demand; % electricity set externally

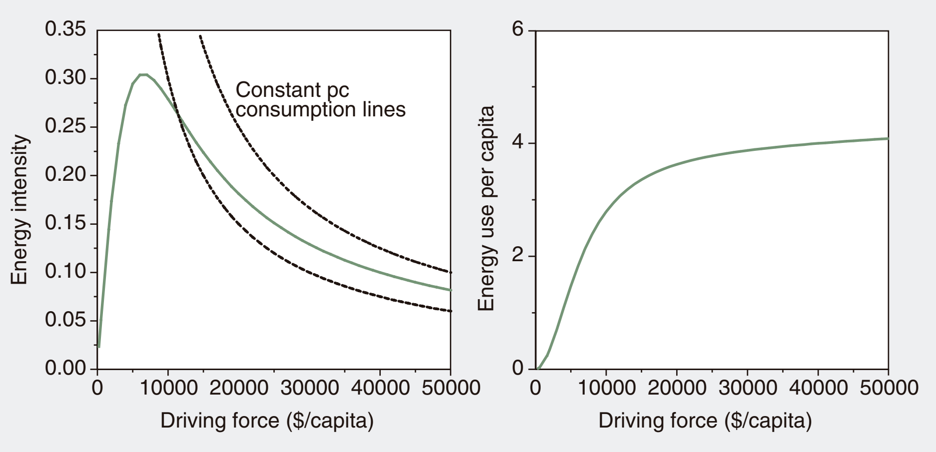

Figure 2.3 Assumed trend in energy intensity per sector (in GJ/$, either sectoral value-added, private consumption or GDP) as a result of structural change (SC) (left) and the corresponding energy use per capita (GJ/cap).

The Autonomous Energy Efficiency Increase (AEEI) multiplier accounts for efficiency improvement that occurs as a result of technology improvement independent of prices (equation 2.3).

$$AEEI(mrg)_{R,S,EF} = f * ACT_{R,S} / ACT_{R,S,t-1} \qquad (2.3)$$

The marginal AEEI, AEEI(mrg), is assumed to be a fraction (f) of the economic growth rate based on the formulation of Richels et al.(2004). The fraction in TIMER varies between 0.45-0.30 and is assumed to decline in time, as the scope for further improvement is assumed to decline (in a similar way, as included in learning curves, see Section 2.3). The marginal AEEI is implemented with the capital turnover rate assuming a vintage model. The current AEEI thus represents the weighted average (by investment rate) of the marginal AEEI over the capital lifetime. In other words, rapid economic growth leads to a more rapid decline in AEEI, both via a rapid decline in the marginal AEEI and via a larger share of the total capital stock that is relatively new. While, the existence of AEEI is somewhat controversial in economics literature, the AEEI is, from an engineering perspective, a logical representation of technological progress and, as such, a specific implementation of the total factor productivity improvement included in most economic models.

A next multiplier, the Price-Induced Energy Efficiency Improvement (PIEEI), describes the effect of rising energy costs on consumers; this is formulated in TIMER on the basis of a simulated energy conservation cost curve (Figure 2.4 and equation 2.4). This multiplier is calculated using a sectoral energy conservation supply cost curve (characterized by a maximum reduction CC_{max} and a steepness parameter CCS) and end-use energy costs (CostUE).

$$EE_{opt} = CC_{\max} - 1 \Big/ \sqrt{CC_{\max}^{-2} + CostUE * PBT / CCS} \tag{2.4}$$

The calibration of this curve is described by De Vries et al. (2001). The basis is the assumption that investments into energy efficiency are made if they are equal or less than to the product of an apparent pay-back time and the current energy prices. The pay-back time formulation (a simplified investment criterion) states that all the investments made earn back the original investment within a given time period. The term “apparent” refers to the observation that while investors in energy efficiency indicate use of a certain pay-back time in their investment decision, in reality, lack of information (or other barriers) imply that not all investments meeting the pay-back criterion are made. Investments into efficiency lead to improvements in efficiency according to the sectoral energy conservation curve (see Figure 2.4). The whole curve slowly decreases over time as a result of technology improvement as a result of economies of scale and innovation lowering CCS (learning-by-doing; see 2.3). The improvement of the PIEEI factor is directly related to EE_{opt}, but includes some delay: it includes partly a direct response (equal to EE_{opt}) and partly to a delayed response via a vintage model. The PIEEI factor corresponds to the short- and long-term price elasticity in economic models. In TIMER different efficient levels between regions can be created by using different pay-back times. The pay-back times implied in developed nations vary from 1 year for transport, 2 years for other sectors and 3 years for industry (these values are low, given the fact they are apparent pay-back times). In modelling response to carbon prices, however, a pay-back time of 6 years is used to identify efficiency improvement responses that can be regarded as cost-effective compared to supply-side investments.

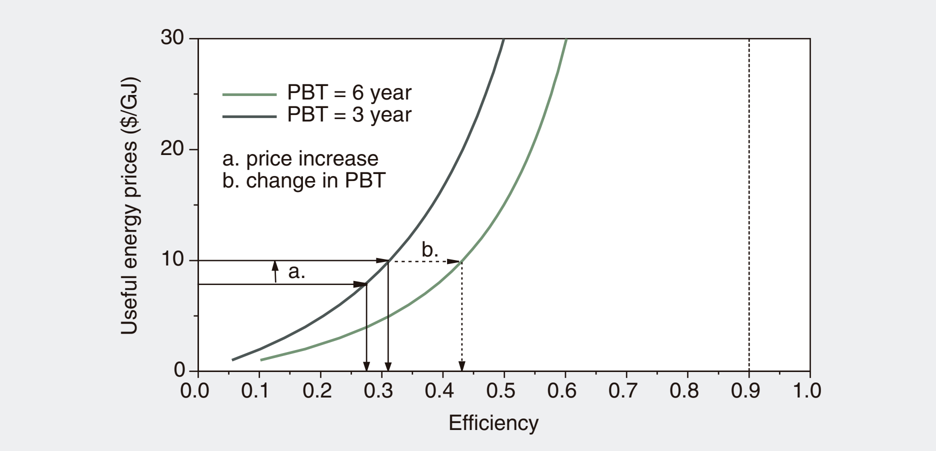

Figure 2.4 Assumed formulation for price-induced efficiency improvement (in other words, the conservation supply cost curve).

Finally, the demand for secondary energy carriers is determined on the basis of the useful energy demand by the relative prices of the energy carriers (see Figure 2.2). For each energy carrier, a final efficiency value (η) is assumed to account for differences between energy carriers in converting final energy into useful energy. This corresponds to equation 2.5:

$$SE_{R,S,EF} = \sum UE_{R,S,EF} * \mu_{R,S,EC} / \eta_{R,S,EC} \tag{2.5}$$

in which SE is secondary energy demand, UE useful energy demand (see eq. 2.1), μ the market share of each fuel, and η the conversion efficiency from secondary to useful energy.

In simulating the market share of each fuel (using a multinomial logit equation; see section 2.3) not only are direct production costs accounted for, but also energy and carbon taxes and so-called premium values. The latter reflect non-price factors determining market shares, such as preferences, environmental policies and strategic considerations. These premium values are determined in the calibration process of the model in simulating correct historic market shares on the basis of simulated price information. The same values are used in scenarios as a way to simulate assumption of societal preferences for clean and/or convenient fuels.

In TIMER, alternative approaches are used for traditional biomass and secondary heat. The market share of traditional biomass is assumed to be driven by per capita income, where a higher per capita income leads to lower per capita consumption of traditional biomass. The market share of secondary heat from, for instance, district heating is determined though an exogenous scenario parameter. Non-energy use of fossil fuels is modelled on the basis of an exogenously assumed intensity parameter (related to industry value-added) and on a price-driven competition of the various energy carriers.

Box 2.1 Ambiguity in model calibration

The behaviour of an energy model depends both on its structure and its parameter settings., Even under a given (simple) structure, different parameter settings for very uncertain factors may still lead to very different results, as is shown for learning in Section 2.3. At the same time, lack of historic information often allows for ultiple interpretations (and this parameter settings of the past).

2.2.2 The Electric Power Generation submodel

The Electric Power Generation submodel (Figure 2.5) simulates investments in various electricity production technologies and their use in response to electricity demand and to changes in relative generation costs (see also Hoogwijk, 2004).

The demand for capacity is derived from the forecast for the simultaneous maximum demand and a reserve margin of about 10%. The simultaneous maximum demand is calculated on the basis of the gross electricity demand (ElDem) that equals the net electricity demand (SE(Elec)) plus electricity trade (ElTrade) and transmission losses (TransLoss).

$$ElDem = (SE(Elec) + Eltrade)\ ^{*}\ (1 + TransLoss) \qquad (2.6)$$

The model determines a monthly load duration curve for each region by multiplying the electricity demand by the relative demand of 10 fraction of electricity ($Frac_{M,T}$). These together describe the load duration curve (LDC). The form of the Load Duraction Curve has been determined by region-specific factors such as heating and cooling degree days, daylight and assumed patterns of appliance use. In general, this results in a monthly variation with a maximum value of 20-30% above the average value and a minimum value 40% below. The SMD equals the highest value found each year (the annual pattern is indicated in Figure 2.6).

$$SMD = Max(ElDem^{*} Frac_{M,T}) \qquad (2.7)$$

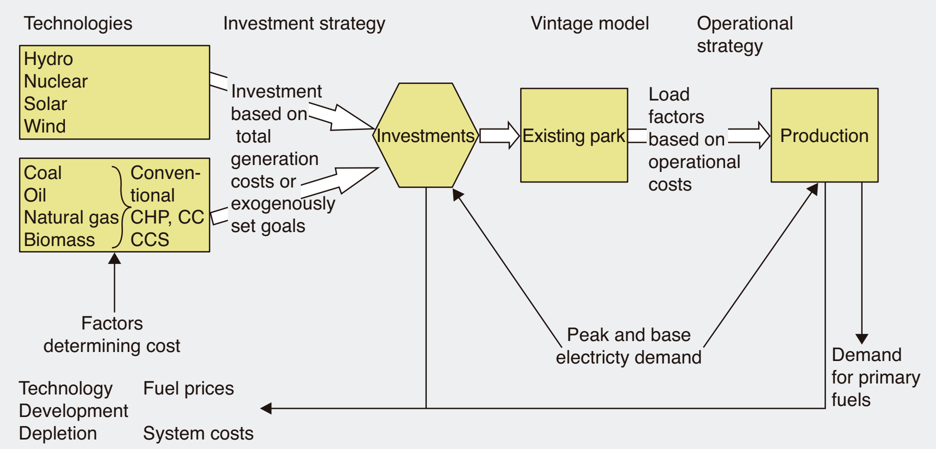

Figure 2.5 Schematic presentation of the Electric Power Generation model.

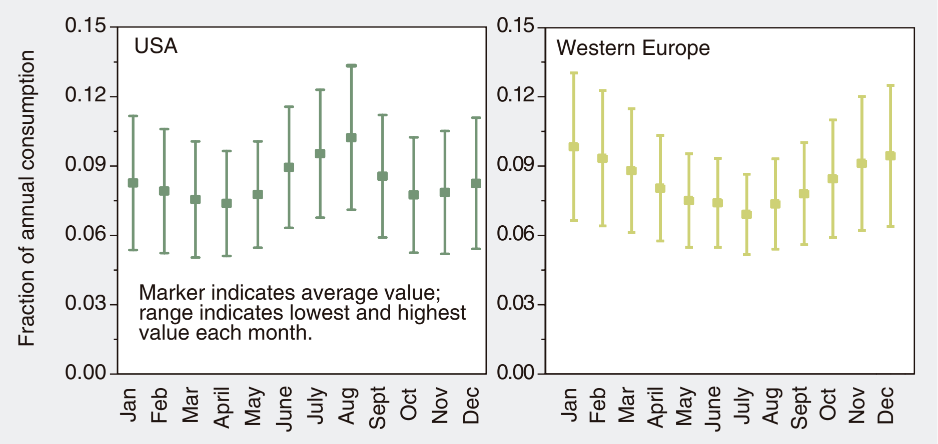

Figure 2.6 Annual pattern of electricity demand shown for two regions.

Different technologies compete for a share in newly installed capacity on their total costs., Different cost categories are specified for each plant: i.e. investment costs, fuel costs, operational and maintenance costs and other costs. The last category may include costs for CO_2 storage and additional costs as a result of the intermittent character of solar and wind power (additional capacity, discarded electricity and additional spinning reserve requirements). The demand for new capacity equals the required capacity minus existing capacity, plus capacity that is going to be replaced (lifetime of plants varies from 30 to 50 years). Notably, an exception is made for hydropower. The capacity for hydropower is exogenously described, given the fact that here often other considerations than electricity production play a role.

The basic rule-of-thumb for the operational strategy is that power plants are operated in order of operational costs (merit order strategy). This implies that capital-intensive plants with low operational costs, such as for renewables and nuclear energy, will therefore in principle operate as many hours as possible. To some degree this is also implied for other plants with low operational costs (e.g. coal). In TIMER, the merit order strategy is simulated in three steps:

1. first intermittent renewable sources are assigned, followed by hydropower;
2. in the next step base load is assigned on the basis of the remaining capacity, using a multinomial logit model (see section 2.3);
3. finally, peak load is assigned, again using a multinomial logit model.

We realize that in reality, the merit order strategy is more complex, given all kinds additional requirements with respect to reliability and start-up times.

Fossil fuels and bio-energy can be used to generate electricity in a total of 20 different plant types that represent different combinations of (i) conventional technology; (ii) gasification and combined cycle technology; (iii) combined-heat-and-power and, (iv) carbon-capture and storage (see also Hendriks et al., 2004). The efficiency and capital requirement of these plant types are determined by exogenous assumptions that describe technological progress of typical component of these plants (the characteristics of the total set are derived from these typical components).

- For conventional plants, the coal-based plant is defined in terms of overall efficiency and investment costs into fuel handling, plant and fuel gas cleaning and operational costs. All other conventional plants (oil, natural gas and bio-energy) are derived by indicating differences for investments for a) desulphurization, b) fuel handling and c) efficiency.
- For Combined Cycle plants, the natural gas combined cycle plant is set as standard. Other plants are defined by indicating additional capital costs for gasification, efficiency losses for gasification and O&M costs for fuel handling.
- Carbon capture and storage plants are assumed to be Combined Cycle plants with correction (as a function of the carbon content of the fuel) for efficiency, investment costs, O&M costs (for capture) and storage costs.
- CHP plants can be based on Combined Cycle plants or conventional plants (the model selects the lowest costs option). In both cases a small increase in capital costs is assumed in combination with a lower efficiency for electric conversion and an added factor for heat efficiency (in other words, the model only includes large-scale CHP).

Table 2.3 provides, as illustration, some of the key parameters for the electric power technologies in Europe (B2 scenario).Apart from thermal plants, the model distinguishes hydropower, solar power, wind power and nuclear power. The costs of technologies are described in terms of learning and depletion dynamics.

For renewable energy sources with an intermittent character (wind and solar power), additional costs are determined for discarded electricity (if production exceeds demand), back-up capacity, additional required spinning reserve (both to avoid loss of power if supply of wind and solar power suddenly drops; spinning reserve is formed by power stations operating below maximum capacity, which can be scaled up in relatively little time) and depletion (see also Hoogwijk, 2004).

- To determine discarded electricity for each load fraction a comparison is made between supply and demand. It is assumed that wind power can be either fully in-phase or fully out-of-phase with electricity demand: both situations are calculated and the average is used. For PV, it is assumed that supply mainly occurs during the central part of the LDC. If supply exceeds demand, this is assumed to be discarded, reducing the effective load factor of wind and solar electricity (and thus increasing their costs).
- Back-up capacity is added to account for the low capacity credit (its contribution to a reliable supply of electricity at any moment of time) of the intermittent sources (Figure 2.7). For the first 5% penetration of the intermittent capacity, the capacity credit equals the load factor of the wind turbines. If the penetration of intermittent sources increases further, the capacity credit decreases. The costs of back-up power (capacity with a high capacity credit but low capital costs) are allocated to the intermittent source.

Table 2.3 Power plants in the TIMER model and some assumed key characteristics (Western Europe, central scenario)

	Capital costs.		Electric Efficiency		OM costs	
	$/MW		%		$/kWh	
	2000	2050	2000	2050	2000	2050
PV	6102	1809	-	-	$ 0.015	$ 0.015
Wind	1377	555	-	-	$ 0.009	$ 0.010
Hydro	1355	1427	-	-	$ 0.017	$ 0.017
Nuclear	2319	2161	-	-	$ 0.008	$ 0.008
Coal (steam-electric)	1280	1113	41%	52%	$ 0.007	$ 0.005
Oil (steam-electric)	1138	1014	42%	53%	$ 0.006	$ 0.004
NG (steam-electric)	900	867	43%	54%	$ 0.004	$ 0.003
Biomass (steam-electric)	1469	1182	39%	51%	$ 0.006	$ 0.005
Coal (IGCC)	1696	1057	44%	54%	$ 0.010	$ 0.007
Oil (IG CC)	1696	1057	44%	54%	$ 0.010	$ 0.007
NG (CC)	716	562	54%	62%	$ 0.003	$ 0.002
Biomass (BIGCC)	3079	1145	42%	52%	$ 0.010	$ 0.007
Coal (CCS)	2180	1330	33%	46%	$ 0.012	$ 0.009
Oil (CCS)	2029	1245	33%	46%	$ 0.011	$ 0.008
NG (CCS)	1052	750	45%	55%	$ 0.005	$ 0.003
Biomass (CCS)	3612	1447	31%	44%	$ 0.014	$ 0.010
Coal (CHP)	1356	1170	34%	47%	$ 0.007	$ 0.008
Oil (CHP)	1259	1107	34%	45%	$ 0.006	$ 0.005
NG (CHP)	822	666	46%	53%	$ 0.003	$ 0.002
Biomass (CHP)	1524	1220	32%	45%	$ 0.007	$ 0.008
Coal (CHP/CCS)	2280	1430	27%	39%	$ 0.012	$ 0.009
Oil (CHP/CCS)	2129	1345	27%	38%	$ 0.011	$ 0.008
NG (CHP/CCS)	1152	850	37%	46%	$ 0.005	$ 0.003
Biomass (CHP/CCS)	3712	1547	25%	37%	$ 0.014	$ 0.010

Note: The use of CHP plants depends on exogenously subscribed heat demand. Progress for all these plants is determined by exogenous assumptions (see main text) except nuclear, PV and wind power that use learning curves.

- The required spinning reserve is assumed to be 3.5% of the installed capacity of the conventional park. If wind and solar photo-voltaic cells (PV) penetrate the market, the additionally required spinning reserve equals 15% of the intermittent capacity (but only after the additional spinning reserve exceeds the capacity already present in the system). These costs are allocated to the intermittent source.
- Depletion is modeled as a function of built-capacity. Hoogwijk (2004) has determined potential supply of solar and wind power at grid basis (0.5 x 0.5 degree) and the associated load factors. By combining this with an estimate of the proximity of the power grid, supply cost curves by region can be derived. These are used in TIMER (see Section on renewable energy supply).

For nuclear power, costs are determined by capital costs and fuel costs. Nuclear fuel (either uranium or thorium) is modeled in a similar way as primary energy.

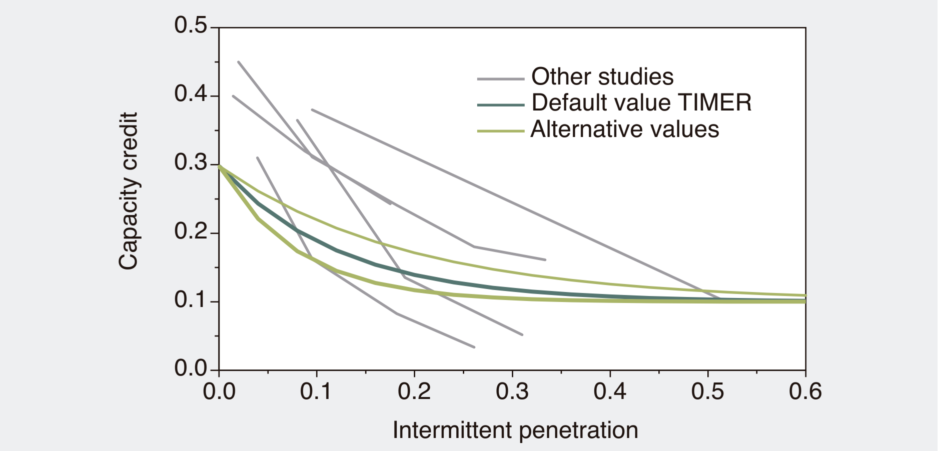

Figure 2.7 Capacity credit assumed in TIMER compared to other studies. It should be noted that actual value at zero penetration depends on the load factor which is time / region dependent. Grey curves indicate relationships found in literature (Namovicz, 2003; Giebel, 2005)

2.2.3 Hydrogen

The hydrogen sub-model simulates the demand for and production, infrastructure and technology dynamics of hydrogen-related technologies (see Figure 2.8). A detailed description is available elsewhere (Van Ruijven et al., in press). Hydrogen production costs are determined by capital and fuel costs and (if relevant) costs of carbon capture and storage. The costs of energy services from hydrogen for the end-user are equal to the production costs (taking into account end-use efficiency), and (additional) costs of end-use capital and infrastructure. The market-share of hydrogen is determined by a multinomial logit formulation, using the difference of the energy service costs from hydrogen and from other energy carriers. A feedback loop due to technological learning tends to lower the hydrogen production costs as cumulative installed capacity increases.

In TIMER 2.0, hydrogen can be produced by coal gasification, partial oxidation of oil, steam reforming of natural gas, gasification of biomass, electrolysis or direct solar-thermal production of hydrogen. For the production of hydrogen from natural gas, the model distinguishes between large-scale and small-scale steam methane reforming (SMR). In this way a transition period can be simulated in which there is no infrastructure and the more expensive small-scale SMR is the only available technology for stationary applications of hydrogen. The capital cost of production technologies declines through learning-by-doing (section 2.3).

Hydrogen can penetrate in all five end-use markets. Another option is mixing up to 5% hydrogen (on an energy basis) into the natural gas grid for use in the residential and service sectors (Hendriks et al., 2002b). We assume exogenous cost decline for fuel

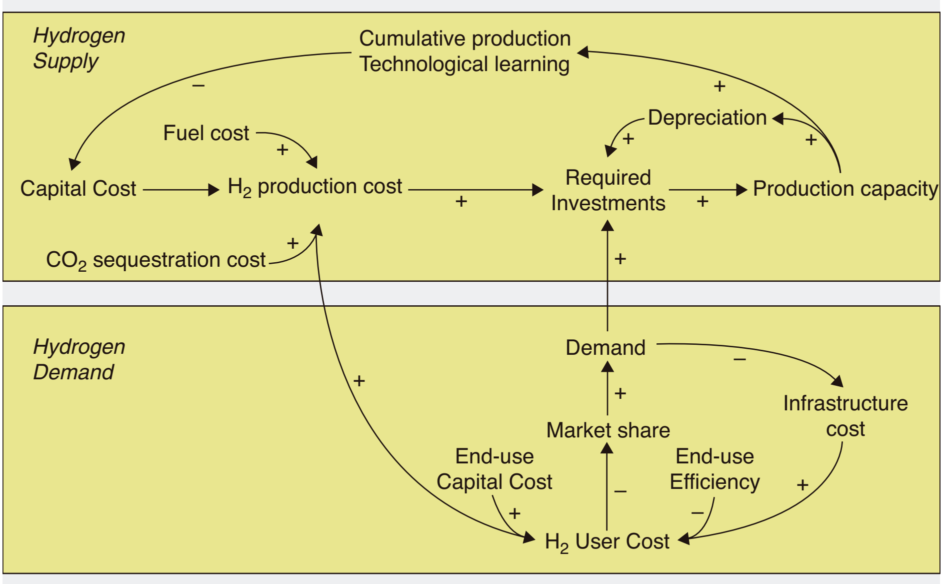

Figure 2.8 System dynamics representation of the TIMER-hydrogen model. Arrows indicate influence factors or inputs for calculation (Van Ruijven et al., in press).

cells, using Solid Oxide Fuel Cells in the industrial sector and Proton Exchange Membrane fuel cells in both stationary and mobile applications (Wurster and Zittel, 1994; Reijnders et al., 2001).

Transport and distribution of hydrogen is a major issue in the transition to a hydrogen energy system. Transport covers the distance from large-scale plants to residential areas or re-fuelling stations and is only considered for hydrogen produced at a large scale (this includes pipelines and trucks). Distribution includes the final distribution of hydrogen, i.e. the small-scale network in residential areas or the re-fuelling station itself. The costs of distribution are added to the cost of hydrogen. Since the development of a hydrogen transport infrastructure is expensive, hydrogen for stationary applications can initially only be produced by small-scale steam methane reforming plants near end-use locations. Investments in large-scale infrastructure (pipelines) will only be made when hydrogen demand density rises above a certain threshold. When this happens, stationary applications can be served by both small-scale and large-scale hydrogen plants. For the transport sector we assume that hydrogen can initially be produced at all scales, since demand is dispersed and transport can be provided by truck.

The implementation of the hydrogen model in the overall TIMER model show that under the default assumption, hydrogen is not likely to penetrate the world market before the mid-21st century, either with or without climate policy, if only costs are considered. Hydrogen could become a major secondary energy carrier later on, but only under optimistic assumptions (in particular breakthroughs are needed in fuel cell technology and infrastructure). The transport sector provides the earliest opportunities. Urban air pollution could provide an important incentive to the use of hydrogen. Coal and natural-gas-based technologies seem to be the most economically attractive to produce hydrogen. Partial oxidation of oil, biomass gasification, electrolysis and solar thermal hydrogen production are more expensive and hence show a lower degree of penetration. Under carbon constraints, the fossil-fuel based hydrogen production technologies are still the most attractive if combined with carbon capture and storage; if this is not available, the preferred hydrogen path shifts towards biomass and natural gas. These outcomes reveal an ambiguous role for hydrogen in relation to climate policy. On the one hand, the most cost-effective production route of hydrogen is from coal. As a result, CO_2 emissions from energy systems with hydrogen are likely to be higher than without hydrogen. On the other hand, energy systems with hydrogen can respond to constraints on CO_2 emissions more flexibly and at lower costs. This is because the use of hydrogen provides new and presumably cheap carbon emission reduction options in the form of centralized carbon capture and storage.

2.2.4 Supply of primary energy

Production of all primary energy carriers is based on the interplay between resource depletion and technology development. Technology development is introduced either as learning curves (for most fuels and renewable options) or by exogenous technology change assumptions (for thermal power plants).

2.2.4.1 Fossil Fuels

To model resource depletion of fossil fuels and uranium, several resource categories are defined that are depleted in order of their costs (12 categories for oil, gas and nuclear fuels, 14 for coal). Production costs thus rise as each subsequent category is exploited (Figure 2.9).

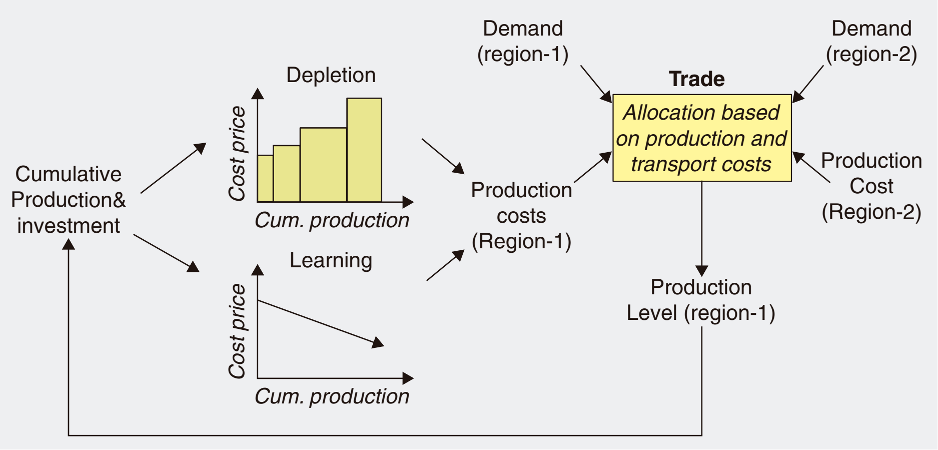

Figure 2.9 Schematic presentation of the sub-models for primary fossil energy production (2 regions are used to illustrate fuel trade).

TIMER includes three fossil-fuel production sub-models for respectively solid, liquid and gaseous fuels. For each region these sub-models calculate the demand for secondary energy carriers, electricity generation, international transport (bunkers) and the demand for non-energy use and feedstocks. The calculated fuel demand accounts for losses (e.g. refining and conversion) and energy use within the energy system. In a next step, demand is confronted with possible supply, both within the region and in other regions by means of the international trade model.

As indicated above, for each region supply of fossil fuels and nuclear fuels is specified in 12-14 categories, defined on the basis of increasing costs levels. Table 2.4 provides an overview of the assumed presence of each resource in default model conditions (aggregated into only 5 global categories). The table indicates that under default assumptions, supply of natural gas and oil is limited to only 2-8 times 1970-2005 production for all categories up to other unconventional sources (the first category of unconventional sources mainly includes reserves of oil from for tar sands and oil shales). For coal, however, even the current reserves equal several times the production of the last 3 decades. It should be noted that if price increases are high enough, also unconventional sources will be produced.

An alternative way of presenting this information is by showing the information aggregated into a long-term supply curve, as done for oil in Figure 2.10. All categories of oil for each region have been sorted on the basis of production costs and aggregated at the global scale. Supply is expressed in terms of 2000 production levels. The production costs shown here do not include technology progress. Figure 2.10 shows the result for low, medium and high assumptions, all three being used in scenario analysis.

The final production costs in each region are thus the combined influence of learning-by-doing and resource depletion. Depletion is determined by subsequent depletion of the 10-14 fuel classes. The learning parameter leads to lower costs with increasing cumulated production.

In the trade formulation, each region imports fuel from other regions depending on the ratios between the production costs in the other regions plus transport costs, and the production costs within the region considered (multinomial logit). Transportation

Table 2.4 Fossil fuels in TIMER under default assumptions aggregated into 5 global supply categories (ZJ) (based on (Rogner, 1997; Mulders et al., 2006))

	Oil	Natural gas	Underground coal	Surface coal
Cum. 1970-2005 production	4.4	2.1	1.6	1.1
Reserves	4.8	4.6	23.0	2.2
Other conventional resources	6.6	6.9	117.7	10.0
Unconventional resources (reserves)	2.9	6.9	25.0	233.5
Other unconventional resources	46.2	498.6	1.3	23.0
Total	65.0	519.2	168.6	270.0

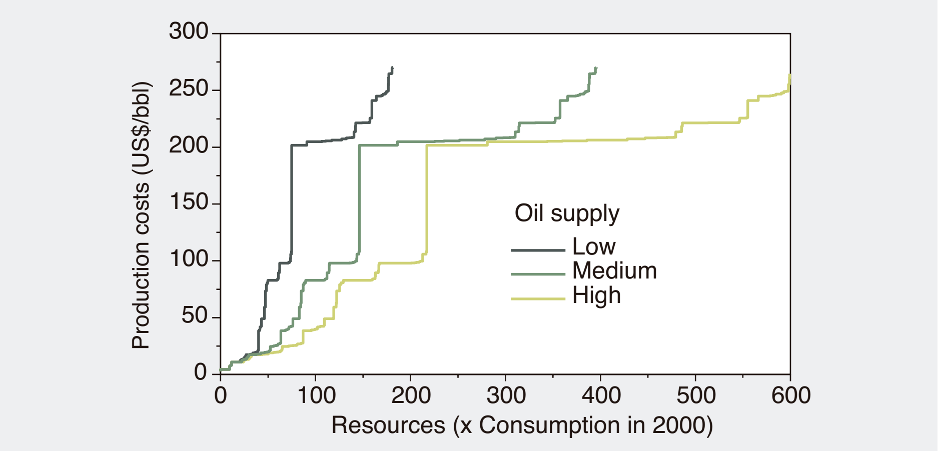

Figure 2.10 Implicitly assumed long-term oil supply cost curve under differ assumptions (based on resource estimates (Rogner, 1997; Mulders et al., 2006)) (the low, high and medium values used in the TIMER uncertainty analysis and are based on the underlying data.)

costs are the product of the representative interregional distances and time and fuel dependent estimates of the costs per GJ per km. To reflect geographical, political and other constraints in the interregional fuel trade, an additional parameter is used to simulate the existence of trade barriers between regions. Finally, a comparison is made between the production costs with and without unrestricted trade. In case some regions are able to supply at much lower costs than the average production costs of "demand" regions (a threshold of 60% is used), these regions are assumed to form a monopoly and will supply oil at a price only slightly below the production costs of the demand regions. Although the rule is implemented in a generic form for all energy carriers, it is only effective in the case of oil trade, where is assumed to simulate to some degree the behaviour of the OPEC cartel.

2.2.4.2. Bio-energy

The structure of the biomass sub-model is similar to that of the fossil fuel supply models but with a few important differences (see also Hoogwijk, 2004) (see Figure 2.11).

- First of all, in the bioenergy model depletion is not governed by cumulative production but by the degree to which available land is being used for commercial energy crops.
- The total amount of potentially available bio-energy is determined on the basis of calculations of the IMAGE crop model. These are able to provide information on bio-energy crop yields at a 0.5x0.5 degree grid under divergent land use scenarios for the 21st century and is based on IMAGE scenario calculations (see also supply cost curves for renewable energy). Potential supply is restricted on the basis of a set of criteria, most importantly bio-energy is only allowed on abandoned agricultural land and part of the natural grasslands. The costs of primary bio-energy crops (woody, maize and sugar cane) are described using a Cobb-Douglas production

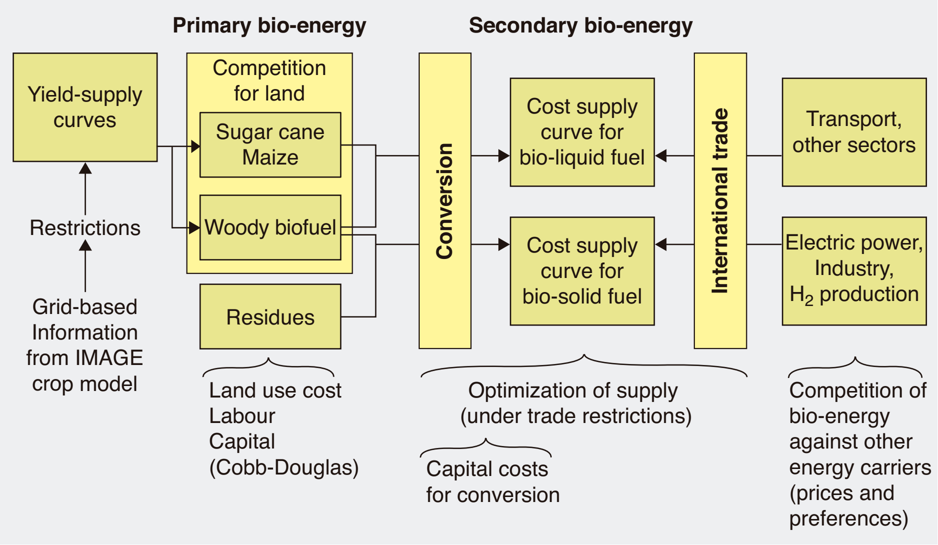

Figure 2.11 Overview of the bio-energy supply model.

function using labour costs, land rent costs and capital costs as input. The costs of land are based on average regional income levels per km^2, which was found to be a reasonable proxy for regional differences in land rent costs. These production functions are calibrated to empirical data as mentioned in Hoogwijk (2004).

- Next, the biomass model describes the conversion of biomass (in addition to wood crops, maize and sugar cane also residues) to two generic secondary fuel types: bio-solid fuels and bio-liquid fuels. The solid fuel is used in the industry and power sector, and the liquid fuel in other sectors, in particular transport.
- The trade and allocation of biofuel production is determined by optimization rather than by the multinomial logit equation used elsewhere in TIMER, to avoid unstable, oscillating model behaviour[ii]. The optimization finds an optimal combination of bio-solid and bio-liquid fuel supply across regions based on the demand for these products. Demand is determined in the end-use and energy conversion models on the basis of prices of the previous time step.

2.2.4.3. Costs Supply Curves for Renewable Energy

The potential of renewable energy (wind, solar photo-voltaic and bioenergy) has been estimated in a generic way on the basis of a methodology developed by Hoogwijk (2004) (an generic description is given by De Vries et al. (2007)).

(i) First, the relevant physical and geographical data for the regions considered are collected at the resolution of 0.5 by 0.5 degree. The wind and solar characteristics are taken from the digital database constructed by the Climate Research Unit (New

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[ii] The multinomial logit equation (discussed in more detail in Section 2.3) determines market share on the basis of current prices, without taking into account the form of the supply curve. As a result, relatively low prices may lead to high implementation rates, followed by steep increases in production costs and thus declining market shares. The alternative optimization approach is able to take the form of the supply curve into account (although oscillations may still occur).

et al., 1997; New et al., 1999). Land use information for energy crops is taken from the IMAGE land use model.

(ii) Subsequently, the model assesses which part of the grid cell area can be used for energy production given its physical-geographical (terrain, habitation) and socio-geographical (location, acceptability) characteristics. This leads to an estimate of the geographical potential. Several of these factors are scenario dependent. The geographic potential of biomass production by energy crops is estimated using suitability/availability factors accounting for competing land use options and the harvested rainfed yield of energy crops.

(iii) Next, the technical potential accounts for the fact that only part of the energy can be extracted in the form of useful secondary energy carriers (fuel, electricity), due to limited conversion efficiency and maximum power density.

(iv) A final step is to relate this technical potential to the on-site production costs. The information at grid level is finally sorted and presented as supply cost curves to TIMER. Supply cost curves are used dynamically and change over time as result of learning effect. Producing more renewable energy also leads to changes along this curve, and thus to higher costs.

The type of information that results from these steps are supply cost curves for wind and PV (used in the electric power model) and for bio-energy (used in the bio-energy submodel). As an example Figure 2.12 summarizes the information of these costs supply curves on global scale for wind and PV. The implementation of the wind and PV supply curves in the electric power model has been discussed already in the section on the electric power generation submodel.

As indicated in the previous section, for bio-energy, the TIMER model includes several routes from energy crops to liquid biofuel (ethanol and Fisher-Tropsch diesel) and solid biofuel. An example of bio-energy costs levels for transport fuel is shown in Figure 2.13.

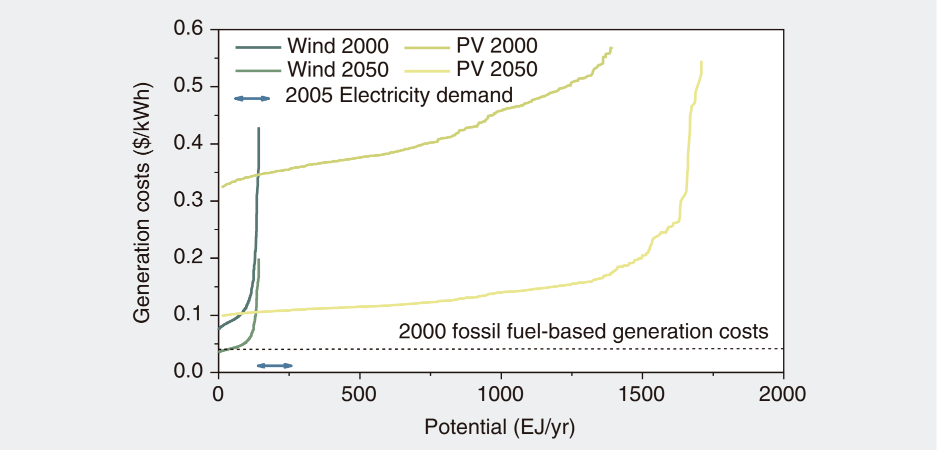

Figure 2.12 Representation of the supply costs curves for wind and solar PV (right) in the year 2000, as well as for the year 2050. Costs are expressed in terms of power production costs.

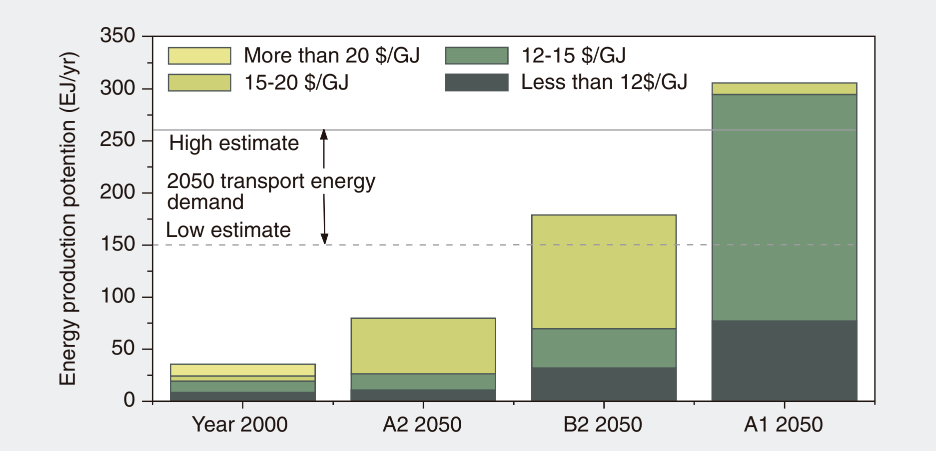

Figure 2.13 Supply costs curve for bio-energy in transport. The estimates vary strongly as a result of different land-use scenarios. The vertical lines indicate high and low estimates of transport energy demand.

2.2.5 The Emissions submodel

The TIMER Emissions Model (TEM) calculates the regional atmospheric emissions from energy and industry-related processes. The model covers carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), nitrogen oxides (NO_x), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC), sulphur dioxide (SO_2) and emissions of halocarbons (CFCs, HCFCs, HFCs, etc.). Emissions are calculated by multiplying primary energy use fluxes and industrial activity levels with time-dependent emission coefficients:

$$Emis_{R,S,EC,Subst} = EnergyFlow_{R,S,ECt} {}^{*}\ EF_{R,S,EC,Subst} \qquad (2.8)$$

where Emis represents emissions (for regions, sectors, energy carriers and substances), energy flow the relevant energy flux (e.g. sectoral energy consumption or production level) and EF the emission factor. Changes in the emission factors represent technological improvements and end-of-pipe control techniques for CO, NMVOC, NOx and SO_2 (FGD in power plants, fuel specification standards for transport, clean-coal technologies in industry, etc.). The emission factors are determined exogenously and calibrated for historic time periods on the basis of the EDGAR emission model.

2.2.6 Carbon capture and storage (CCS)

For carbon capture and storage, three different steps are identified in the model: CO_2 capture and compression, CO_2 transport and CO_2 storage. Capture is assumed to be possible in electric power production, half of the industry sector and hydrogen production. Here, alternative technologies are defined that compete for market share with conventional technologies (without CCS). The former have higher costs and slightly lower conversion efficiencies and are therefore not chosen under default conditions;

however, these technologies increase much less in price if a carbon price is introduced in the model. Capture is assumed to be at a maximum 95%; the remaining 5% is still influenced by the carbon price. The actual market shares of the conventional and CCS-based technologies are determined in each market using multinomial logit equations. The capture costs are based on Hendriks et al. (Hendriks et al., 2002a; Hendriks et al., 2002b; Hendriks et al., 2004). In the electric power sector, they increase generation costs by about 40-50% for natural gas and coal-based power plants. Expressed in terms of costs per unit of CO_2, this is equivalent to about 35-45\$/tCO_2. Similar cost levels are assumed for industrial sources.

CO_2 transport costs were estimated for each region and storage category on the basis of the distance between the main CO_2 sources (industrial centres) and storage sites (Hendriks et al., 2002a). The estimated transport costs vary from 1-30 \$/tCO_2 – the majority being below 10\$/tCO_2.

Finally, for each region the potential for 11 storage categories has been estimated (in empty and still existing oil and gas fields, and on and off shore – thus a total of 8 combinations); enhanced coal-based methane recovery and aquifers (the original aquifer category was divided into two halves to allow more differentiation in costs). For each category, storage costs have been determined with typical values around 5-10\$/tCO_2 (Hendriks et al., 2002a). The model uses these categories in the order of their transport and storage costs (the resource with lowest costs first). Figure 2.14 summarizes the assumed default assumptions for storage capacity for aggregated regions and storage categories. It should be noted that the aquifer storage capacity is far more uncertain that the other categories (and thus in scenario studies, one may decide to use only part of this potential).

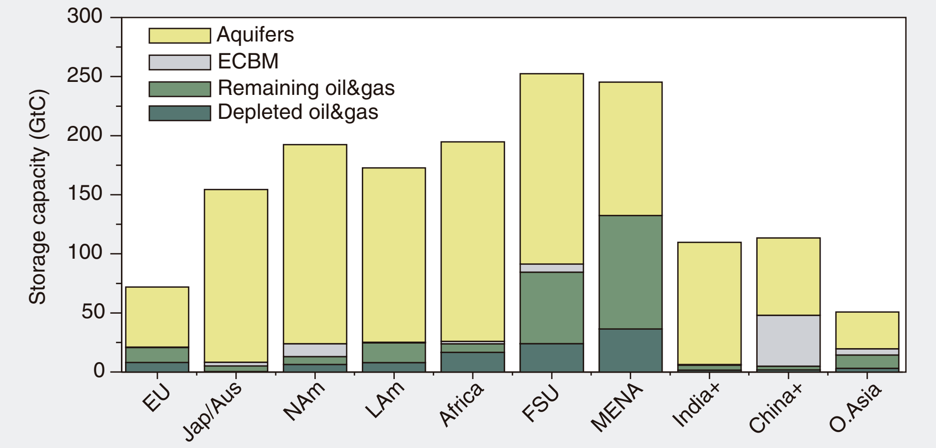

Figure 2.14 Summary of the assumed CO_2 storage capacity in TIMER (aggregated into larger categories and regions) (note: category ECBM refers to coal-bed methane; oil and gas refer to currently depleted fields and new fields).

2.3 Common Model Elements

The TIMER model has several elements that are included in various sub-models. Important elements include depletion, the capital vintage structure, technology development and substitution. Given the fact that depletion has already been discussed earlier, we only pay attention to the last three elements.

2.3.1 Capital vintage model

Throughout the model, capital stocks of production capital (e.g. oil production capacity, power plants and end-use equipment) are described using a capital vintage structure. This element describes the investment in and depreciation of capital stock on the basis of the assumed lifetime of different forms of capital stocks. Its use implies that changes in energy use and production can only be adopted by the system at a rate equal to new investment and the depreciation of existing capital. In other words, the vintage model forms an essential element of system inertia. The equations used for the vintage model are indicated below:

$$CapRq = FlowRq * COR \tag{2.9}$$

$$CapDepr = \sum_{n} {}^{1}\!/_{n} * Inv_{t-LT+n-5} \tag{2.10}$$

$$CapInv = CapRq - CapCr + CapDepr \tag{2.11}$$

Here, CapRq indicates the required capital level based on the required energy production level (FlowRq) and the ratio between capital and output (COR). The depreciated capital in each time period equals the capital that has reached the end of its lifetime (LT). To introduce some heterogeneity, in the model part of the capital has depreciated, in fact, a little earlier, while another part has depreciated a little later (n determines the number of years sampled around the average lifetime). CapInv, finally, equals the required capacity minus the existing capacity, but plus the depreciated capacity.

2.3.2 Technological development

An important aspect of the TIMER model is the endogenous formulation of technological development on the basis of “learning-by-doing”. This phenomenon is considered a meaningful representation of technological change in global energy models (Azar and Dowlatabadi, 1999; Grübler et al., 1999; Wene, 2000). The general formulation of learning-by-doing is that a cost measure, y, tends to decline as a power function of an accumulated learning measure, *Q*:

$$y = \alpha * Q^{-\pi} \tag{2.12}$$

where π is the learning rate, Q the cumulative capacity or output and α a constant. Often π is expressed by the progress ratio ρ, which indicates how fast the costs measure, y, decreases with the doubling of Q ($\rho=2^{-\pi}$). Progress ratios reported in empirical studies lie mostly between 0.65 and 0.95, with a median value of 0.82 (e.g. Argotte and Epple, 1990).

In the TIMER model, learning-by-doing influences the capital-output ratio of coal, oil and gas production, the specific investment cost of renewable and nuclear energy, the cost of hydrogen technologies and the rate at which the energy conservation cost curves decline. The value of ρ ranges between 0.7 and 1.0 based on historic values (see Figure 2.15). The actual values used depend on the technologies and the scenario setting. The ρ of solar/wind and bioenergy have been set at a lower level than those for fossil-based technologies, based on their early stage of development and observed historic trends (e.g. Wene, 2000; Junginger et al., 2005). There is evidence that in the early stages of development ρ is higher than for those technologies that have already been in use for long time periods. For instance, values for PV are typically below 0.8, while those for fossil fuel production are around 0.9-0.95 (see Figure 2.15). For technologies in early stages, other factors may also contribute to technology progress, such as relatively high investment in research and development (Wene, 2000). In TIMER, ρ values are exogenous, scenario-dependent assumptions. They are typically assumed to increase over time for technologies with values below 0.9 to represent maturation (but these pathways are typically strongly scenario-dependent).

It is an interesting question whether learning curves should be applied separately on the scale of regions or for the world as a whole. On the one hand, technologies developed in one region will often also be available in other regions. On the other hand, a significant part of cost reduction comes from experience gained by applying the technology and developing the associated infrastructure which may not be so easily transferred. In TIMER, we postulate the existence of a single global learning curve. Regions are then assumed to pool knowledge and "learn" together or, depending on the scenario assumptions, to be (partly) blocked from this pool. In the latter case, only the obviously smaller cumulated production within the region itself drives the learning process and costs will decline at a slower rate.

2.3.3 Substitution of fuels and technologies

The multinomial logit mechanism is used in TIMER to describe substitution among end-use energy carriers, different forms of electricity generation (coal, oil, natural gas, solar/wind and nuclear) and substitution between fossil fuels and bioenergy. This mechanism is also used to determine the production shares of different regions in international markets. The mechanism is based on the following equation:

$$IMS_i = \frac{\exp(-\lambda\, c_i)}{\sum_j \exp(-\lambda\, c_j)} \qquad (2.13)$$

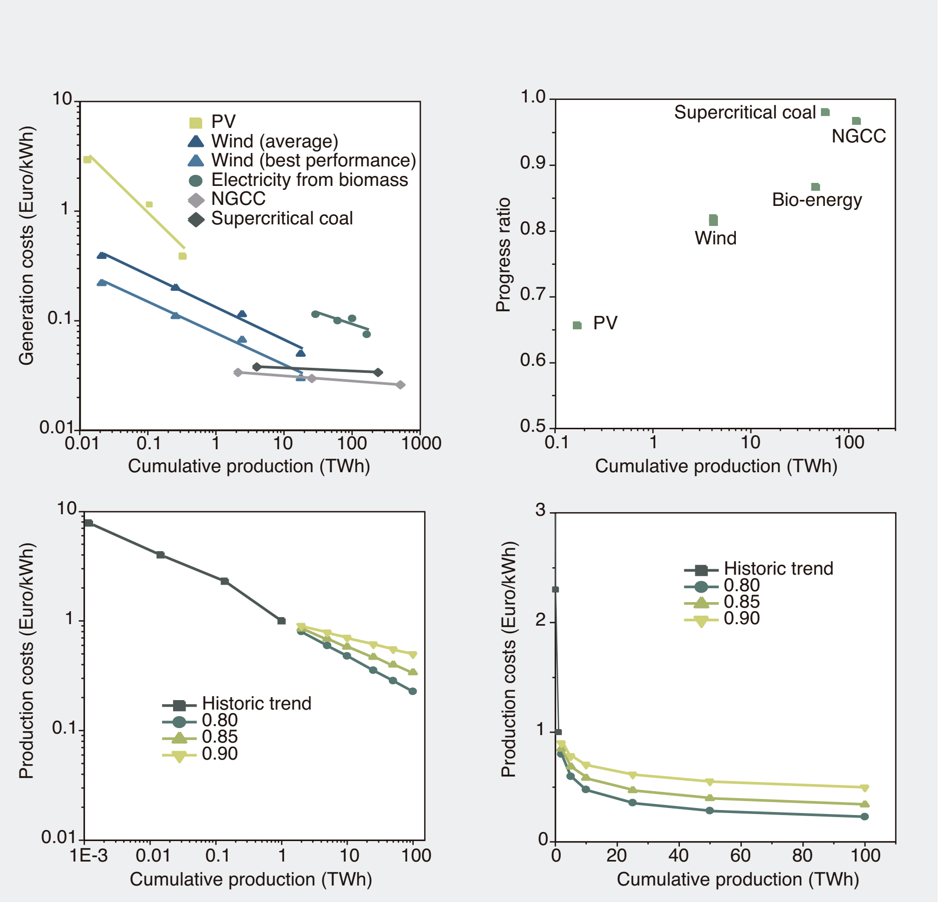

Figure 2.15 Learning curve and resulting dynamics. The upper panels shows empirical data from Wene for the 1970-2000 period. The lower left figure shows - on a logarithmic scale (for both x and y axes -) the potential technology improvement at different progress ratios (0.8-0.9) (historic data is based on the improvements of wind power plants). The same data is shown using linear axes on the right-hand side.

where IMS_i is the share of total investments for fuel or production method I (-), c_i the "price" of production method i and λ the so-called logit parameter, which reflects the sensitivity of markets to relative differences in production costs. The "price" ci does not only encompass production costs but also other factors such as premium factors, additional investment costs and cost increases as a result of a carbon tax. These premium factors include all kinds of non-monetary preferences, such as convenience in handling or environmental consequences. For the calibration period, these premium factors are chosen so that historic market shares are reproduced on the basis of modeled prices.

The multinomial logit model implies that the market share of a certain technology or fuel type depends on costs relative to competing technologies. This is illustrated in Figure 2.16 for two competing technologies and for three different values for λ. The option with the lowest costs obtains the largest market share, but in most cases not the

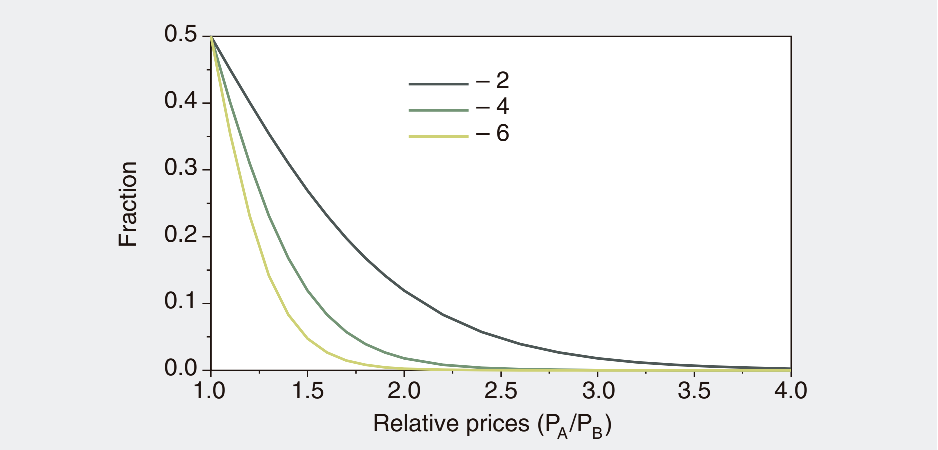

Figure 2.16 Multinomial logit equation. Outcomes for different values of the logit parameter λ, showing the fraction of technology, A, as a function of the price ratio between technology A and B.

full market. We interpret the latter as a representation of heterogeneity in the form of specific market niches for every technology or fuel. The value of the logit parameter determines the price sensitivity of the market and can be compared to substitution elasticities in economic models: a value of zero gives equal market shares to each technology, while a high value leads to full optimization. Given the fact that the preferences for different fuel types are not known in the quantitative sense for the historic situation, it is hard to determine the value of the logit parameter on an empirical basis. The value in TIMER is therefore determined by calibrating the formula against historically observed responses to price changes (but its value remains somewhat arbitrary).

2.3.4 The combination of innovation and substitution dynamics

Figure 2.17 shows how the learning curve formulation and the multinomial logit market share formulation interact.

The figure describes the competition between a rapidly learning technology using a learning curve, and a technology with a constant price. The combined behavior of technology learning and the market share formulation are shown in Figure 2.17. Technology B reduces its costs over time thanks to learning by doing. The market share of this technology increases in response, leading at first to further costs reductions – although this slows down once the technology has moved far enough along the learning curve. The resulting market share for technology B reflects a so-called logistic (s-form) penetration curve emerging from the combination of the two dynamic elements. Many engineering optimization models assume that penetration of new technologies occurs along such a curve using a exogenous formulation.

Obviously, the same uncertainties discussed for the learning curve and multinomial logit model separately also determine the outcomes of their combination. In Figure

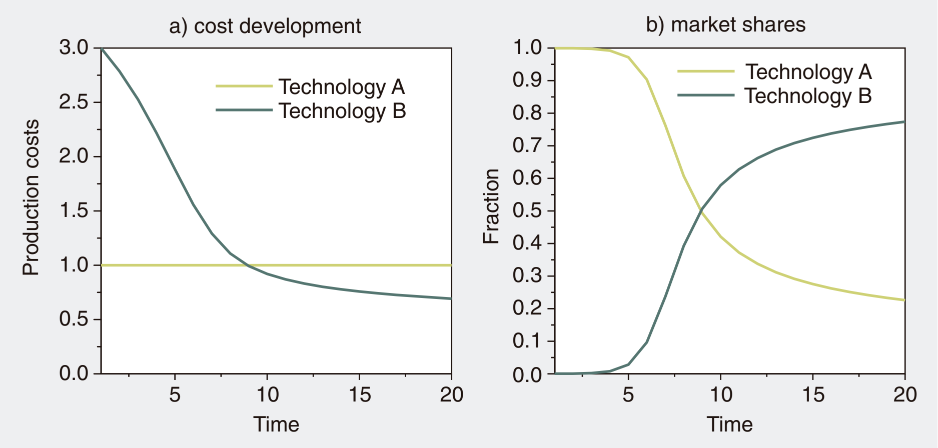

Figure 2.17 The combined behavior of a learning curve and the multinomial logit model for 2 technologies. Production costs (left) and market share (right).

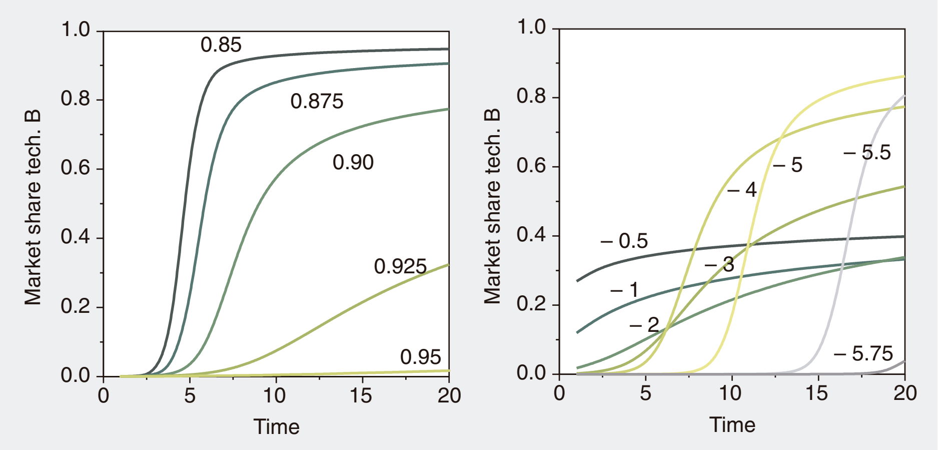

Figure 2.18 Market share of technology B in competition with technology A. The combined behavior of a learning curve and the multinomial logit model. Sensitivity to learning rate assumptions (left) and logit parameter assumptions (right).

2.18 the market share of technology B is now shown for different assumptions for the learning (ρ) and logit (λ) parameters. The results are demonstrated to critically depend on both parameters. Slower learning implies that technology B only penetrates the market slowly or even fails to do so, while faster learning results in a very rapid transition from technology A to technology B.

The impact of the logit parameter is more complex. Low values imply that technology B captures a large market share early on, but it also implies that the market is insensitive to price differences and thus, it can only capture half the market. Higher logit values (thus more price-sensitive markets) imply a low market penetration at first, but also imply that once technology B starts to benefit from learning (and its costs decrease), it is able to penetrate the market at a much more rapid rate.

2.4 Using TIMER in Conjunction with FAIR and IMAGE for Mitigation Analysis

The TIMER model is often used in combination with the FAIR model (den Elzen and Lucas, 2005) and the climate and terrestrial sub-models of IMAGE to develop scenarios that explore how such low greenhouse gas concentration stabilization levels could be reached. As TIMER forms part of the IMAGE modeling framework, a short description of IMAGE is first given. Next, the links between the sub-models for energy climate modeling are indicated.

2.4.1 IMAGE 2 Integrated assessment framework

IMAGE 2 is an integrated assessment modelling framework describing global environmental change in terms of cause–response chains (Alcamo et al., 1996, Bouwman et al., 2006). The most important subsystems are the “socio-economic system” and the “earth system” (Figure 2.19). In the socio-economic system, detailed descriptions of the energy and food consumption and production are developed using TIMER and agricultural trade and production models. The two main links between the socio-economic system and the earth system are land use and emissions. First, production and demand for food and biofuels lead to a demand for managed land. Second, changes in energy consumption and land-use patterns give rise to emissions that are used in calculations of the biogeochemical circles, including the atmospheric concentration of greenhouse gases and some atmospheric pollutants, such as nitrogen oxides and sulphur oxides. Changes in concentration of greenhouse gases, ozone precursors and species involved in aerosol formation form the basis for calculating climatic change. Next, changes in climate are calculated as global mean changes and downscaled to grid level.

The land-cover submodels in the earth system simulate the change in land use and land cover at 0.5 x 0.5 degrees (driven by demands for food, timber and biofuels, and changes in climate). A crop module based on the FAO agro-ecological zones approach computes the spatially explicit yields of the different crop groups and the grass, and the areas used for their production, as determined by climate and soil quality. Where expansion of agricultural land is required, a rule-based “suitability map” determines the grid cells selected (on the basis of the grid cell’s potential crop yield, its proximity to other agricultural areas and to water bodies). The earth system also includes a natural vegetation model to compute changes in vegetation in response to climate change. An important aspect of IMAGE is that it accounts for important feedbacks within the system, such as temperature, precipitation and atmospheric CO_2 feedbacks on the selection of crop types, and the migration of ecosystems. This allows for calculating changes in crop and grass yields and, as a consequence, the location of different types of agriculture, changes in net primary productivity and migration of natural ecosystems.

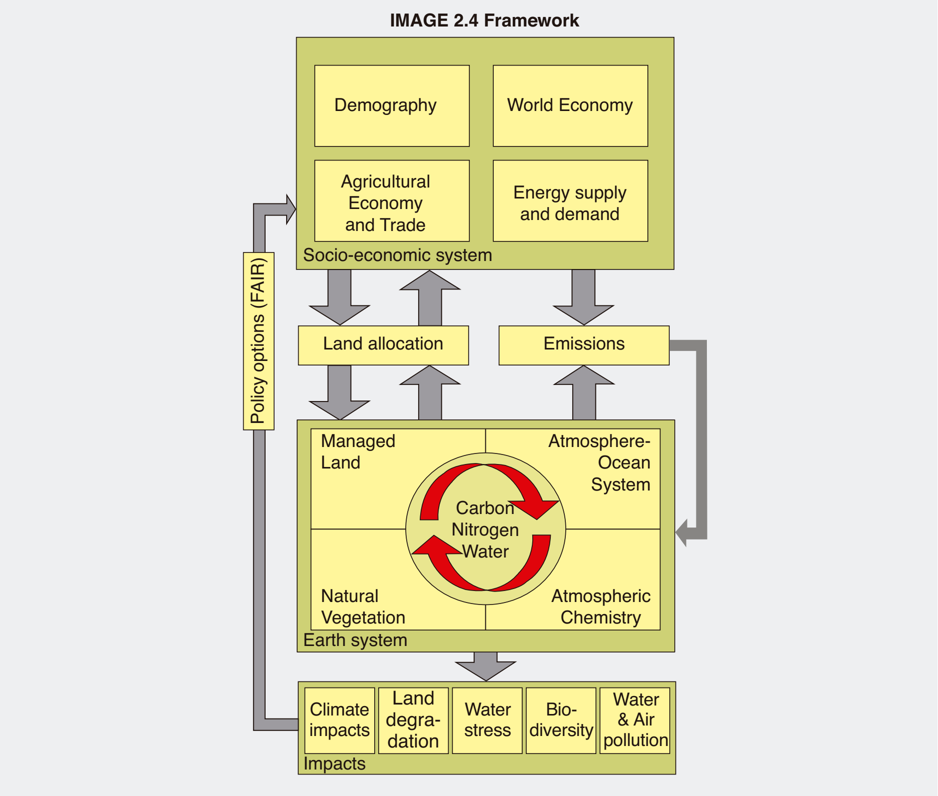

Figure 2.19 IMAGE 2 Integrated Assessment Framework.

2.4.2 Linkages between TIMER, IMAGE and FAIR for energy–climate modeling

The links between the sub-models are indicated in Figure 2.20. In the combination of the three models, FAIR not only adds information on climate policy but also a relatively simple framework that allows for costs optimization of reduction of energy-related greenhouse gas emissions (as described in TIMER) against other forms of emissions. IMAGE provides information for TIMER on the potential for bio-energy use, adds the ability to evaluate environmental and land-use impacts of different energy scenarios and, finally, describes other sectors that are relevant for climate change.

The scheme in which TIMER, and the rest of IMAGE and FAIR are often applied consists of three steps (Figure 2.20):

(i) a baseline emission scenario is constructed using the full IMAGE model, including TIMER. The terrestrial submodels of IMAGE and TIMER are also used to provide information on abatement through carbon plantation and measures in the energy system, respectively;

(ii) global emission pathways are developed using the FAIR model ; this leads to a stabilization of the atmospheric GHG concentration. The FAIR model distributes

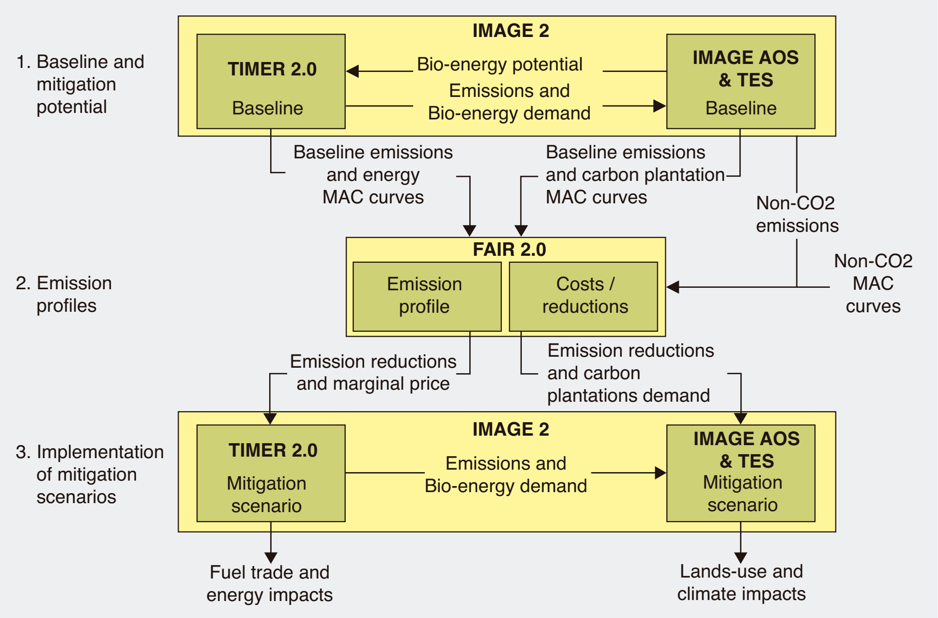

Figure 2.20 Linkage and information flows of the applied modeling framework integrating TIMER, IMAGE and FAIR (note CP = carbon plantations; MAC = Marginal Abatement Curve; AOS = atmosphere ocean system; TES = terestrial ecosystem system).

the global emission reduction across the different regions, gases and sources in a cost-optimal way, using the information on marginal abatement costs derived in step (i);

(iii) finally, the emission reductions and permit price determined in the previous step were implemented in the IMAGE/TIMER model to develop the final mitigation scenario (emissions, land use and energy system).

In step (i) estimates for reduction costs and potential from TIMER are made by imposing an emission permit price (carbon tax) and recording the induced reduction of CO_2 emissions. TIMER responds to the addition of an emission permit price in several ways. On the energy supply side, options with high carbon emissions (such as coal and oil) become more expensive compared to options with low or zero emissions (such as natural gas, CCS, bioenergy, nuclear power, solar and wind power). The latter therefore gain in market share. On the energy demand side, investments in efficiency become more attractive. Technology change can strongly influence the results. Different sets of response curves to carbon tax levels are constructed to take this influence into account. Chapter 8 of this thesis discusses the construction of response curves in detail. Chapter 7 describes an analysis in which the overall framework is applied.

2.5 Concluding Remarks

The TIMER 2.0 model has been developed to explore different pathways of the global energy system in the context of climate change or long-term depletion of fossil fuel resources. Several applications of the model, mostly coupled to other elements of IMAGE, such as the land-use model and the FAIR model, have shown its capacity to fulfil this aim. However, the model can be improved further. Issues that merit our future research attention include: (i) the implication of the energy transition in developing countries. In most scenarios, increasing energy demand in developing countries represents the main driving force behind increasing global energy consumption. Nevertheless, representation of developing country energy issues in global energy models like TIMER is limited. We will explore whether improvements can be made; (ii) modelling physical drivers of energy demand. At the moment, primarily monetary indicators are used to determine energy demand. By modelling the underlying physical drivers (passenger kilometres or steel production), deeper insight can be obtained in opportunities to change the energy system.

3. THE CONSISTENCY OF THE IPCC SRES SCENARIOS CONSISTENT WITH RECENT LITERATURE AND RECENT PROJECTIONS

Abstract. The greenhouse gas emissions scenarios published by the IPCC in the *Special Report on Emission Scenarios* (SRES) continue to serve as the primary basis for assessing future climate change and possible response strategies. These scenarios were developed between 1996 and 1999; sufficient time has now passed to make it worthwhile to examine their consistency with more recent data and projections. Population, GDP, energy use, and emissions of CO_2, non-CO_2 gases and SO_2 are compared in this chapter. Findings revealed that the SRES scenarios are largely consistent with historic data for the 1990–2000 period and with recent projections. Exceptions to this general observation include: (1) population growth assumptions in SRES in some regions, particularly in the A2 scenario, which are relatively high compared to new scenarios (long term); (2), economic growth assumptions in the ALM (Africa, Latin America and Middle East) region in the A1 scenario, which are relatively high compared to recent projections (medium-term); (3) CO_2 emissions projections in A1 that are somewhat higher than the range of current scenarios (short term); and (4) SO_2 emissions in some scenarios that are substantially higher than in historic data and recent projections. In conclusion, given the relatively small inconsistencies for use as global scenarios, there seems to be no immediate need for a large-scale IPCC-led update of the SRES scenarios that is solely based on the SRES scenario performance vis-a-vis data for the 1990–2000 period and/or more recent projections. Based on reported findings, individual research teams could make, and in some cases, already have made useful updates of the scenarios.

This chapter was published earlier as: Van Vuuren, D.P. and O'Neill, B.C. (2006). The consistency of IPCC's SRES scenarios to recent literature and recent projections Climatic Change Volume 75, Numbers 1-2. 9-46.

3.1 Introduction

In 2000 IPCC published a new set of emission scenarios in the *Special Report on Emission Scenarios (SRES)*, designed to serve as a basis for assessments of climate change and possible response strategies (Nakicenovic and Swart, 2000). The SRES scenarios were developed in a relatively open process that started in 1996. Six modeling teams participated officially in the exercise to develop new scenarios.[i]

The IPCC scenarios cover very long time periods (1990–2100) so as to capture the large inertia present in the climate system and the long time scales involved in fundamental changes to energy systems. Uncertainties obviously play a major role over such a long

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[i] In addition, draft results of the modeling groups were put on a website for comments by outside reviewers. The scenarios were also reviewed by both experts and government representatives.

time period. Future greenhouse gas emissions result from complex dynamic processes, including demographic and socio-economic development, and technological change. The future evolution of these factors is highly uncertain, with various development patterns capable of introducing very different futures. The SRES process addressed uncertainty in two ways. First, the scenarios were based on a set of storylines describing alternative broad development patterns. Each storyline was intended to represent consistent demographic, social, economic, technological and environmental developments. Second, , the SRES process included six different models for creating quantitative interpretations of each of the storylines in order to capture uncertainties related to model structure.

The IPCC SRES scenarios have been used extensively since their publication, and a considerable amount of this work was evaluated in IPCC's Third Assessment Report (Houghton et al., 2001; McCathy et al., 2001; Metz et al., 2001). This included research into possible climatic change, impact and adaptation studies, and analysis of potential mitigation policies. The SRES scenarios will also serve as the basis for many of the impact studies to be assessed in the IPCC Fourth Assessment Report now underway. The SRES scenarios have also served as a basis or inspiration for numerous other exercises at global, regional and national levels – where new modeling was often consistent with the overall SRES storylines and published parameters (UNEP, 2002; de Mooij and Tang, 2003; Kainuma et al., 2003; van Vuuren et al., 2003c).

At the same time, several criticisms of the SRES scenarios have been made, mainly outside of the peer-reviewed literature (Economist, 2003b; Economist, 2003a). These are mostly concerned with economic growth assumptions of some of the scenarios (growth considered too high), but also include the argument that SRES researchers have ignored some of the historic trends in the drivers used to develop the emission scenarios (Castles and Henderson, 2003). A claim was also made that the IPCC scenarios were already off track with respect to historic emission trends (e.g. Corcoran, 2002). Apart from the validity of these specific criticisms, it is clear that scenarios do not have an unlimited lifetime. The information on which they are based can become outdated; actual events can proceed in ways substantially different than foreseen in the scenarios, and/or the specific questions for which the scenarios were developed can change (e.g. emphasis can shift toward identifying policy options, and away from exploring the consequences of inaction). In fact, there are numerous examples of scenarios that have not stood the test of time, including energy forecasts made before and during major events such as the oil price spikes of the 1970s and early 1980s (Smil, 2000; O'Neill and Desai, 2004). Past population scenarios have also sometimes become quickly outdated, as fertility or mortality trends showed rapid and sharp divergence from anticipated directions (O'Neill et al., 2001).

Although the SRES scenarios were published in 2000, most models used to develop the scenarios were calibrated on 1990 and 1995 data, and most of the calculations were done well before 1999 (when the review process started). New information is now available that can be compared against the SRES scenarios. First, new historic data for the 1990–2000 period can be compared against SRES assumptions for this time period. Second, new projections can be compared to the SRES outlook. These new projections can be expected to include the latest data, knowledge and insights into events that have occurred since the development of SRES and projections that could affect future trends. Such outlooks often focus on shorter time frames than SRES (20–30 years rather than 100 years). In some cases, however, new long-term scenarios have been published.

Here, we examine the consistency of the IPCC SRES scenarios with available 1990–2000 data and recent projections. We also consider the implications of these comparisons for the credibility and validity of the scenarios – and consequently for the desirability of using SRES in further assessment. It should be noted that from the perspective of comprehensive assessments of the climate change, such as those carried out by IPCC, there are good reasons to prefer the use of a given set of emission scenarios for a sufficiently long time period to allow their use in assessments of potential future climate change, its impacts, and the costs and benefits of climate policies. Thus minor inconsistencies between the scenarios and recent trends are unlikely to outweigh the benefits of a consistent basis for different types of assessment studies.

Section 3.2 discusses several methodological issues, followed by the results of the comparison for a set of driving forces (population, economic growth and energy use) in Section 3.3 and emissions in Section 3.4. Conclusions are presented in Section 3.5.

3.2 Methodology

We focused our assessment on the SRES scenarios as published by IPCC (Nakicenovic and Swart, 2000).[ii] Box 3.1 discusses some of the terminology used in SRES scenarios and its relevance to this exercise. In our analysis, we focus on the so-called marker scenarios since they have been the most often used in different applications, including the IPCC Third Assessment Report. These markers were also references for the alternative elaborations of each scenario by other modeling groups. Where possible, we have added ranges associated with the alternative elaborations of each storyline as uncertainty ranges around the IPCC marker scenarios.

From the total set of data published by SRES, we selected a set of the most crucial variables for our comparison, i.e. GDP, population, energy use and emissions of $CO_{2,}$ other greenhouse gases and SO_2. Comparison was done at the level of aggregation reported by SRES – four geographical regions: 1) OECD-1990, 2) Reforming Economies (Central and Eastern Europe and Former Soviet Union, REF), 3) Asia and 4) Africa, Latin America

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[ii] While in SRES, all results were reported for the four large regions only, each of the models used has a much more detailed regional breakdown. The more geographically detailed results, however, do not form part of SRES as it is officially adopted and are therefore not included in this review. The regional disaggregation of the different models and their basic set-up are described in the SRES report.

and Middle East (ALM).[iii] Three types of comparisons were made, namely, comparison to : 1) data covering the (by now) historic 1990–2000 period, 2) short-term projections published since 2000 and 3) long-term projections published since 2000. The projections used in our comparison have been selected on the basis of their recent publication dates and the fact that they are often used as reference projections within their specific domains. In addition, we excluded projections that assume climate policies. Since all SRES scenarios exclude climate policy (based on the aim to explore events in the absence of such policies), comparisons with intervention scenarios would not be meaningful.

Box 3.1 Terminology from the IPCC SRES scenarios

Marker scenarios

In total, the SRES report discusses six scenario storylines, grouped into four scenario families. The assumptions of these families differ in two fundamental ways (two axes): 1) emphasis on ongoing globalization versus regional identity (these scenarios are marked as “1” and “2”, respectively) and 2) the emphasis on economic development versus social and environmental factors (these scenarios are marked as “A” and “B”, respectively). Combining these axes results in the four scenario families, named A1, A2, B1 and B2, alluding to the underlying fundamental assumptions: In addition, two other scenario storylines (termed “illustrative scenarios”) result from different technology assumptions within the A1 family. For each storyline, there are several quantitative scenarios produced by different modeling groups (40 in total). Four of them were designated as “marker” scenarios by the SRES writing team, as they were considered to be illustrative of a particular storyline. These marker scenarios are by far the most often used (and have also served partly as a guiding light for the other scenarios within the family). Our comparison focuses on these marker scenarios.

Standardization of base-year data (emissions only)

For the 1990-2000 period the emission data from the SRES scenarios were subject to a process of “base-year data standardization”. This was done because the underlying data of the different models showed notable differences for base-year emissions, mostly reflective of scientific uncertainty in emissions data, but also of differences in model calibration and model base year. To improve scenario comparability, a decision was made to adopt standardized numerical values for reported greenhouse gas emissions for the 1990 base year and for 2000. These standardized values were derived by taking the average of the different models for those years. Since the purpose of this exercise was to evaluate the SRES scenarios as they are published, and normally used (and not to evaluate the performance of the underlying models), we compared these numbers to current data inventories for the same period. This means that only 1 set of (SRES) emissions data for 1990 and 2000 needs to be compared against historic data. In contrast, the data for driving forces has not been standardized and individual model results and assumptions cannot be compared to historic trends.

Based on (Nakicenovic and Swart, 2000)

In theory, a fourth comparison might include comparing historic trends to (short-term) trends in the SRES scenarios. However, we consider this kind of comparison outside the scope of our current analysis, which focuses on new information since the publication of SRES. Moreover, the SRES scenarios, in fact, deliberately assume that trends in driv-

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[iii] As indicated in the SRES report, the different regional breakdown of the different models did not always allow for consistent aggregation into the IPCC regions. In these cases, slightly different regional definitions were used. For example, in the IMAGE 2.2 model Mexico is part of the Central America region, and therefore cannot be separately added to the OECD region. The small discrepancies caused by these regional definitions is indicated where relevant in the SRES report – and for some variables can also be seen here.

ing forces in the future could be substantially different than the past (hence the storylines). However, since short-term projections often rely substantially on past trends, our comparison implicitly accounts for these trends to some degree. In one case (SO_2 emissions) we also explicitly note that SRES outcomes break with 1990–2000 trends.

The most important comparisons have been made with the projections of the International Energy Agency's World Energy Outlook (IEA, 2002; IEA, 2004b) and with the US Department of Energy's International Energy Outlook (US.DoE, 2004b) (both report on GDP, energy use and CO_2 emissions), and the results of the model comparison study done by the Energy Modelling Forum (EMF-21) (Weyant et al., 2006). We used the so-called "modeler's reference scenario" from the last study which are usually "medium-growth" scenarios. In total, available data from this study included long-term data for 14 models, 3 of which were also included in SRES. Given the fact that these three models have been further updated, and do not dominate the results of the total EMF study, this study can safely be used as an independent source of information from SRES. In addition, for population we used projections from the UN Population Division (UN, 2003), IIASA (IIASA, 2001; Lutz et al., 2004) and the US Census Bureau (US.BoC, 2003). For GDP, we used the global economic prospects of the World Bank/GEF (WorldBank, 2004), and for emissions data we used selected modelling studies. It should be noted that the historic data can be accompanied by considerable levels of uncertainty. Where possible, we commented on the degree of certainty attached to the specific data sources. It should also be noted that several recent scenario studies such as UNEP's Global Environment Outlook (UNEP, 2002) have not been selected because they are, at least partly, based on the IPCC scenarios and therefore cannot be regarded as sufficiently independent.

In the remainder of this section, we cover two more methodological issues: 1) the assumptions underlying the SRES scenarios, and 2) the relevance of comparing SRES scenarios to short-term projections (and derived criteria for comparison).

3.2.1 Assumptions underlying the IPCC scenarios

The main assumptions underlying the four scenario families (A1, A2, B1 and B2) are indicated in Table 3.1. The scenarios are defined along two main axes (globalization versus regionalization, and economic orientation versus orientation to social development and environmental protection), but differ in many other ways too. The total set is considered to represent a wide range of outcomes. At the same time this does not mean that the four families represent all possible outcomes or a representative sample across the possible outcomes. In fact, the assumed trends for drivers include (see also Table 3.1):

- more "high to very high" economic growth scenarios (A1 and B1) than "low" economic growth scenarios (A2),
- more "high to very high" energy use scenarios (A1 and A2) than "low" energy use scenarios (B1) and
- more "low" population scenarios (A1-B1) than "high" population scenarios (A2).

Table 3.1 Main storyline assumptions underlying the SRES scenarios

	A1			A2	B1	B2
Storyline	Globalization; liberalization			Heterogeneous world; self-reliance; fragmentation	Globalization; orientation on social and environmental sustainability	Local solutions to sustainability ; regional emphasis
Population	Low			High	Low	Medium
Economic growth	Very high			Low in developing countries; medium in industrialized countries	High	Medium
Primary energy use	Very high			High	Low	Medium
Technology development	Rapid			Slow	Rapid	Medium
Type of technology development	Balanced (A1B)	Primarily fossil fuels (A1FI)	Primarily non-fossil energy (A1T)	Balanced	Primarily energy efficiency and non-fossil energy	Balanced

3.2.2 The relevance of comparing SRES scenarios to recent projections

There are two important aspects in which the SRES scenarios differ from some of the other types of projections in the literature: (1) SRES scenarios explore alternative possible futures rather than attempting to identify a single most likely outcome and (2) the SRES scenarios have a very long time horizon. These differences raise questions about the relevance of comparisons between SRES and other projections.

When comparing the SRES scenarios to “best-guess” studies, differences between best-guess projections and SRES scenarios do not necessarily indicate important inconsistencies. By definition, the SRES scenarios are intended to capture a wide range of possible outcomes. At the same time, a comparison of the SRES range with current best guess projections can give one a sense of relative bias of the SRES scenarios with respect to the current outlook. For example, in an extreme case, if all SRES scenarios occurred below the current best guess outlook for a particular variable, we can conclude that SRES was biased substantially to the low side of the current outlook. This would not necessarily mean that the SRES scenarios were implausible (because best guess projections in themselves give no indication of the range of plausible outcomes). However, it would indicate that SRES did not cover the full range of plausible outcomes (and in this extreme case would not even include the outcome considered most likely).

When comparing SRES scenarios to short-term studies that include a range of possible outcomes, attention must be paid to what this range is intended to represent. For example, interpreting the results of the comparison for its implications for the validity of the SRES scenarios is difficult if the range simply represents the result of a sensitivity analysis, but includes no characterization by the authors of the likelihood of the outcome. The UN population projections form one such example; they include a most likely “medium” scenario as well as high and low variants demonstrating the sensitivity of outcomes to assumptions on future fertility rates (UN, 2003). Similarly, the EIA global energy projections include a single best guess outcome, and high and low scenarios that reflect sensitivity to assumptions regarding GDP growth (US.DoE, 2004b). In such cases, if some SRES scenarios fall outside alternative high and low projections, it does not necessarily imply that the SRES results are unlikely. Indeed, there is evidence from the examination of errors in past projections that it is not uncommon for actual developments to quickly exceed the low or high boundary of such projections, even over relatively short time horizons (Shlyakhter et al., 1994).

One can only conclude that the SRES scenarios are unlikely if the high and low projections to which they are compared are associated with some judgment of likelihood. Probabilistic projections for population (Lutz et al., 2001) and CO_2 emissions (Webster et al., 2002; O’Neill, 2004) exist and can be used in this way, although it must be kept in mind that the probability distributions involved in these examples are subjective.

Regarding the issue of the different time horizons of various projections, it is important to keep potential methodological differences in mind when developing longer vs. shorter term outlooks. The modeling tools used in SRES focus primarily on long-term processes such as capital turnover, technological progress, resource depletion and substitution. In contrast, analysis concentrated on the short term (i.e. 10–20 years) generally demands different tools and scenarios that take specific national policies and circumstances more directly into account. Still, one might reasonably expect the SRES scenarios to describe the transitions from the present to the long-term, underlying logic with some degree of plausibility, at least at an aggregate level. In this context, there are (at least) three valid arguments on why consistency between long-term scenarios (like SRES) and short-term historic trends and outlooks is relevant:

1. If inconsistency with historic trajectories and/or near-term expectations is large enough, it could render part (or all) of the long-term scenario logic, driving force assumptions or scenario results unlikely or even implausible.
2. The medium term (e.g. around 2025) can be a crucial period in mitigation and adaptation analysis – even if studies cover a much longer time frame. Long-term scenarios, like SRES, are often used as baselines in such studies. Moreover, while SRES is not intended to capture short-term uncertainty, if short-term trends in SRES are implausible then this is important information for potential users.
3. An insufficient match between SRES and short-term trends or historic data can undermine credibility of the scenarios, whether or not such a match is meaningful in substantive terms.

The relevance of these arguments clearly depends on the type of application (the two extremes being formed by climate modeling versus mitigation analysis). In mitigation analysis, required measures and costs in the first few decades tend to be crucial for overall results. This implies that for mitigation analysis, all of the above arguments are relevant. In contrast, given the long-term focus of climate modeling (a hundred-year time frame or more), only the first and third arguments apply. It should also be noted that because climate modeling generally requires large resources and time, the turnover rate of scenarios needs to be much slower as well. The use of SRES in impact assessment occupies an intermediate position, both in terms of the appropriate turnover rate of scenarios and the outlook period for this type of assessment. Given the fact that SRES scenarios are used for a wide range of applications, we have decided to focus on a *reasonable* match between the SRES scenarios and new information on historic data, short-term outlooks or long-term scenarios. Our judgment on reasonableness take into account that (a) a good performance on trends is more essential that an exact reproduction of specific results for any given year and that (b) historic data also show some uncertainty, so that “matching” such data is to some extent a statistical concept.

3.3 Results for Main Driving Forces

3.3.1 Population

3.3.1.1. Historic Trends

The SRES emissions scenarios use three population projections produced in 1996 by the UN (UN, 1998, for the B2 scenario) and the International Institute for Applied Systems Analysis (A1/B1 and B2) (Lutz et al., 2001). Both of these projections used the base year of 1990. As shown in Table 3.2, the SRES population values for 1990 and 2000 are quite close to the most recent estimates of population size for the world and the four SRES macro regions. Some differences are to be expected since historic population estimates undergo regular revision. In particular, the most recent population estimates have the benefit of drawing on data from the censuses held around the year 2000 in many countries of the world, but not available at the time the projections used in SRES were produced. While revisions to population totals for particular countries can be substantial, at larger levels of aggregation they are generally small. This is reflected in the close agreement between the updated estimates and the SRES values.

A second reason that the SRES values are relatively close to recent estimates for the year 2000 is that short-term projections (for example, from 1990 to 2000) have a relatively small uncertainty (particularly for large world regions) due to the large influence of demographic inertia (momentum) on short term population trends. Given a particular base-year population in 1990, much of the population change over the next decade is already built in to the existing age structure. Partly for this reason, the current estimate of a global population size of 6.07 billion in 2000 is not much different from the SRES figures of 6.09–6.17 billion. While differences are larger at the world region level, in no case are they large enough to question the credibility of the SRES scenarios on the basis of historic trends in population size.

Table 3.2 Comparison of SRES population trends with 1990-2000 data (in millions)

		UN data	A1/B1	A2	B2
OECD	1990	*866*	*864*	*864*	863
	2000	*929*	*919*	*923*	916
	Ratio	*1.07*	*1.06*	*1.07*	*1.06*
EIT	1990	*412*	*412*	*412*	412
	2000	*411*	*419*	*421*	415
	Ratio	*1.00*	*1.02*	*1.02*	*1.01*
Asia	1990	*2791*	*2807*	*2807*	2788
	2000	*3245*	*3260*	*3295*	3248
	Ratio	*1.16*	*1.16*	*1.17*	*1.16*
ALM	1990	*1195*	*1200*	*1200*	1188
	2000	*1484*	*1519*	*1530*	1510
	Ratio	*1.24*	*1.27*	*1.28*	*1.27*
World	1990	*5264*	*5282*	*5282*	5251
	2000	*6069*	*6117*	*6171*	6089
	Ratio	*1.15*	*1.16*	*1.17*	*1.16*

Source: (UN, 2003).

3.3.1.2. Recent Projections for the Medium Term (up to 2050)

The population projections used in SRES were consistent with the demographic outlook at that time (Gaffin, 1998). The projection used in the B2 scenarios was the UN medium variant (UN, 1998). The A1 and B1 scenarios all shared a common, relatively low, population projection from IIASA, while the A2 scenario used a relatively high population projection from IIASA (Lutz et al., 1996). These two projections spanned, at the global level, approximately the 90% uncertainty interval associated with the IIASA probabilistic projections (i.e. a level just within the 5th and 95th percentiles of the distribution).

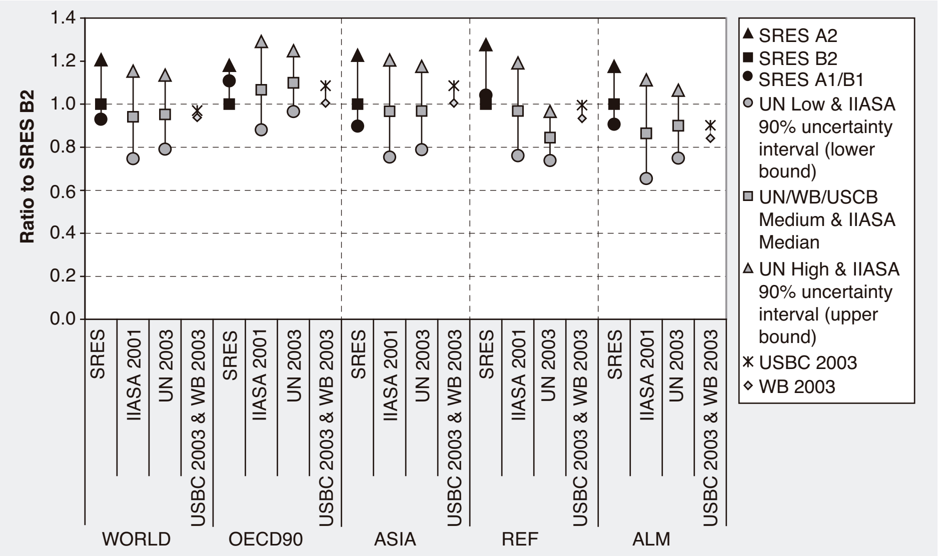
Updated projections, however, generally anticipate less global population growth than the projections used in the SRES scenarios. Since the early 1990s, birthrates in many parts of the world have fallen surprisingly fast and the AIDS epidemic has taken an unexpectedly large toll. These changes have led demographers to revise their outlook on future population size downward, toward smaller, older populations than previously anticipated. For example, Figure 3.1a compares the projections for 2050 used in SRES to the most recent IIASA (Lutz et al., 2001; Lutz et al., 2004), UN (2005), World Bank (2005) and the US Census Bureau (US.BoC, 2005) projections for the world and the four SRES macro regions. For comparability, the figure plots all population sizes relative to the projected population in the SRES B2 scenario for each region (i.e. the UN medium scenario produced in 1996).

For the world as a whole, population was projected at 9.4 billion in 2050 in the SRES B2 scenario. Figure 3.1a shows that the A2 scenario anticipated a 21% larger global population, and the A1 and B1 scenarios, a 7% smaller population than the B2 scenario.

When these scenarios are compared to more recent projections for the world, some changes can be noted. First of all, there is a small downward revision to the medium (or "best guess") projections. Second, small downward revisions also occur at the high end of the uncertainty range. Finally, a relatively large downward revision can be noted to the low end of the uncertainty range. As a group, updated medium projections foresee a 3–10% (0.3 to 0.9 billion) smaller global population in 2050 relative to the SRES B2 projection. Similarly, the high end of the range has shifted downwards, so that the SRES A2 scenario now no longer falls within the 90% uncertainty interval; it now lies 6–7 percentage points (0.5–0.7 billion people) above the updated UN high scenario and the 95th percentile of the IIASA uncertainty range. At the low end of the range changes are much larger: the SRES A1/B1 assumptions lies 11–18 percentage points (1.0–1.7 billion people) above the UN low scenario and the 5th percentile of the IIASA uncertainty range.

Considering the four SRES macro regions, Asia and ALM drive the global results due to their very large absolute sizes. Analysis of smaller sub-regions (not shown) indicates that changes are primarily due to changes in the outlook for Sub-Saharan Africa, the Middle East and North Africa region, and the East Asia region, particularly China. Recent data showing lower than expected fertility in these regions has led to less projected population growth. In addition, a much more pessimistic view on the extent and duration of the HIV/AIDS crisis in sub-Saharan Africa has also lowered anticipated growth in that region.

(a)



(b)

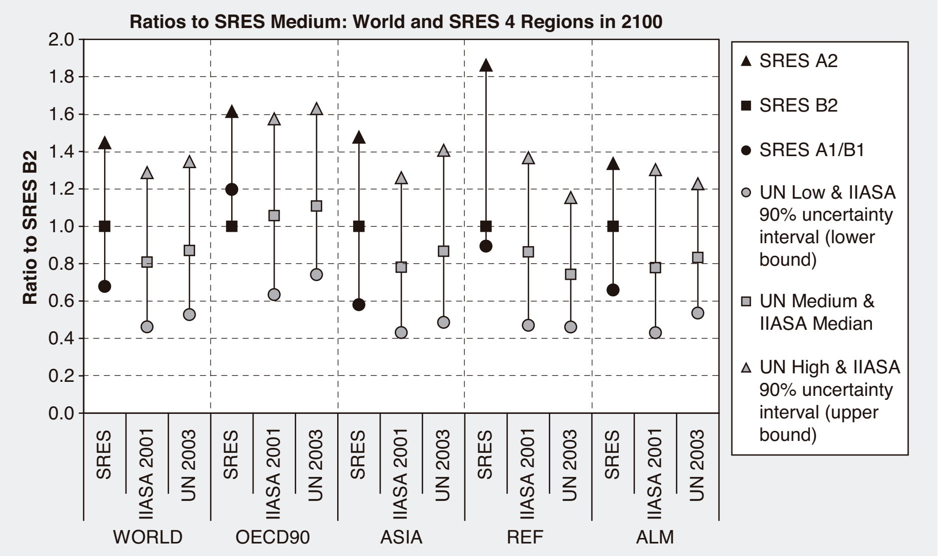


Figure 3.1 Population size worldwide and for four SRES macro regions relative to the population size in the SRES B2 projection for (a) 2050 and (b) 2100. Source: (Nakicenovic and Swart, 2000; Lutz et al., 2001; UN, 2003; US.BoC, 2003; WorldBank, 2005).

Changes in the outlook in the industrialized countries differ substantially from the global pattern. In the OECD region, the UN projections are actually about 12% *higher* than previously, despite continuing low fertility in these regions due mainly to changes in assumptions on migration. Previous UN projections did not attempt to project migration beyond 2025, assuming instead that it was zero afterwards; the updated projections assume non-zero migration through 2050, while updated IIASA assume more optimistic projection of future life expectancy. In the REF region, projections from both institutions have been revised downward, especially in the UN projections and for the high end of the uncertainty range. These changes have been driven by recent data showing very low fertility levels and mortality that is quite high relative to other industrialized countries, particularly in the Former Soviet Union.

It should be noted that the SRES A1/B1 assumptions for the industrialized countries (OECD and REF regions) cannot be directly compared to the low-end range of more recent scenarios, because SRES did not assume a low population growth projection for these regions (even though growth was relatively low in A1/B1 for the world as a whole). Rather, SRES assumed a medium fertility scenario coupled with relatively low mortality in these regions, which in combination resulted in a future growth in these regions that was actually somewhat high relative to a "best guess" projection.

3.3.1.3. Recent Projections for the Long Term

Because population growth is a path-dependent process, changes in the estimates for the base year and in the short-term outlook can have important implications for the plausibility of long-term population growth paths. Therefore it is worth comparing the SRES population assumptions to updated projections for the end of the century. Among the major institutions that regularly produce population projections, IIASA and the UN are the only ones that have produced updated projections for the world that extend to 2100, shown in comparison to the SRES assumptions in Figure 3.1b. Patterns are qualitatively similar to those found for 2050, but larger in magnitude: a general downward shift in the full range of projections that is somewhat larger at the lower end. For example, the most recent central projections for global population are 13–19% (1.4–2.0 billion people) lower than the medium population scenario used in the SRES B2 scenarios. Similarly, the SRES A2 population assumption of 15 billion in 2100 is now 10–16 percentage points (1.1–1.7 billion) above the UN high and IIASA 95th percentile. At the low end differences are larger: the UN low and IIASA 5th percentile are 15–22 percentage points (1.6–2.2 billion) below the SRES A1/B1 assumptions. Just as for 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 the China region, Middle East and North Africa, and Sub-Saharan Africa.

3.3.1.4. Credibility of SRES Assumptions

Although the range of projected population sizes has shifted downwards since the development of the SRES scenarios, this does not automatically imply that the SRES population assumptions are no longer credible. For example, the assumptions used in the SRES B2 and A1/B1 scenarios still fall within the plausible range of population outcomes according to more recent outlooks (see Figure 3.1). What is clearly missing, however, in the SRES set is a population projection that is representative of the lowest end of the current range of projections. This implies that if new scenarios were to be developed today it would make sense to choose lower population growth assumptions, and for this reason some researchers have produced revised versions of the SRES population assumptions. For example, Hilderink (2004) provides an alternative interpretation of the demographic implications of the SRES storylines, and produces four new global population projections that span a range of 8 to 12 billion in 2100 (as compared to 7 to 15 billion in SRES).

At the high end of the range, the comparison of SRES to the updated outlook is less favorable. The population projection used in the A2 scenarios now lies above the 95th percentile in the IIASA projections and above the most recent UN high scenario. Differences are especially large in particular regions such as East Asia, Middle East, North Africa and the Former Soviet Union. In these regions, the SRES assumptions now strain credibility, a fact that should be taken into account by scenario users. It is advisable to use revised projections for the regions with the largest differences, if possible. For example, IIASA has recently produced a new population scenario for use in a stabilization variant of an A2 storyline that results in a population of about 12 billion in 2100. All else being equal, lower population growth projections are likely to lead to lower emissions levels (however, there are dynamic feedbacks such as lower fossil fuel consumption leading to less depletion, thus lower prices). This could, in turn, partly offset fuel reduction).

It should also be kept in mind that while in the few regions discussed above there is a clear inconsistency between the SRES A2 population assumptions and the more recent outlook, there is, in general, a substantial range of population outcomes that is consistent with any given SRES storyline (O'Neill, 2004). As long as there is consistency between the population assumptions used to generate emissions and to evaluate impacts, researchers need not feel tightly bound to a single population projection for each storyline.

3.3.2 Economic growth

Growth of economic activities is clearly a dominant driver of energy demand. In terms of long-term scenarios, economic growth is usually reported in the form of growth of Gross Domestic Product (GDP) or Gross National Product (GNP). It should be noted, however, that in reality emissions are driven by the individual activities, each measured in their own (physical) units. Monetary values function as an (imperfect) means for aggregation of these activities. Historically, there has been a relatively good correlation between growth of GDP and growth of energy demand, except for periods of strongly rising energy prices. Comparison of GDP data among different sources is somewhat complicated by the relatively large uncertainty, resulting, among other aspects, in exchange rates and the influence of base year. The World Bank (2005), the main source of historic GDP data used in our comparisons, does not quantify the associated uncertainties, but indicates that the quality of its data is based on the data that has been reported to the World Bank, and also on aggregation of underlying data by the Bank. For growth rates, however, the impact of base year is much smaller.[iv] Therefore, we will focus on growth rates rather than the absolute numbers (see Table 3.3 for world data and the data for the four SRES regions).

For international comparison, data on GDP (or other economic measures) must be converted into a common unit, which is generally done in terms of US$ based on market exchange rates (MER). Purchasing-power-parity estimates (PPP), in which a correction is made for differences in price levels among countries, are considered to be a better alternative for comparison of income levels across regions and countries. Measurement of PPP data, however, is somewhat more problematic, and scenarios expressed in PPP terms are scarce. In SRES, most GDP data are reported in MER terms – although for one model, PPP-based values are also given. Recently, the use of MER-based economic projections in SRES has been questioned (Castles and Henderson, 2003), suggesting that as a result of the use of MER, the economic growth projections in SRES are inflated. SRES

[iv] At the country level, there is a small impact of base year on long-term growth rates. On the regional level, the impact can be somewhat larger as the relative income of different countries (and therefore their weight in the overall growth rate) may be influenced.

authors have argued that the use of MER or PPP data does not in itself lead to substantially different projections for emissions, (and that the use of PPP data was at the time impossible due to lack of existing projections) (Nakicenovic et al., 2003).

The ensuing debate has not yet ended One element of the debate is formed by the purpose of the GDP scenarios, i.e. whether they are projections of the world economy per se or used as an intermediate variable for developing emissions projections. For the former, the debate on the most appropriate measure seems to be the most undecided. Nordhaus (2005), for instance, recommends an intermediate approach, using a PPP-based exchange rate for aggregating across regions, and updating over time using a superlative price index. Timmer, in contrast, prefers the use of MER data in long-term modeling because data is more available and many international relations are based on MER exchanges (Timmer, 2005).

If the purpose is to project emissions, it is less likely that the choice of exchange rate will have a substantial effect. Here, monetary units function as a means to aggregate the real drivers of emissions, i.e. physical activities. In addition to the aggregated drivers, an aggregated emission coefficient is calculated by comparing base year emissions with base year economic activity measures in monetary units. The economic activity is then projected into the future as is the development of the emission coefficients. At the end of the simulation period, the two are combined to produce emission levels. If the choice of metric influences the outlook on growth of economic activities, it simultaneously also influences the outlook on development of emission coefficients. Therefore, if a consistent set of metrics is employed, it seems unlikely that the choice of metric will substantially affect emissions.

Nevertheless, results from modeling studies have been contradictory. Manne and Richels (2003) found a small effect of switching from MER- to PPP-based measures, while McKibben et al. (2004) found substantial differences in outcomes. However, results critically depend on the convergence assumptions employed, and it is not clear that all relationships within the models have been adjusted to be consistent with the change in metric. Holtsmark and Alfsen (2005) showed that in their simple model consistent replacement of the metric for economic activities expressed in monetary terms (PPP for MER) throughout the model (i.e. for income levels, but also for underlying technology relationships) leads to a full cancellation of the impact. On the basis of these studies, we conclude that using PPP-based values instead of MER-based values would at most only mildly change results in terms of physical parameters, such as energy use or greenhouse gas emissions.

At the global level the choice of PPP versus MER estimates also influences global economic growth rates, since using PPP values implies a larger contribution of low-income countries to global GDP. This then also increases the contribution of their higher growth rates to the global average increase. MER-based and PPP-based growth estimates can therefore not be directly compared at the global level. In order to compare growth rates in studies that report in PPP values (IEA, for instance), their growth rates were first assigned to MER income estimates on a regional basis in the base year.

3.3.2.1. Historic Trends

The historic data used (WorldBank, 2005) indicates an overall 13% growth between 1990 and 2000 in per capita GDP.[v] In general, there is a reasonable agreement with the data reported for the four SRES scenarios and the historic trends. In absolute numbers, there are larger differences (due to the different data sources). All SRES scenarios included the economic downturn in the REF region and the fast growth rates in the Asia region. There are, however, a few quantitative differences. According to World Bank data, GDP in the REF region declined by 22% between 1990 and 2000. The A2 and B2 markers show a somewhat larger decline, while the A1 and B1 scenarios show a smaller decline than the historic data. In the Asia region, the A2 and B2 markers show higher economic growth rates than historic data. Finally, the A2 scenario shows too low growth rates in the OECD. But overall, it can be concluded that the SRES scenarios have captured the direction and the relative magnitudes of growth rates across the four regions reasonably well (Table 3.3).

Table 3.3 Comparison of SRES per capita GDP trends with 1990-2000 data (in US$ per capita)

		WB data	A1	A2	B1	B2
		1990 US$				*1990 US$*
OECD	1990	19777	19092	19154	20651	19092
	2000	23333	22307	20260	23793	23035
	Ratio	1.18	1.17	1.06	1.15	*1.21*
REF	1990	2329	2663	2153	2427	2663
	2000	1828	1909	1900	1632	2410
	Ratio	0.78	0.72	0.88	0.67	*0.90*
Asia	1990	532	536	358	503	536
	2000	871	828	698	832	1078
	Ratio	1.64	1.54	1.95	1.65	*2.01*
ALM	1990	1800	1594	1964	1632	1594
	2000	1985	1779	2222	1941	1787
	Ratio	1.12	1.12	1.13	1.19	*1.12*
World	1990	4128	3972	3805	3977	3972
	2000	4656	4365	4084	4378	4646
	Ratio	1.13	1.10	1.07	1.10	*1.17*

Source: (Nakicenovic and Swart, 2000; WorldBank, 2005).

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[v] The World Bank data is reported in 1995 US$, while the SRES scenarios are reported in 1990 US$. For comparison, the World Bank data has been recalculated into 1990 US$ (at the country level) using inflation and exchange rate derived from the same World Bank data base.

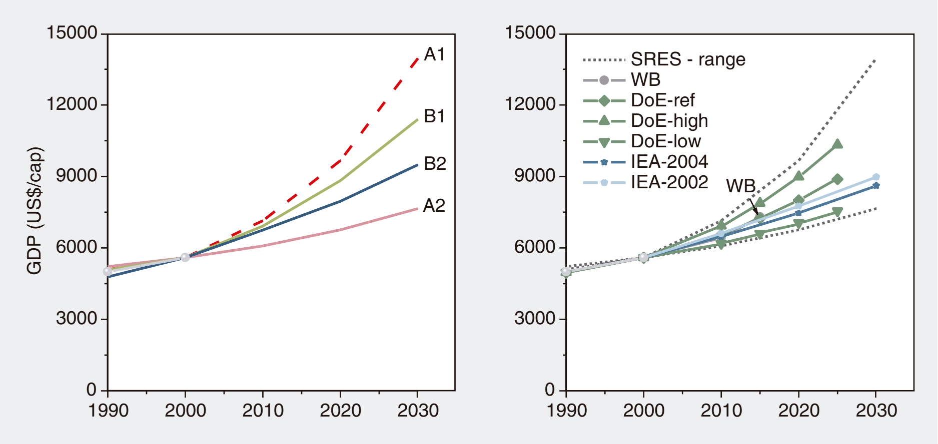

Figure 3.2 Comparison of global GDP growth in the SRES scenarios and more recent projections. SRES = (Nakicenovic and Swart, 2000), WB = World Bank (WorldBank, 2004), DoE = assumptions used by US Department of Energy (US.DoE, 2004b), IEA assumptions used by IEA (IEA, 2002; IEA, 2004b).
Note: In order to allow comparison, reported regional growth rates for all studies were used on the basis of World Bank data (in market exchange rate 1995 US$) for base year (2000).

3.3.2.2. Recent Projection for the Medium Term (up to 2050)

As points of comparison for economic projections, we have used the World Bank's Economic Prospects 2004 (WorldBank, 2004), and the economic scenarios included in the 2002 and 2004 World Energy Outlook (IEA, 2002; IEA, 2004) and the International Energy Outlook (US.DoE, 2003) (Figure 3.2). In the 2004 version, the economic scenarios of IEA's World Energy Outlook are based on OECD, World Bank and IMF projections, while in the long-term, growth rates for each region are assumed to converge to a long-term rate based on demographic and productivity trends. The economic scenarios of the US.DoE's Intern ational Energy Outlook are on country base developed by Global Insight, Inc. (2003), except for the USA for which official US projections are used. The US.DoE outlook includes two alternative projections (low and high) based on alternative assumptions with respect to economic growth: depending on the type of country, between 0.5% and 1.5% was added/subtracted to the annual growth rate[vi].

The world economic growth projections included in the World Energy Outlook between 1994 and 1998, particularly in the short term, have been revised slightly upward in each consecutive edition of the outlook (where projections are around 3.0% global growth, measured in PPP$). In fact, real growth rates turned out to be on average 0.5% higher than the assumptions. From the 1998 edition up to the present, growth rates have been revised downward to some extent. The five most recent World Bank projections published between 2000 and 2004 show a downward trend in growth rates anticipated for the 2000–2010 period. For example, the 2000–2010 per capita growth

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[vi] In other words, economic projections are in all these studies exogenous inputs into the energy projections – and there is no dynamic link between the two.

rate in the group of low-income countries was projected to be around 3.8% per year in the 2000 edition and 3.4% in the 2004 edition. This revision was due to the relatively slow growth of the world economy between 2001 and 2003, while the longer term projection remained more-or-less the same. Similarly, between the 2003 and 2004 edition, the Department of Energy's central projection was revised downward from 2.1% to 1.8% annually over the projection period. Its high projection was revised even more, from 3.3% to 2.5% annually, also implying a decrease in the uncertainty range (US.DoE, 2003; US.DoE, 2004b).

The SRES scenarios project a very wide range of global economic growth rates from 1.0% (A2) to 3.1% (A1) (based on MER). This range is somewhat wider than the range covered by the US.DoE high and low scenarios (1.2–2.5%). The central projections of US.DoE, IEA and World Bank all note growth rates of around 1.5–1.9%, thus occurring in the middle of the range of the SRES scenarios (near the B2 trajectory). Other medium-term energy scenarios are also reported to have growth rates in this range (IEA, 2004b). It should be noted that although the SRES A1 scenario lies outside the range of the scenarios included here, it is equal to US.DoE's 2003 high-growth projection.

A similar picture emerges on the regional scale (Figure 3.3). The range of the SRES scenarios is generally consistent with the more recent studies, but there are some important differences. For the OECD and the REF regions, the correspondence between SRES outcomes and recent scenarios is relatively good, although the SRES GDP growth rates are somewhat conservative. This is certainly the case for the low growth SRES scenarios

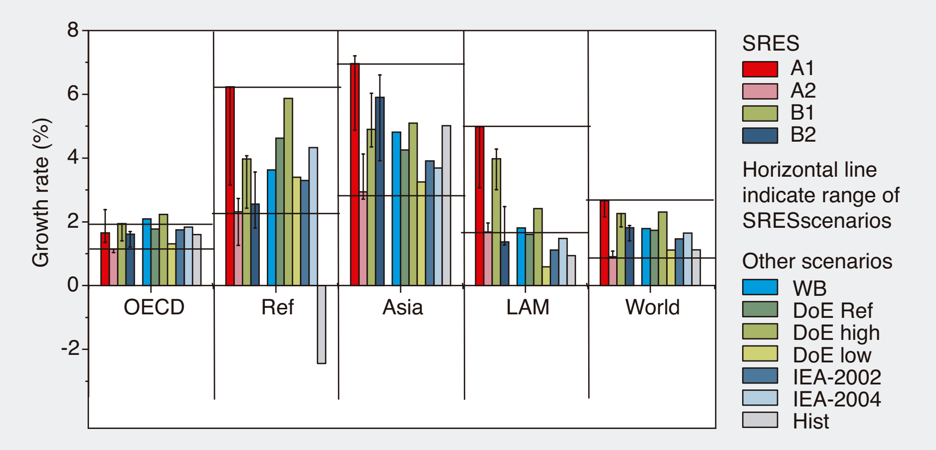

Figure 3.3 Comparison of the regional annual average growth rate of per capita GDP between 2000-2015 in the SRES scenarios and more recent studies. WB = (WorldBank, 2004), DoE = Reference, high and low scenario of US.DoE (2004b), IEA = International Energy Agency (IEA, 2002; IEA, 2004b). Hist = Historic data from World Bank (WorldBank, 2005). Note: The horizontal lines in the figure indicate the range of growth rates set out by the SRES marker scenarios. The vertical lines showing uncertainty bars for the SRES scenarios indicate the range of different outcomes of SRES scenarios within the same family (while the bars indicate the growth rates of the Marker scenarios). The historic rate represents the 1990-2000 period.

for the REF region (2% growth rate) compared to the more recent projections (ranging from 3–6%). For the REF region, all scenarios (both SRES and alternatives) show a clear contrast to the negative growth in the 1990–2000 period, which was caused by the economic restructuring process. In the Asia region, the SRES range and its median value have a small upward bias compared to recent studies. This can be explained by the explicit assumption of the A1b storyline that further globalization and rapid technology progress could lead to high growth rates in low-income countries consistent with the high growth rates in East Asia during the late 1980s and 1990s (above 5%). In fact, the B2 growth rates are also considerably higher than the current medium estimates. As the uncertainty bars indicate, some of the non-marker SRES scenarios (in particular for A1) project lower growth rates – making the range of SRES even more consistent with the current projections. The differences between the SRES outcomes and more recent projections are largest in the ALM region. Here, the A1 and B1 scenarios clearly lie above the upper end of the range of current projections (4–5%), while A2 and B2 lie near the center of the range (1.4–1.7%). The 1990–2000 growth rate for this region was 1.0% – and current short-term projections range from 1.1–2.4%.

Again, the A1 and B1 storyline emphasizes rapid economic growth in developing countries; however, one could question whether the conditions for growth in the ALM region can be achieved in this relatively short time period. Apparently, the recent short-term projections used here expect current barriers to economic growth in these regions to slow down growth, at least until 2015. Projections from SRES scenarios other than the marker in each family contain somewhat lower growth rates for A1 and B1.

An important axiom in both the A1 and B1 scenarios is that economic growth will be faster in low-income countries than in high-income countries (leading to partial convergence). The literature on convergence and economic growth, also discussed in the SRES report, indicates a relationship between degrees of governance, stages of development and the potential for economic growth (Nakicenovic and Swart, 2000). In the more recent projections, the same trend is found in the relative growth rates of the OECD, REF and Asia regions; however, the ALM region is an exception. Specific barriers (such as lack of good governance, the AIDS crisis, or the dependency on foreign finance) in this region apparently lead current economic projections to assume that these regions will not yet experience an economic take-off similar to what the East Asian economies achieved over the past two decades (WorldBank, 2005).

Overall, our comparison shows that the full range of the SRES scenarios seems to comply relatively well with the most recent medium-term projections. Consistency at the global level is generally good. Although the A1 scenarios lie just above the range of current projections, the full set of SRES projections spans a modestly larger range than the recent projections included here. At the regional level, consistency is also generally good, with the exception of the ALM region. In that region, the degree of rapid economic growth assumed under A1 and B1 scenarios in the next two decades (and to a lesser degree the A1 scenario in the Asia region) is inconsistent with the range of current projections. In addition, the assumptions of the SRES low-growth scenarios for the ALM region, rather than representing the low end of a plausible range, could themselves be considered as still being fairly optimistic. On a global scale, this means that A1 is somewhat outside the range of current projections.

3.3.2.3. Recent Projections for the Long Term

There are no official organizations that publish long-term economic scenarios. The only available information comes from individual economic modeling teams active in the field of climate change research, who develop long-term economic scenarios as part of their work. Some groups cooperate within the context of the Energy Modelling Forum (EMF). These scenarios are meant as medium scenarios – and are not intended to explore the upper or lower range of possible growth rates. Richels et al. (2004) published long-term economic projections with uncertainty ranges. Figure 3.4 shows the A1 and B1 scenarios to be clearly situated above the medium growth projections of EMF-21. The A1 scenario is also found just outside the range of economic growth scenarios of Richels et al. (2004). The B2 scenario seems to be reasonably representative of medium-growth scenarios. For A2, it should be noted that low economic growth in SRES is combined with rapid population growth, causing the somewhat upward bias compared to current low-growth projections. Apart from this, the A2 scenario seems to be representative of current low-growth scenarios for per capita income.

3.3.2.4. Credibility of SRES Assumptions

The comparisons show that while the SRES scenarios are largely consistent with current projections at the global level, the set represents mainly high-growth scenarios for the ALM region in the first decades. As a result, the global growth trend in the first few decades of the A1 scenario lies outside the range of current projections. Whether this has longer term implications for the scenario is unclear. A slower start in economic growth than assumed in the A1 scenario could put the region on a growth path that is

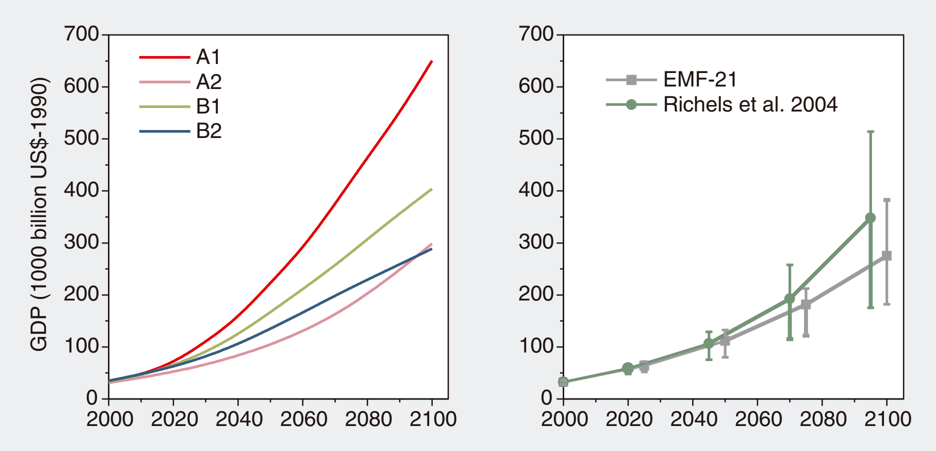

Figure 3.4 Comparison of the SRES scenarios with the range of GDP projections used in recent long-term scenario studies. The range in EMF-21 (Weyant et al., 2006) indicates the lowest and highest projections included in a set of baseline projections of different models. The range for Richels et al. (2004) represents the 5th and 95th percentiles of the distribution in that study.

permanently separated from the high-growth projections (i.e. the implications are persistent into the long term), but could also mean a delay without substantial long-term consequences. While updates of SRES might want to focus on variants that delay high economic growth rates in the ALM region and that include a slow global economic growth scenario, the current inconsistency in the ALM region might only be a problem in using the SRES scenarios for this specific region. One may question whether SRES researchers have appreciated enough that long-term storylines, particularly in the ALM region need to overcome important inertia. With respect to global application, the contribution of the ALM region to global greenhouse gas emissions in the short term will be small, even under high-growth assumptions.

3.3.3 Energy use

3.3.3.1. Historic Trends

For energy use, we compared the changes in SRES primary energy use between 1990 and 2000 to the estimates included in IEA's Energy Balances and Statistics for OECD and non-OECD countries (IEA, 2003b) (Table 3.4). It should be note that the absolute difference between A2 and the IEA data is caused by the fact that the former does not include the use of traditional biofuels.[vii] As a result, growth rates in low-income regions in the SRES A2 scenario as well are higher, resulting from the substitution of traditional fuels with commercial fuels. In terms of trends, there are only a few differences between historic trends and those included in SRES. These differences are consistent with (and possibly a result of) the differences in GDP trends that were observed earlier: B1's low 2000 energy use for the FSU, and A1's lower and A2's higher 1990-2000 increase for Asia.

3.3.3.2. Recent Projections for the Medium Term (up to 2050)

Figure 3.5 shows that the range covered by the set of near-term projections nearly capture that of SRES, and that the projections from IEA's World Energy Outlook (IEA, 2002; IEA, 2004b) and US.DoE's central projection (US.DoE, 2004b) are near the SRES median.[viii] The A1 scenario is somewhat above the range, while the US.DoE low economic growth scenario follows a trajectory somewhat below the lowest of the SRES scenarios (B2). The higher energy consumption in A1 is consistent with its higher income growth (as observed earlier). Because the results for energy are very similar to those for CO_2 emissions, regional trends are discussed only for the latter.

3.3.3.3. Credibility of SRES Assumptions

The results for energy are consistent with our earlier findings for GDP assumptions in SRES. SRES reflects historic trends reasonably well, and compares well on a global scale with near-term projections in recent studies. The energy use in the A1 marker

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[vii] The A2 marker scenario was developed by the ASF modeling team. This model does not calculate traditional biomass numbers; A2 elaborations of other modeling teams do include traditional biofuel projections.

[viii] For a description of the differences between the reference, low and high projections of US.DoE see the section on GDP growth.

Table 3.4 Comparison of SRES trends in primary energy use with 1990-2000 data (in EJ)

		IEA	A1	A2	B1	B2
OECD	1990	172	167	155	151	159
	2000	201	191	176	178	180
	Ratio	1.17	1.14	1.14	1.18	*1.13*
REF	1990	70	71	67	95	70
	2000	50	51	45	52	62
	Ratio	0.70	0.72	0.67	0.55	*0.89*
Asia	1990	71	80	53	79	74
	2000	100	100	82	113	103
	Ratio	1.41	1.25	1.55	1.43	*1.39*
ALM	1990	45	58	38	43	49
	2000	62	82	57	64	63
	Ratio	1.38	1.41	1.50	1.49	*1.29*
World	1990	358	376	313	368	352
	2000	413	424	360	407	408
	Ratio	1.15	1.13	1.15	1.11	*1.16*

Source: (Nakicenovic and Swart, 2000; IEA, 2003b)

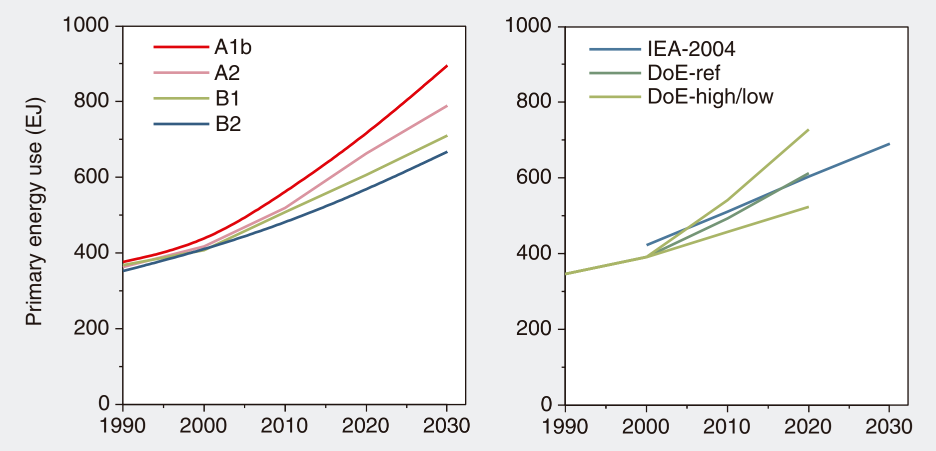

Figure 3.5 Comparison of trends in SRES total primary energy consumption with more recent studies by US.DoE and IEA. DoE = Projections from US.DoE (2004b), IEA-2004 = Projection from the International Energy Agency. (IEA, 2004b). Note: Original A2 scenario as reported in SRES does not contain non-commercial biomass use. Therefore for A2 biomass data has been taken from IEA energy data – and held constant after 2000.

scenario lies somewhat above the range of near-term projections and therefore might be considered somewhat less likely than other scenario outcomes, although a specific conclusion cannot be drawn, given that the high end of the range of recent projections is defined by an EIA scenario that is not associated with any judgement of likelihood by the developers.

3.4 Results for Emission Projections

For all the published emission data, the SRES report used a standardization process (see methodology). This means that the comparison in the historic period is done for the standardized 1990–2000 data (and not for individual model results).

3.4.1 CO_2 emissions from energy and industry

3.4.1.1. Historic Trends

Emission estimates are affected by inevitable degrees of uncertainty. The SRES report reviews the relevant literature, which gives a range from 6.0 to 8.2 GtC for total CO_2 emissions in the year 1990 (compared to a standardized value of 7.1 GtC retained for the SRES scenarios) (Nakicenovic and Swart, 2000). By far the largest part of this uncertainty range is attributable to emissions from land-use change, although for industrial sources of CO_2 emissions (fossil fuel burning, flaring of natural gas and cement manufacturing) some uncertainty also exists. Some of the differences between the different data sources on CO_2 emissions come from differences in coverage (cement manufacturing, bunker emissions and feedstocks are often not included), but also from differences in underlying energy data, detail in energy carriers, and emission factors. Olivier and Peters (2002) show that revisions in different databases for the last few years of published data create an error for that year of 1–8%. The total uncertainty in the EDGAR CO_2 emission inventory is estimated to be around 10% (Olivier, 2004). Here, we will focus on the emissions from energy and other industrial sources on the basis of the most recent emission inventories (see Table 3.5).

Table 3.5 illustrates the uncertainties in past and current emission estimates by showing the difference between the various inventories. Of these sources, IEA and EDGAR

Table 3.5 Emission inventories of industrial CO_2 emissions (in MtC)

		1990	1999	2000	Growth 2000-1990	Ratio 2000/1990
Fossil fuel combustion	CDIAC	5925	6242	6353	428	1.07
	EDGAR	6078	6608	6700	622	1.10
	IEA	5980	6558	6738	758	1.13
	US.DoE	5928		6468	540	1.09
Total, including cement	CDIAC	6126	6492	6611	485	1.08
	EDGAR	6297	6877	6972	676	1.11
	IEA+	6144	6776	6973	829	1.13
	US.DoE+	6092		6703	611	1.10
	SRES	5999		6896	897	1.15

Note: Figures do not include emissions from non-energy use of fossil fuels (e.g. feedstocks). Numbers include gas flaring and emissions from international bunkers, coming to approximately 50 and 200-300 $MtCO_2$, respectively).

+ The US.DoE and the IEA inventories do not include emissions from cement productions. For them, emissions from these sources have been estimated on the basis of USGS production figures. Source: (Nakicenovic and Swart, 2000; Olivier and Berdowski, 2001; IEA, 2003a; Marland et al., 2004; US.DoE, 2004a) are the most detailed[ix]. Absolute emissions in 2000 according to SRES are within the literature range, although SRES emissions in 1990 are somewhat below the currently estimated range for that year. The increase in the SRES emissions between 1990 and 2000 (15%) is somewhat higher than in any of the currently available global emissions inventories (which range from 8–13%).

The underlying regional data (not shown) indicate small differences in emission growth rates for the OECD, REF and ALM regions. In contrast, there is a larger difference in the Asia region (45% increase in IEA and EDGAR versus a 55% increase in SRES). The "overestimation" in CO_2 increase in this region in SRES results from expectations in the late 1990s that Chinese emissions would continue to grow rapidly. In reality, emission growth in China has probably been relatively slow in the second half of the 1990s. However, development of Chinese CO_2 emissions during this period has been subject to debate. In the early 2000s, some data sources (e.g. CDIAC) indicated a decline in Chinese emissions in the late 1990s, caused by both a slowdown of economic growth and Chinese reform of the coal market – in particular, closing small mines. These effects were regarded as temporary, and unlikely to affect long-term emission trends (van Vuuren et al., 2003c). Since then historic data on coal use during the late 1990s has been revised upwards (decreasing the difference with the SRES figures). This uncertainty in Chinese emissions is one important cause of the differences between the global emission inventories.

Given the uncertainties within the inventories, the overestimation of global CO_2 emission increase in SRES can either be regarded as acceptable, when compared to the IEA, US.DoE and EDGAR inventories, or considerable, when compared to the CDIAC numbers, which indicate only an 8% growth.

3.4.1.2. Recent Projections for the Medium Term (up to 2050)

The IEA and US.DoE projections are again used as references for expected near-term trends. In addition, we use the highest and lowest projections from the Energy Modelling Forum (EMF-21) (Figure 3.6). These scenarios (called the "modeler's preference baseline") represent "medium"-growth scenarios, and the range should be interpreted as an indication of how different modeling groups, using different models, assess the range of such medium projections.[x] The comparison shows results similar to those for energy projections. In most cases, the SRES emission scenarios are consistent with near-term projections. A clear exception is formed by the high-economic growth A1 scenario, which is above the range, especially around 2010. After 2010, the differences between the A1 projection and the high growth US.DoE projection decline, and almost converge in 2025. The IEA 2004 baseline projection, the US.DoE's reference scenario

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[ix] There are still considerable differences between the different inventories, despite our attempts to harmonize the coverage. For most inventories the differences are consistent with the uncertainty estimate for the EDGAR CO_2 emission inventory. Differences may result from calculation methods, detail and emission factors used.

[x] Since the SRES scenarios deliberately choose more extreme assumptions to explore possible alternative futures, one would expect them to fall somewhat outside this range.

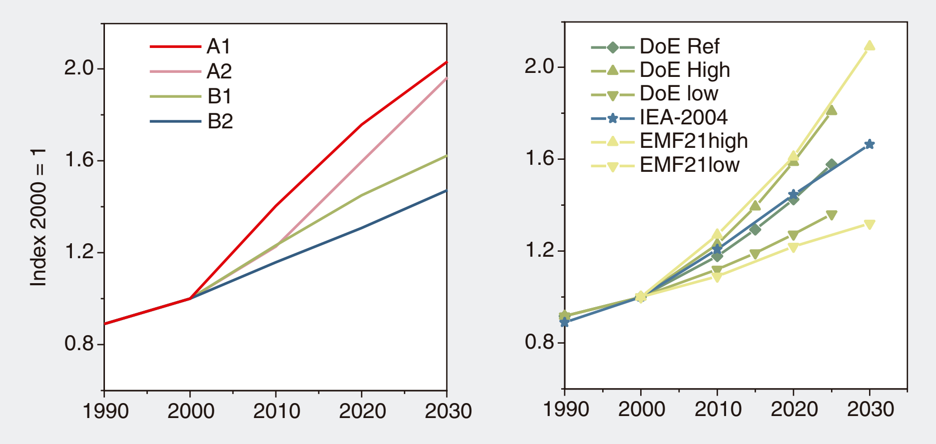

Figure 3.6 Comparison of trends in global CO_2 emissions, SRES versus more recent projections. DoE = Projections from US. DoE (2004b), IEA = Projection from the International Energy Agency. (IEA, 2004b). EMF-21 indicates the range of the lowest and highest reported values in the EMF-21 study (Weyant et al., 2006).

and the EMF-21 range are all found near the more central projections of SRES (with the IEA-2002 projection displaying virtually the same emissions).

On a regional scale, comparison confirms the results for the main emissions drivers found earlier (Figure 3.7). For the OECD region, emission increases in the SRES scenarios are somewhat lower than those in the studies used for comparison. This is, in particular, the case for B1 (likely to be a result of the emphasis on environmental protection), but also for A1 (possibly due to swift technology development and less coal use). The highest projections of the SRES range (A2) more-or-less coincide with the central US.DoE and IEA projections. A similar situation holds for the REF region. In the Asia region, the range of the SRES scenarios lies somewhat above that of the more recent projections, but differences are small. The most important ones are found for the ALM region, for which the A1, B1 and A2 scenarios clearly project a somewhat faster increase than more recent projections. This reflects the fairly high GDP and energy growth assumptions for this region discussed above, which are part of the A1 and B1 storyline by design. Since the ALM region produces a relatively small share of global emissions, the impact on global results is limited.

3.4.1.3. Long-Term Projections

As in the case of GDP, there are no official institutions publishing long-term CO_2 emission scenarios independent of SRES. Instead we use scenarios from individual modeling groups (Figure 3.8), taken from the EMF-21 set (Weyant et al., 2006) (upper panel) and the two available studies that have estimated probability ranges (Webster et al., 2002; Richels et al., 2004) (lower panel). For the comparison with the EMF-21 set, again it should be noted that most of these scenarios represent trends considered to be medium trends by the individual modeling teams. Taken collectively, the set of SRES scenarios lies somewhat below the EMF-21 set – with the B1 scenario standing out as

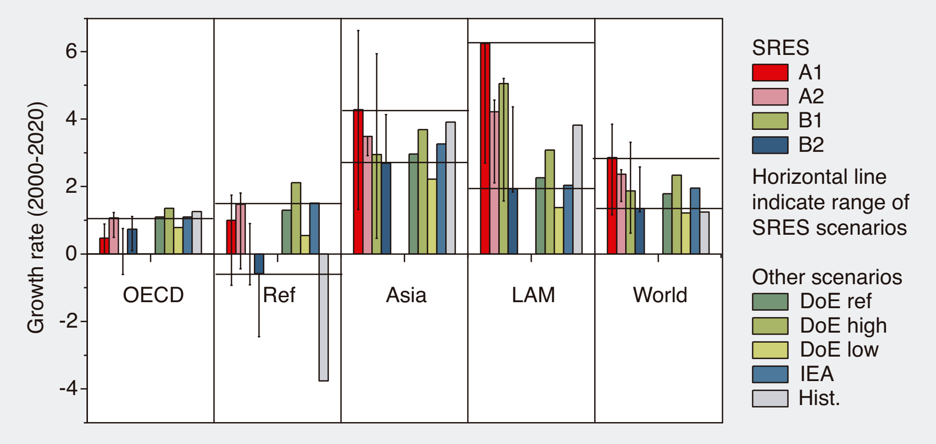

Figure 3.7 Comparison of trends in regional CO_2 emissions, SRES versus more recent projections (2000-2020 annual average growth rates). DoE = Projections from US. DoE (2004b). IEA = Projection from the International Energy Agency (IEA, 2004b). Hist = Historic data from the IEA energy database. The horizontal lines in the figure indicate the range of growth rates set out by the SRES marker scenarios. The vertical lines showing uncertainty bars for the SRES scenarios indicate the range of different outcomes of SRES scenarios within the same family (while the bars indicate the growth rates of the Marker scenarios). The historic rate represents the 1990-2000 period.

being much lower than the EMF-21 range. The B1 scenario is based on the intention to explore the consequences of sharp increases in efficiency and environmental technology (driven by environmental policies other than those for climate). The comparison with the set of probabilistic projections shows a similar result: the SRES scenarios cover a similar range, with the mean and range of the SRES set somewhat below the range of other two other studies.

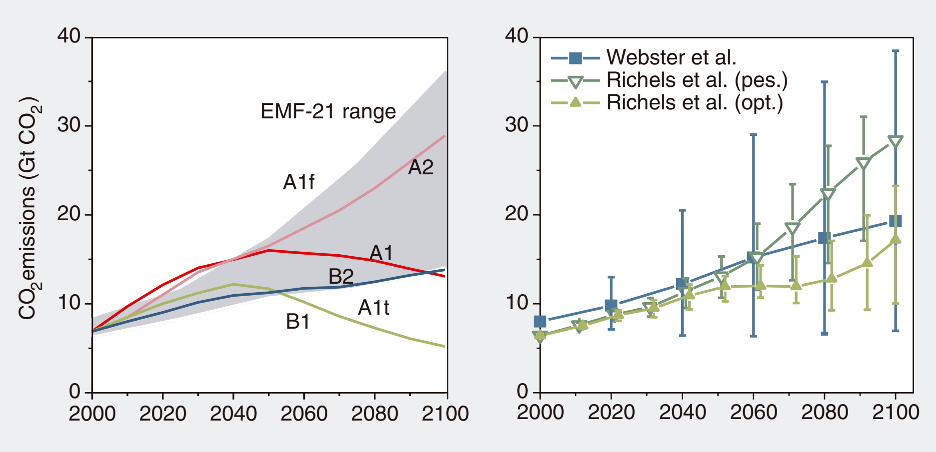

Figure 3.8 Comparison of the SRES scenarios to recent long-term scenarios for CO_2 emissions. EMF-21 indicates the range of the lowest and highest reported values in the EMF-21 study (Weyant et al., 2006). Webster et al. (2002) and Richels et al. (2004) indicate the mean and reported ranges of these studies.

3.4.1.4. Credibility of SRES Assumptions

For CO_2, the comparison of the SRES scenarios with more recent information shows that the SRES scenarios are generally consistent with historic data on the magnitude of current emissions, and with the range of recent projections. There are a few noteworthy exceptions. First, in the 2000–2025 period, the global results for the A1 scenario are significantly higher than current projections. Second, the complete set of SRES scenarios shows an upward bias for the ALM region compared to recent projections. However, these two exceptions do not seem to lead to an upward bias in the long term. In fact, the SRES scenarios cover a range that is even somewhat below the range of recent long-term studies.

3.4.2 Non-CO_2 greenhouse gases

3.4.2.1. Historic Trends

Uncertainties in current inventories are larger for non-CO_2 gases than for CO_2, since non-CO_2 gas emissions are driven to a much greater extent by diffuse agricultural sources (with high uncertainty). The EDGAR historic database (Olivier and Berdowski, 2001) is one of the most reliable sources of historic data.

Worldwide, methane emissions were virtually stable in the 1990–2000 period (1% increase). This global trend is, in fact, a net result of increasing emissions in developing countries and decreasing emissions in the Former Soviet Union. The SRES scenarios actually assumed a small increase in the 1990–2000 period (+7%). In EDGAR, the total uncertainty for annual methane emissions was estimated at plus and minus 23% of the mean value, coming, in particular, from uncertainty in emissions from animals and rice cultivation (Olivier and Peters, 2002). Given the uncertainty in methane emissions, the difference between SRES and the historic estimate cannot be taken as statistically significant,. For N_2O, SRES and EDGAR indicate nearly the same rate of increase (6% and 7%, respectively). The comparison is complicated by different definitions on anthropogenic versus natural emissions.[xi] The uncertainty in N2O emission inventories is considered to be substantially larger than for CH4, i.e. about 50–100 % (Olivier, 2004).

There is a substantial difference between the SRES data and current 1990–2000 emission estimates for emissions of the halocarbons (HFCs, PFCs and SF6). In fact, at the time SRES was developed, relatively little was known about emissions of these gases. Since then, considerable attention has been paid to updating the emission inventories for these gases. However, uncertainty levels in the EDGAR database (Olivier, 2004) are still assessed to be about 50–100 %.

[xi] This involves, in particular, emissions from agricultural soils. Some studies include all emissions from such soils. Others only include emissions above the level that would have occurred on a natural soil. A further complication is formed by indirect emissions.

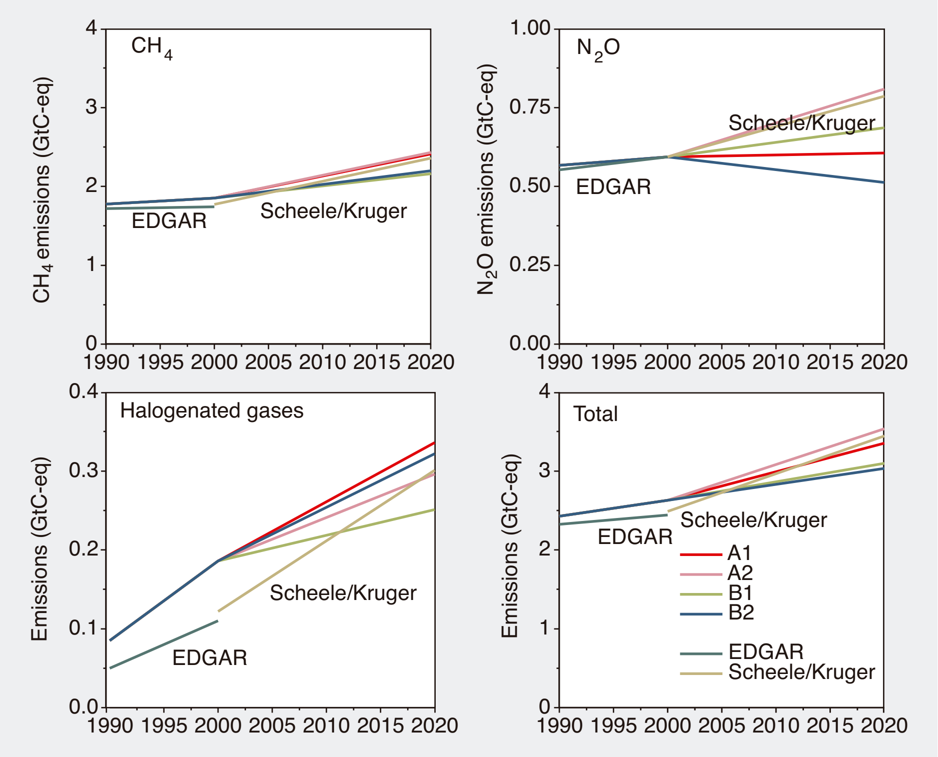

Figure 3.9 Comparison of trends in global non-CO$_2$ emissions, SRES, versus more recent projections. EDGAR indicates the historic data included in the EDGAR database (Olivier and Berdowski, 2001), Scheele/Kruger indicates the projections of Scheele and Kruger (2006).

3.4.2.2. Recent Projections for the Medium Term (up to 2050)

The most useful comparison for medium-term term projections of non-CO$_2$ emissions is found in the recent projection made by Scheele and Kruger (2006) on the basis of national communications to UNFCCC and expert judgement. Figure 3.9 shows that the SRES scenarios compare well to the current near-term projection. For most gases, particularly N2O, the SRES scenarios show slightly lower growth rates than the scenario of Scheele and Kruger (2006), which is consistent with the fact that the latter does not assume any technological progress in emission factors, while SRES scenarios do include some improvement. The same conclusion holds for the emissions of HFCs, SF6 and PFCs.

3.4.2.3. Long-Term Projections

In the context of EMF-21 a major modeling effort was made to update the capability of long-term integrated assessment models for modeling non-CO$_2$ gas emissions. It should be noted, however, that the majority of the models involved are energy– economy models – and therefore less well-equipped to model non-CO$_2$ emissions, which result mainly from agricultural activities. Some of the models involved in EMF-21 (in particular IMAGE, AIM, MiniCam and MIT) represent agricultural drivers in more detail. We have used all model outcomes of EMF21 as an indication of the range of model

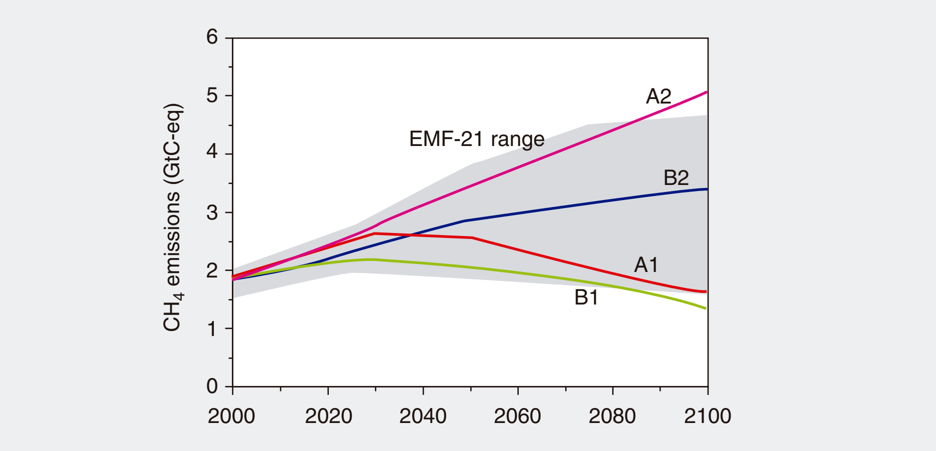

Figure 3.10 Long-term trends in methane emissions, SRES versus more recent projections (EMF-21). EMF-21 indicates the range of the lowest and highest reported values in the EMF-21 study (Weyant et al., 2006).

Note: The results of one model have not been used to indicate the EMF-21 range, as the emissions of this model clearly form an outlier within the total set (emissions increase to 11 GtC-eq).

outcomes to date, but note that the "more detailed" models mentioned above tend to cluster in the middle of this range. Nonetheless, results show that the trend and range of the SRES scenarios strongly coincides with the trends and ranges in the EMF-21 study (Figure 3.10). In general, methane and nitrous oxide in both SRES and EMF-21 display somewhat slower growth rates than CO_2 emissions as these emissions are coupled, in particular, with agricultural drivers – which show lower growth rates than energy drivers (important for CO_2).

3.4.2.4. Credibility of SRES Assumptions

The SRES scenarios seem to be fully in line with more recent projections for the non-CO_2 greenhouse gases.

3.4.3 Sulfur-oxide emissions (SO_2)

3.4.3.1. Historic Trends

Aerosols from SO_2 emissions can have a significant cooling effect and therefore form an important element of the SRES scenarios. Table 3.6 shows the 1990–2000 SO_2 data according to three different estimates (Amann, 2002; Stern, 2003; Smith et al., 2004) in comparison to the assumptions included in SRES. It should be noted that here again, there is considerable uncertainty involved in SO_2 emissions inventories, mainly with regard to the degree to which desulfurization technology is applied in different regions. Qualitative uncertainty estimates amount to 10–50% (Olivier, 2004). As for CO_2, a major cause of uncertainty in the late 1990s is the uncertainty involved in the coal use trend in China. While some sources assume a decline in coal use in the late 1990s, others only indicate a stabilization of coal use.

Table 3.6 Emission trends for sulfur emissions 1990-2000 (in Tg S)

		(Stern, 2003)	(Smith et al., 2004)	Amann, 2002	SRES
OECD	1990	22.4	22.6	33	22.7
	2000	16.5	14.5	19	17.0
	Ratio	0.74	0.64	0.60	*0.75*
Ref	1990	16.0	17.1	14	17.0
	2000	6.5	8.5	11	11.0
	Ratio	0.41	0.50	0.78	*0.65*
Asia	1990	16.2	17.8	16	17.7
	2000	18.8	23.9	16	25.3
	Ratio	1.16	1.34	1.00	*1.43*
ALM	1990	8.0	10.3	9	10.5
	2000	10.1	10.6	10	12.8
	Ratio	1.26	1.03	1.13	*1.22*
World	1990	62.6	70.8	72	67.9
	2000	51.9	57.5	57	66.1
	Ratio	0.83	0.81	0.79	*0.97*

In SRES, worldwide SO_2 emissions were assumed to decline by 3% in the 1990–2000 period: the net result of a clear decrease in the OECD and REF regions, and a considerable increase in Asia and the ALM region. Studies that estimate actual trends in that period now find that worldwide emissions actually decreased by a much larger amount (around 20%). The main reasons for this difference are a faster decline in the REF region (than assumed in SRES) and a slower increase in Asia. Again, a considerable portion of the differences can be attributed to assumed lower coal use in China between 1998 and 2000, but actual trends are highly uncertain. In the ALM region, the projected SRES emission increase lies between that of Smith et al. (2004) and Stern (2003).

3.4.3.2. Recent Projections for the Medium Term

The SRES scenarios can be compared to more recent near-term projections of Amann (2002) and Smith (2005). The projections of Amann (up to 2020) were made on the basis of existing country-level projections and reduction plans,[xii] but did not include all countries. Therefore, the data set was extended to the global level using 2000 emission levels from Stern (2003), assuming similar growth rates as for the regions for which data was directly available. The work of Smith (2005) is based on the MiniCam model (one of the SRES models) and uses the SRES storylines. However, as the model has been fully recalibrated on the basis of new historic emissions data and since the modelers have paid much more attention to the trends in SO_2 emissions, the study can be regarded as an independent source.

[xii] Amann's inventory included the OECD, REF and the Asia regions. It did not fully include the ALM region. This region has been added here by using 1990 and 2000 figures from Smith et al. and assuming a trend in this region similar to the Asia region.

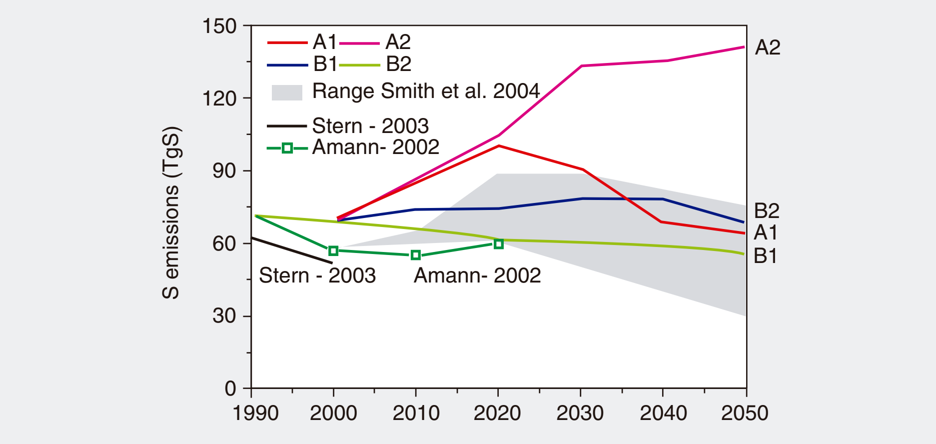

Figure 3.11 Comparison of SRES sulfur emissions and more recent projections. Data based on (Amann, 2002; Stern, 2003; Smith et al., 2004).

The comparison (Figure 3.11) shows the highest of the SRES projections te be apparently very high (this certainly holds for A2 and for the first 20 years of A1) and as a consequence rather unlikely. Furthermore, the lower range of the scenarios has shifted downwards by about 10–20% or so. At the same time, however, the trends in the Amann study are consistent with the lower SRES scenarios (those assuming more pro-active environmental policies). The insight that worldwide SO_2 emissions might not increase as rapidly as a result of desulfurization policies in low-income countries is in fact relatively recent. It is interesting to note that during the review procedure, the SRES scenarios were actually criticized for including too low SO_2 emission scenarios. Compared to all other variables then, the degree of inconsistency of SRES with both historic emission trends and near-term expectations is highest for SO_2 emissions. Correction of the SRES emission projections downwards (for A2 and A1) would have an upward effect on the near-term temperature ranges associated with the SRES scenarios.

3.5 Discussion and Conclusions

We have investigated the consistency of the IPCC SRES scenarios with available 1990–2000 data and recent projections, primarily short-term outlooks. The most important inconsistencies are summarized in Table 3.7.

- **In almost all the cases of (now) historic development, the SRES assumptions for 1990 and 2000 are reasonably consistent with available data, but there are some exceptions.** For the global projections for income, population, energy and non-CO_2 gases only small differences were found for these variables on the regional scale, in particular, for income trends and energy trends in Asia and REF. For CO_2 emissions, the SRES scenarios indicate a slightly more rapid global increase between 1990 and 2000 than is now apparent from emission inventories (15% versus an average of 11%), but the difference in terms of absolute emissions in 2000 is

Table 3.7 Main inconsistencies found between the SRES scenarios and more recent scenarios and data

Parameter	*Inconsistencies noted in comparison*
Population	• SRES does not include a representation of the current low-end population scenarios • The A2 scenarios outside the current 95% probability estimate • For specific regions (in particular sub-Sahara Africa and China), differences between SRES and current projections larger
GDP	• Global economic projection for A1 outside range of current projections in the first two decades • The set of SRES scenarios for the ALM region seemingly representative of the upper end scenarios only
Energy	• See GDP
CO2	• See GDP for short-term projections • Slightly too high for 2000 emissions
Non-CO2 gases	• Historically seen, somewhat too high for the F gases • Several forcing agents (black carbon) not yet included
Sulfur	• 2000 sulfur emissions too high. • Emissions in the first decades of the high emission scenarios unlikely

small (mostly caused by the decline in coal use in the late 1990s in China). Finally, for SO_2 emissions, there seems to be a clear difference between the assumed change in SRES in the 1990–2000 period and the trend in current inventories (a global 3% versus 20% decline, respectively), mostly resulting from diverging trends in the Asia and REF regions. In both the case of CO_2 and SO_2 it should be noted that trends in China in the late 1990s are still uncertain.

- **Comparing the SRES scenarios to current near-term projections shows the SRES scenarios in most cases to be within the range of these projections, both globally and for individual regions. It should also be noted, however, that the range of population and economic projections has shifted downward since SRES publication.** While SRES assumptions regarding these drivers still fall in most cases within the range of new literature, in a few they go beyond the literature. In addition, the low end of the current range is under-represented in the SRES scenarios for both population and economic growth. Revisions of the SRES scenarios based on the same storylines could therefore be based on somewhat lower population projections and near-term economic projections. This is more important in particular regions and scenarios.

- **In the case of economic growth, assumptions for the ALM region (the A1 scenario, in particular) deserve the most attention. In the case of population, the assumptions for the Asia and ALM regions in the A2 scenario would be the most important to consider for revision since they differ the most from the updated range of projections.** In addition, our results show the differences between SRES and more recent population projections for the medium term (2050) to be magnified in the long term (2100) due to the path dependency of population growth. Lower population pathways, all else being equal, are likely to lead to lower greenhouse gas emissions, and the associated increases in aging may exacerbate this effect (Dalton et al., 2005). For economic growth, the potential impact of lower economic growth scenarios (for the ALM region) is less obvious, as downward revisions of economic growth will also have consequences for technology development and fuel trade. At the same time, it should be noted that except for the first two decades for A1, in terms of emissions the SRES scenarios still seem to be fully consistent with the current range of more recent outlooks.

- **Comparison on the regional scale shows that the most important differences between SRES and the current near-term projections occur for the ALM region (income, energy use and CO_2 emissions).** Here, the range of SRES economic growth assumptions and resulting growth rates for energy use and CO_2 emissions are near or beyond the upper end of current projections. By now, the assumed rapid change in conditions for economic growth in this region seem to have become (even more) questionable. The impact of this region on the global emissions projections is limited. The GDP and emission growth rates of the Asia region in the A1 scenario are also high compared to the recent projections, although to a much smaller degree.

- **Another important difference between the SRES scenarios and more recent insights is seen for SO_2.** As a result of the rapid decline in global emissions in the 1990–2000 period and expectations about desulfurization policies in low-income countries, a rapid increase in SO_2 emissions, as in some of the SRES scenarios for SO_2 between 2000 and 2030, has become very unlikely. Despite the fact that the exact trend in Chinese emissions during the 1990s remains an important uncertainty, a revision of scenarios is likely to result in lower SO_2 emissions. Other factors being equal, such a revision would imply an increase in the expected short-term temperature change associated with the SRES scenarios.

- **There are a few elements such as black and organic carbon and grid-based land-use projections that have not been included in the SRES scenarios in much detail and which recently have become much more important for climate change projections.** Non-official projections consistent with SRES assumptions have now become available from individual modeling teams.

- **At this point in time there seems to be no need for a large-scale IPCC-led update of the SRES scenarios on the sole basis of their performance in the 1990–2000 period, or of a comparison with more recent projections. At the same time, however, individual modeling groups could decide to update their scenarios.** Regarding the question of whether the SRES scenarios have become outdated or not, there are obviously no hard criteria. With a few exceptions, the study reported here has shown the SRES trends to still be plausible. In addition, there is no evidence that the underlying axioms of the storylines have been falsified. Individual modeling groups could nevertheless decide to update their scenarios, making them fully consistent with current trends, while still preserving the connection with the

SRES storylines and harmonization criteria. Such an approach has been taken, for instance, by the IMAGE group when it published its detailed elaboration of the SRES scenarios in 2001 (IMAGE-team, 2001). Variants of SRES scenarios could also be developed by independent research teams to cover parts of the range of drivers or outcomes that are less well represented in SRES; the low end of the range of future population size is one example. In fact, the SRES report itself allowed for a great diversity of elaboration of the same scenarios – indicating particular criteria that scenarios would have to meet in order to maintain consistency. Most of these criteria are formulated for the longer term (first criteria to be applied in 2025). The option of updating SRES scenarios (by individual modeling groups), while upholding the connection with the SRES storylines and criteria, will, in general, keep results compatible with earlier work and allow for more comparability (and easier communication) in assessment (as in IPCC's Fourth Assessment Report, for instance). At the same time, the SRES updating option will allow research groups to produce long-term scenarios that are also well suited to shorter term applications.

Acknowledgements

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4. IPCC SRES-BASED ENERGY AND EMISSION SCENARIOS FOR CHINA IN THE 21ST CENTURY

Abstract Using the global energy simulation model, TIMER, a set of energy and emission scenarios for China between 1995 and 2100 were developed based on the global baseline scenarios published by IPCC. The purpose of the study was to explore possible baseline developments and available options to mitigate emissions. The two main baseline scenarios differ in particular in the openness of the Chinese economy. Both scenarios indicate a rapid growth in carbon emissions (2.0% and 2.6% per year in the 2000–2050 period). In the mitigation analysis, a large number of options were evaluated in terms of impacts on investments, user costs, fuel imports costs and emissions. It is found that a large potential to mitigate carbon emissions in China was found, for example, in the form of energy efficiency improvement (with large co-benefits) and measures in the electricity sector. By combining all options considered, it appears to be possible to reduce 2050 emissions compared to the baseline scenarios by 50%.

This chapter was published earlier as D.P van Vuuren, Zhou Fengqi, B. de Vries, Jiang Kejun, C. Graveland and Li Yun (2003). Energy and emission scenarios for China in the 21st century. Energy Policy 31. Pages 369-387.

4.1 Introduction

As China is the world”s most populous country with a rapidly growing economy, trends in China”s energy future will have considerable consequences for both China and the global environment. Two important trends characterise China’s energy use over the last two decades: on the one hand, energy intensity has fallen dramatically (by around 4% per year), and, on the other, China”s primary energy consumption has more than doubled (Zhang, 2001). Greenhouse gas (GHG) emissions have increased at a similar rate. While per capita emissions are still very low, China is likely to become the world’s largest carbon dioxide-emitting country in the next ten years. In view of this, there has been considerable attention paid to potential development of Chinese emissions from both scientists and policy makers (see e.g. Müller, 2001). Despite the fact that China currently still has no obligations to limit its emissions, it does seem necessary to explore the policy options for reducing GHG emissions in China. Crucial questions are, for instance, what could be the trends in China without explicit climate policies? Is it possible to significantly reduce China”s emissions during the first half of this century and how? What are the costs of such policies, what could be the co-benefits? In this chapter, we explore these questions using the IMAGE/TIMER integrated assessment model and a set of newly developed storyline-based scenarios.

Future GHG emissions are the product of complex dynamic processes determined by driving forces such as demographic development, socio-economic development, and technological and institutional change. The future of these factors is highly uncertain. Various development patterns could introduce very different futures. New scenario approaches using storyline-based and multiple scenarios intend to identify some of these possible futures, by developing alternative images of how the future might unfold. These images (scenarios) can function as appropriate tools for analysing how driving forces may influence future emissions and for assessing the associated uncertainties. Such an approach has been used in IPCC"s recently published Special Report on Emission Scenarios (SRES) (Nakicenovic and Swart, 2000) (see also Section 1.3.2). Using the SRES approach, we have developed several baseline and policy scenarios in this study to explore the possible development in the energy system in China and related environmental pressure. The scenarios enable us to analyse the strategic decisions involved in the different types of development, the possible impacts of climate change and possibilities for mitigation and adaptation.

In this chapter, we will first briefly discuss the process and the methodology of the research, followed by a presentation of the key aspects of baseline scenarios for China, both in terms of storyline and quantitative simulation results from the energy model. The next section will discuss several options and scenarios aimed at mitigating the Chinese GHG emissions between 2000 and 2050. Finally, the chapter will be rounded off with conclusions.

4.2 Process and methodology

In this analysis, we used the TIMER model, which provides a good description of changes within the energy system, including some of the relevant dynamics such as fuel substitution and technology development. Moreover, the energy model TIMER is directly linked with the larger framework of the integrated assessment framework IMAGE, which enables us to analyse the chain of relevant changes from driving forces to impacts of climate change (see Chapter 2).

The Integrated Model to Assess the Global Environment (IMAGE) was developed to study the long-term dynamics of global environmental change, in particular, changes related to climate change. The version used in this chapter (IMAGE 2.2) consists of a set of coupled submodels (IMAGE-team, 2001). It includes submodels related to food demand and land-use changes (Terrestrial Environment System, TES), energy demand and supply, and energy and industrial GHG emissions (Energy-Industry System, EIS), and, finally, to the role of various GHGs in the ocean and atmosphere (Atmosphere–Ocean System, AOS).

The version of TIMER applied here is TIMER 1.0. An extensive description of the model can be found in Chapter 2 of this thesis and in the TIMER 1.0 model documentation (de Vries et al., 2001). The TIMER 1.0 model is a system-dynamics simulation model at an intermediate level of aggregation: 17 world regions, 5 energy-demand sectors (Industry, Transport, Residential, Commercial and Other) and 6–8 energy carriers (Figure 4.1). The model is a simulation model: it does not optimise scenario results on the basis of perfect foresight, but instead, simulates year-to-year investments decisions based on a combination of bottom-up engineering information and specific rules about investment behavior, fuel substitution and technology.

The time horizon in the present analysis covers the period from 1995 to 2100—although for the policy options we will focus mainly on the 1995–2050 period. The model calibration is based on historical data for the 1971–1995 period. This time horizon is in accordance with many other scenario studies, notably the SRES report (Nakicenovic and Swart, 2000). It puts short-term decisions in a long-term perspective. It should, however, be noted that in time the future becomes inherently more uncertain, and beyond the scope of current policy makers. In this study, only GHG emissions from energy use have been considered, which means that emissions and uptake from forestry and land use are not included. We will describe our scenarios mostly in terms of their carbon dioxide emissions. However, in the IMAGE model emissions of other (greenhouse) gases such as methane, nitrous oxide and sulphur dioxide are also calculated (Figure. 4.1).

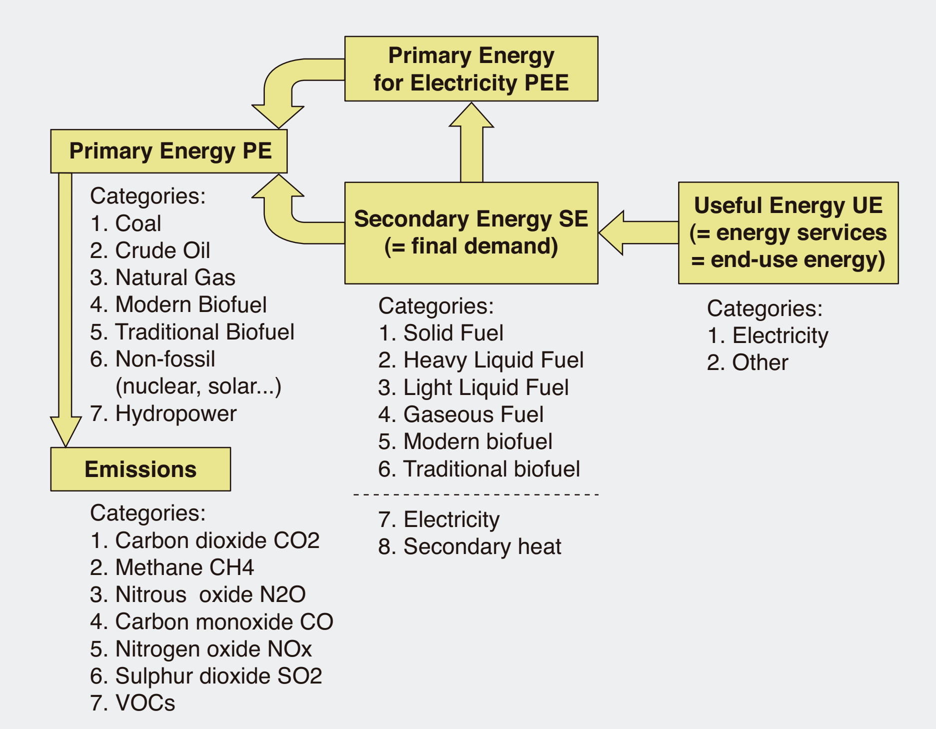

Figure 4.1 Overview of categories and calculation flows in the TIMER model.

We have gone through various steps in the process to develop our emission scenarios:

1. First, the development of storylines for China on the basis of existing global storylines from other IMAGE/TIMER projects (IMAGE-team, 2001): the storylines, reviewed by various Chinese experts, have been adjusted to achieve a degree of consensus.
2. Second, the development of a set of quantified scenarios using the IMAGE/TIMER energy model: the model serves as a means to translate qualitative storylines into consistent scenarios of quantified system variables.[i]
3. Third,the development of several mitigation scenarios. These scenarios aim to identify the potential of different policy options to abate GHG emission in China.

More information on the scenarios and the assumptions made can be found in a separately published background report (van Vuuren et al., 2001).

4.3 Baseline scenarios for China

The global IPCC SRES scenarios are based on the development of narrative "storylines" and the quantification of these storylines using six different integrated models from different countries. The storylines describe many different developments in social, economic, technological, environmental and policy dimensions, but not all possible developments. They do, for instance, not include "disaster" scenarios. Moreover, none of the scenarios include new explicit climate policies. The names of the IPCC scenarios are A1, B1, A2 and B2 (see Chapter 1 and 5 of this thesis.for more details of these global scenarios).

On the basis of the existing global SRES scenarios, we developed four new scenarios specifically oriented to China. Two of the scenarios are described here in detail, while the other two are essentially used to indicate the larger range of uncertainties related to baseline development. The new scenarios represent some mainstream views in China and provide sufficient contrast for policy evaluation. None of the scenarios includes explicit climate policies.

In the next section we will discuss the scenario assumptions and results. Appendix 4.1 gives an overview of the major assumptions made within the TIMER model for the Chinese baseline scenarios. The assumptions made for the other global regions have been maintained as given in the SRES scenarios (IMAGE-team, 2001). Table 4.1 summarises some of the results, comparing China with Western Europe and USA.

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[i] For this purpose, we have adjusted the existing TIMER 1.0 model to describe mainland China, instead of the East Asia region included in the normal TIMER model used at RIVM. The East Asia region of IMAGE 2.2 includes China, North and South Korea, Taiwan, Mongolia, Hong-Kong and Macau.

*Table 4.1 Kaya indicators for China and selected regions under scenario A1b-C and B2-C**

		Historic		A1b-C			B2-C		
		1990	1995	2010	2030	2050	2010	2030	2050
Population (million)	China	1,158	1,211	1,389	1,525	1,598	1,389	1,525	1,598
	(growth rate)		0.9%	0.9%	0.5%	0.2%	0.9%	0.5%	0.2%
	USA	257	267	305	352	386	305	352	386
	Western Europe	379	384	407	425	426	407	425	426
	World	5,281	5,601	6,897	8,235	8,905	6,897	8,235	8,905
GDP per capita (US$1995)	China	357	578	1611	4461	10228	1495	3594	7486
	(growth rate)		10.1%	7.1%	5.2%	4.2%	6.5%	4.5%	3.7%
	USA	24,727	26,316	38812	52704	72531	37613	46977	58274
	Western Europe	20,122	21,636	29563	44332	62065	28308	37547	46126
	World	4,705	4,830	6388	10866	20789	6084	8681	12945
Energy intensity (MJ/ppp$)[ii]	China	34.4	27.8	18	13.4	10.7	17.2	12.1	9.8
	(growth rate)		-4.2%	-2.9%	-1.5%	-1.1%	-3.2%	-1.7%	-1.0%
	USA	11.9	11.4	9.2	7.5	5.6	9.1	6.8	4.8
	Western Europe	7.7	7.4	6.9	6	4.9	6.6	5.2	3.9
	World	12.2	11.6	10.1	8.4	6.3	9.8	7.7	5.8
Carbon intensity (kg-C/GJ)	China	18.8	19.1	19.8	18.9	17.6	19.8	19.2	18.6
	(growth rate)		0.3%	0.2%	-0.2%	-0.4%	0.2%	-0.2%	-0.2%
	USA	18.4	18.3	17.9	16.9	15	17.7	15.3	12.5
	Western Europe	17.4	17	16.6	15.6	13.9	16.4	14.6	11.2
	World	16.4	16.2	16.8	16.8	14.9	16.6	16	14.1
CO_2 (billion tonnes)	China	0.7	0.9	1.6	2.6	3.8	1.4	2	2.7
	(growth rate)		5.2%	3.9%	2.5%	1.9%	3.0%	1.8%	1.5%
	USA	1.4	1.5	2.1	2.5	2.5	1.9	1.8	1.4
	Western Europe	1	0.9	1.3	1.6	1.6	1.2	1.1	0.8
	World	5.7	5.9	9.6	16.4	20.9	8.8	11.6	11.9
CO_2 per capita (tonne)	China	0.6	0.7	1.1	1.7	2.4	1	1.3	1.7
	(growth rate)		3.1%	3.1%	2.2%	1.7%	2.4%	1.3%	1.4%
	USA	5.6	5.7	6.8	7.1	6.4	6.3	5.1	3.6
	Western Europe	2.5	2.5	3.2	3.8	3.8	2.9	2.6	1.9
	World	1.1	1.1	1.4	2	2.4	1.3	1.4	1.3

Source: TIMER model results, based on underlying data from ERI (China) and RIVM"s international database (other countries).

* Since the time period in which this research was performed (2001), the Chinese emissions have been revised upward. As a result they are already near the USA emissions levels in 2010. While this fact influences some of the absolute numbers in this chapter, it has no real influence on the major trends.

[ii] Energy intensity has been expressed in terms of purchasing power parity dollars. By correcting for differences in purchasing power, energy intensity better reflects real differences in energy efficiency – although energy intensity is still also influenced by other factors such as the structure of the economy.

4.3.1. A1b-C Scenario: an "open" China in a globalised world

The first scenario follows the storyline for the SRES A1b scenario[iii], describing a case of rapid and successful economic development both in China and the rest of the world. Globally, the fast economic development is driven by such factors as human capital (education), innovation and free trade. We assume that China will continue to pursue its open-door policies, thus enabling strong technology development. By the end of the 21st century, China will almost have caught up in income with the OECD countries, the service sector (tertiary sector) showing the largest growth, with the size in the total economy increasing from about 34% in 2000 to about 60% in 2050 (see also Table 4.1). The population growth path in China follows the current expectations of the planning commission—in which population reaches a level of around 1.6 billion by 2050 and then decreases to around 1.5 billion in 2100. The economic development in the A1b-C scenario provides support for technology R&D and innovation. As globalization allows for rapid spread of technologies, renewable energy and other clean energy technologies will become available on a large scale.

As a result of economic growth and the orientation to material-intensive lifestyles, the demand for energy increases rapidly. Per capita consumption of primary energy increases from 37 GJ per capita in 1995 to more than 150 GJ per capita in 2050. The latter is equal to the current energy consumption of many OECD countries. Energy demand grows fastest in transport, still a small sector in 1995 but representing 25% of total energy use in 2050. In terms of end-use, traditional biofuels and coal rapidly lose market shares. Traditional biofuels are replaced as a consequence of the "modernization" process. Coal is under pressure in the residential and service sectors due to its inherent environmental and comfort inconveniences. Electricity and natural gas, with their grid character, wide applicability and local cleanliness, rapidly gain market shares. Oil also gains market shares, along with the growing transport sector, but starts to feel competition from both natural gas (LNG) and biofuels from 2020 onwards (Figure. 4.2). At the moment, electricity generation in China is dominated by coal-fired power plants. In the A1b-C scenario, this situation changes only slowly, with natural gas and later zero-carbon options making inroads. The reason for this is the strong competitive position of coal in China. Increases in the use of nuclear power and hydropower are substantial—but both energy sources still cover only 5–10% of total primary inputs in 2050.

The current energy intensity (GJ/ppp$) in China is considerably higher than the other regions caused by such factors as China"s reliance on heavy industry and energy inefficiency in industry and electric power generation (see Table 4.1; 27.8 in China versus 7.4 GJ/ppp$ in Western Europe). In the A1b-C scenario, rapid technology transfer spurred on by free trade allows China to close the gap in energy intensity compared to OECD

[iii] There are three subfamilies in the A1 group; these are based on assumptions regarding the energy system. The A1b-C scenario describes a world with balanced energy technology, developed in terms of supply options; while, the other two sub-families describe a technology development that is either geared towards fossil fuels (A1f) or new technologies (A1t).

countries by about a factor of 2. As a result, primary energy use per year grows at rates slightly lower than those in the past (2.8% in the 2000–2050 period versus 4.0% over the last 10 years) (Figures 4.2–4.5). Gradually, energy use will become less dominated by coal. In this scenario, the huge demand for energy, the relative shortage of energy resources and the open markets imply that China will depend more and more on international energy resources. More than 20% of the domestic demand will have to be met by the imported energy by the middle of this century. For oil and natural gas, these percentages are far higher: 80% and 50%, respectively, in 2050.

Investments in energy will increase gradually, reaching about US$ 200 billion in 2020, 520 billion in 2050 and 1660 billion in 2100. It will clearly be a challenge for China to be able to realise these investment rates—certainly in the first part of the century. The ratio of investment in energy to GDP is about 4.5% in 2000, slightly increasing to 4.7%

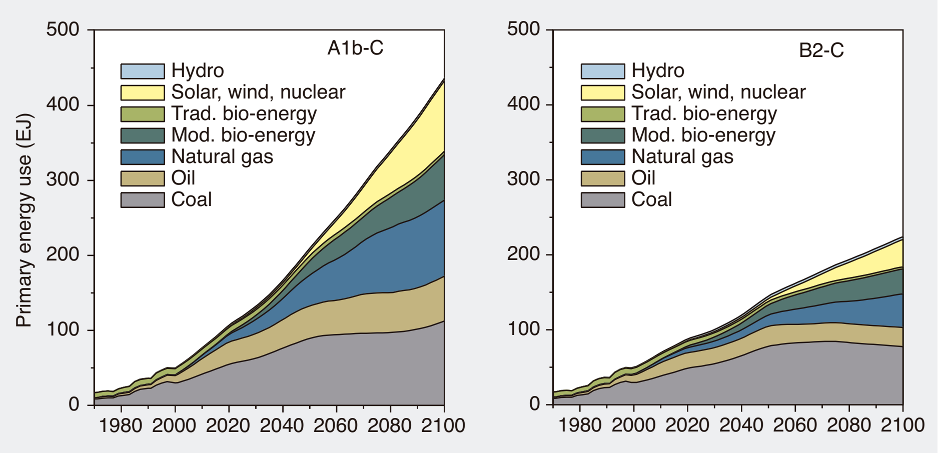

Figure 4.2 Primary energy use according to the A1B-C (left) and B2-C (right) scenarios. (NTE : Non-thermal electricity, such as nuclear, solar and wind)

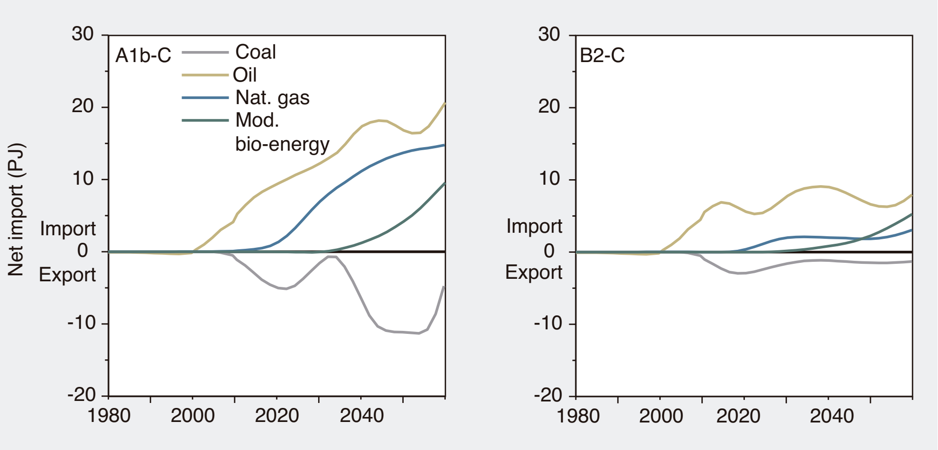

Figure 4.3 Net trade in energy carriers according to the A1B-C (left) and B2-C (right) scenario.

in 2020, decreasing to 3.1% in 2050 and further decreasing to 1.8% in 2100. This trend reflects the decreasing relative role of energy in the economic development.

Several factors will have an impact on fuel prices. On the one hand, energy resources will become less abundant and more difficult to develop, which raises the price, while on the other, people have more experience and more advanced technologies, which reduces the price. In the case of A1b-C, the prices of oil and natural gas are relatively stable at US$4 per GJ up to 2015; due to slow depletion of cheap Middle East oil and gas prices, these increase slowly afterwards to US$7 per GJ in 2050. The price of coal will continue to increase in the whole simulation period; however, its costs are much lower than those of oil and gas.

4.3.2. B2-C Scenario: China geared to solving regional environmental problems

This scenario follows the SRES B2 storyline. It assumes a slightly lower economic growth (see Table 4.1) with limited trade and technology transfer among world regions. The basic consideration in this scenario for China is that economic development will utilize domestic resources so as to maintain equity for the future, while maintaining balance among regions as well as between urban and rural areas. Environmental issues—food and water, air pollution and the like— are recognized as serious problems and make environmental sustainability an important priority. This scenario can be described as regional stewardship. The growth of the population is assumed to be the same as in the A1b-C scenario. The energy system will to a larger extent rely on domestic resources, while technological progress is lower for both energy production and end use because of limited trade and transfer. Coal use in this scenario will be based on clean coal technology.

The assumption of the B2-C scenario is that development in China will be oriented to solving regional problems using predominantly domestic resources. As the main energy resource of China is coal, the strong focus to preserve local environmental resources requires the development in this scenario of clean coal technologies. In addition, energy efficiency will be important to prevent demand for oil and natural gas growing too fast. Thus, an important difference between the B2-C and A1b-C scenarios is the energy demand, which, by the end of the century, is only about half of that in the A1bC scenario. The structure of energy use per sector follows a similar path to that in the A1b-C scenario: the share of industry decreases while the share of transport increases. However, the changes are slower than in the A1b-C scenario. Although the share of industry will slowly decrease to 38% by the end of the century, industry will still be the largest energy consumer.

With respect to the structure of primary energy demand by energy carrier, the share of natural gas, modern biomass, solar and wind energy will increase. However, in comparison to the A1b-C scenario, China will depend on domestic energy resources, which means that coal will continue to be the most important energy source in China even

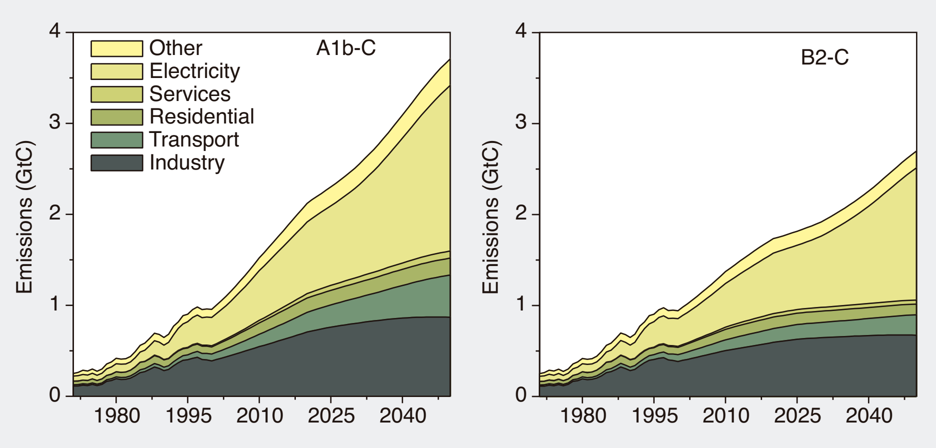

Figure 4.4 Carbon dioxide emissions following the A1B-C (left) and B2-C (right) scenarios.

though its share will gradually decrease to 53% in 2050 and 34% in 2100. Fuel trade is lower in terms of both the absolute value and the ratio to total primary energy use compared to that in the A1b-C scenario, although some imports of oil and natural gas seem to be inevitable.

In this scenario, investment in energy are smaller than in the A1b-C scenario but the ratio of energy investment to GDP will follow the same trend as in the A1b-C scenario. The structure of energy investment will also be similar to that in the A1b-C scenario; fossil fuel will lose its share while non-thermal electricity (nuclear and/or renewables) will gradually gain a larger share. Fuel price development shows one remarkable difference. In the B2-C scenario, China depends more on domestic energy resources. Due to depletion of domestic oil and natural gas resources in the late 2010s, the price of these products , especially the price of natural gas, will therefore rise sharply. As a result, the difference between the coal price, and the oil and natural gas prices, are larger than in the A1b-C scenario in the first half of the 21st century.

4.3.3. Energy-related carbon dioxide emissions

In 1990, carbon dioxide emissions of China were 0.68 GtC, which rapidly increased to 0.90 GtC in 1995. In contrast, between 1996 and 1999 China experienced a decrease in the emissions of carbon dioxide as a consequence of a set of short-term trends (reduction in economic growth and improvement in coal quality) and longer-term trends (e.g. efficiency improvement) (Sinton and Fridley, 2000). We have captured some of the relevant factors in our model simulations, for example, as strong improvements in autonomous energy efficiency. In both scenarios, however, the decline in emissions has only a temporary effect. Emissions increase up to 2050 by a factor of 2.7 and 3.8, in B2-C and A1b-C, respectively. For the mitigation scenarios discussed further in this chapter, it is important to know where the emissions come from. In both scenarios, electricity generation—based on coal-fired power plants—will become the most important source of emissions (around 50% of all emissions in 2050). The second important source is represented by emissions from (coal use in) industry. Although transport is projected to become a much more important sector in total energy use in China, its share in carbon emissions still remains relatively low.

In both scenarios Chinese carbon dioxide emissions will have surpassed those of the USA in the near future and further increase to 2.7 billion tonne carbon under B2-C, and 3.8 billion tonne carbon under A1b-C in 2050 (Table 4.1). The differences reflect mainly the differences in assumed economic growth rate. It should be noted, however, that the carbon dioxide emissions per capita in China are still very low. Per capita emissions will be close to the world average around 2030 and 2050 under B2-C and A1b-C, respectively. Compared to GDP per capita, the relative convergence of China”s carbon dioxide emissions per capita to global averages is more rapid. This is because China relies more on carbon-intensive energy resources, especially under the B2-C scenario.

4.3.4. Alternative scenarios: B1-C and A1f-C

The two scenarios described above are only two of many possible developments in China. Two other scenarios in the SRES set, elaborated upon for China, might be of interest here. These are the B1-C scenario, a scenario based on globalization but time-oriented towards sustainable development, and the A1f-C scenario, which shares many of its assumptions with the A1b-C scenario but assumes stronger technology development for fossil fuels and less development for new technologies. As for the other two baseline scenarios, the B1-C and A1f-C scenarios assume no explicit climate policies.

The B1 scenario describes a world dominated by high levels of environmental and social consciousness and successful global cooperation. Compared to A1b-C, economic development is slightly slower and there will be a much stronger trend towards that of a service economy. In B1-C scenario, we assume China will not adopt the current energy- and material-intensive lifestyles of the Western world, but choose for a less material, more service-oriented lifestyle (the Western countries will also move in this direction in B1). In such a scenario we see a rapid improvement in efficiencies. The 2100 energy consumption of 70 GJ per capita is relatively low but comparable to the projected OECD average in that year and based on its efficiency, this energy consumed is able to facilitate a much higher level of welfare. The environmental consciousness assumed means that in the scenario, coal use declines and more environmentally friendly fuels such as natural gas and modern biofuels gain market shares. Technology development will also enable extensive use of solar and wind power.

The A1f-C scenario describes a world with strong economic growth and a supply orientation in the energy system. This implies a strongly growing energy demand and large investments in energy supply. Penetration of alternative fuels to fossil fuels is slowed down significantly as we assume more rapid technological development for the latter and slower development for the former. As a result, the energy system remains dominated by coal over the whole century, and later on, also by oil and natural gas, which will take over the use of coal in the transport and building sectors.

Figure 4.6 summarises the four scenarios under three main characteristics: energy use per capita, carbon emissions per unit of energy use (carbon factor) and carbon dioxide emissions. In the A1f-C scenario Chinese carbon dioxide emissions are shown to increase to 8 GtC, a level about 30% higher than the current global emissions, caused by high energy use and a very high carbon factor. In the A1b-C scenario emissions reach a level of 30% below those in the A1f-C scenario, the difference mainly being caused by differences in the energy mix (the carbon factor)—with non-fossil-based fuels gaining a significant market share in the second part of the century. The B2-C scenario results in carbon dioxide emissions that are about a factor 2 lower than in A1b-C, pushed by its lower energy use. In fact, the relative share of coal in B2-C is higher than in

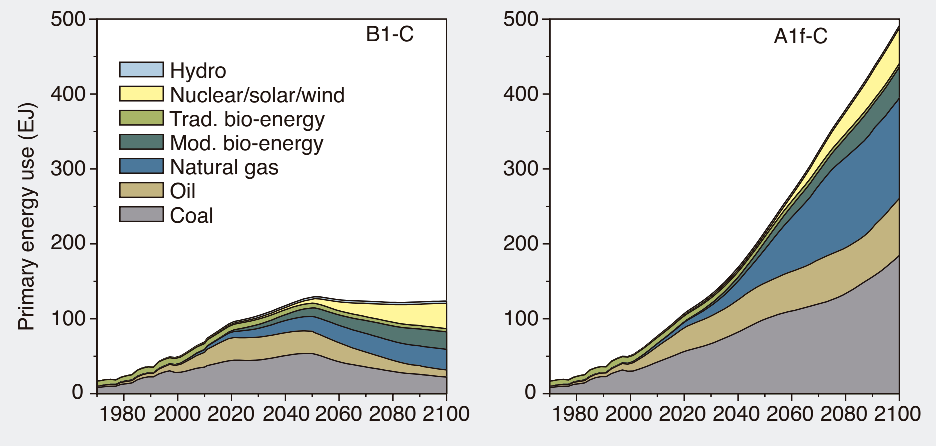

Figure 4.5 Primary energy use in the alternative B1-C (left) and A1F-C (right) scenarios (NTE : Non-thermal electricity, such as nuclear, solar and wind)

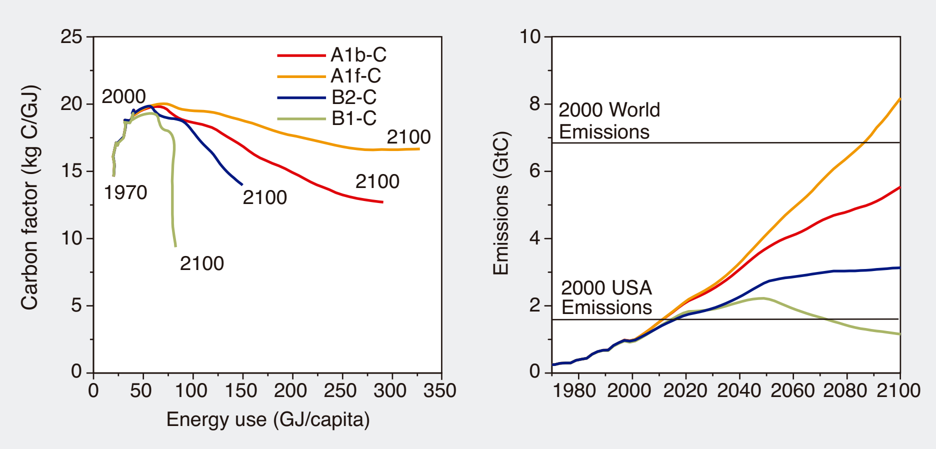

Figure 4.6 Trajectory of energy use (GJ per capita) and carbon factor (tC/GJ) (left), and CO2 emissions (right) in the four scenarios developed for China in this analysis.

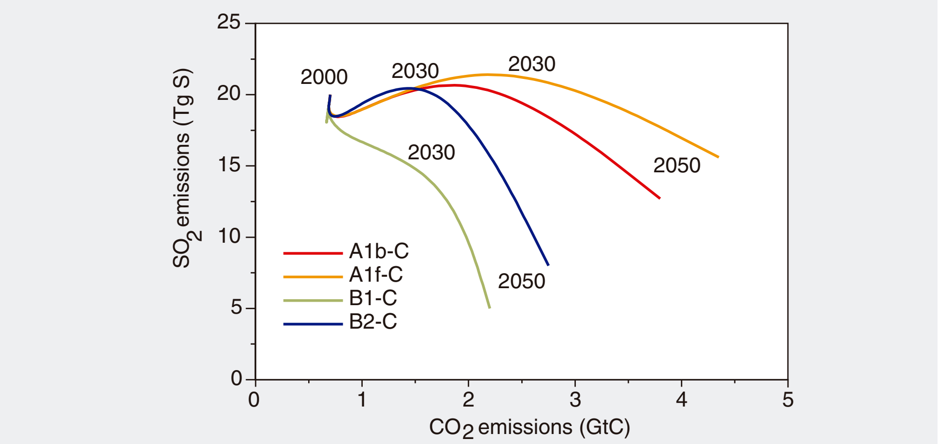

Figure 4.7 Carbon and sulfur emissions under four scenarios.

A1b-C (reflected in a higher carbon factor). Finally, the B1-C scenario sees emissions doubling in the first half of the century—but consequently declining to slightly above the present level in the second half. This decline compared to A1b-C is caused by both low energy use per capita (efficiency and structural change) and major changes in the energy supply.

The current level of sulfur emissions in China (around 18 Tg SO2) contributes to both regional air pollution (in particular, acidification) and urban air pollution. In addition, sulfur emissions can have an important impact on climate change. Therefore, it might be worthwhile to have a look at trends in these emissions. In all scenarios, we have assumed that the Chinese government will intensify its effort to reduce sulfur emissions. However, the level of effort employed here differs—and obviously so does the energy mix. In Figure 4.7, where the carbon emissions of the scenarios are plotted against the sulfur emissions,, the main differences between the scenarios are caused by the high level of environmental protection in B1-C and B2-C and the less strict protection levels in A1b-C and A1F. In addition, however, we can see that sulfur emissions are also a function of the changes in energy mix—B1-C has fewer sulfur emissions than B2-C; A1b-C has fewer emissions than A1F. In other words, lower carbon emissions coincide with lower sulfur emissions. The sustainability- oriented B1-C scenario benefits in particular from this.

4.3.5. Comparison with other scenario studies

The scenarios presented here can be compared to other baseline scenarios. Figure 4.8 shows a set of recent baseline scenarios taken from various studies, in addition to the historic trend between 1990–1999 (IEA, 2000; Sands and Kejun, 2001; US.DoE, 2001; Weyant, 2001). All scenarios shown expect emissions to increase—with growth rates ranging from 2.5% to 4.5% per year. Both the A1b-C and B2-C scenarios lie within the range drawn up by these baseline scenarios. Up to 2020, A1b-C follows the emission trend of the World Energy Outlook (IEA, 2000) while B2-C ends up very near to the pro-

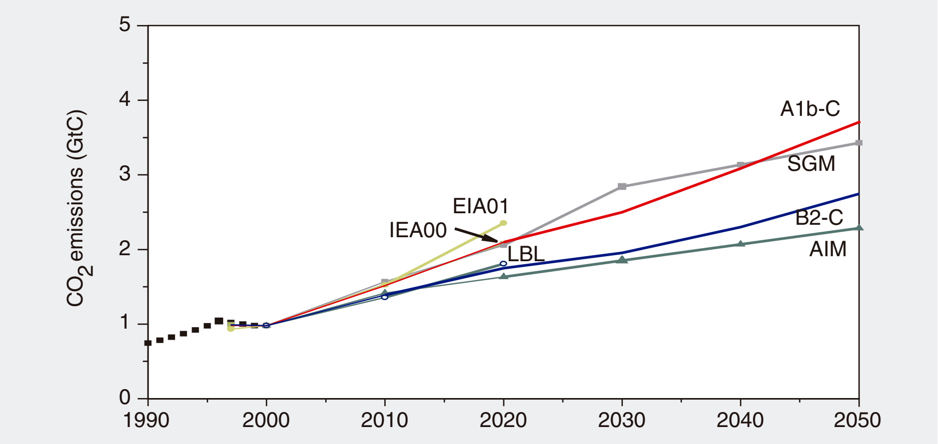

Figure 4.8 Carbon dioxide emissions in different baseline scenarios. (EIA indicates the projection by Dof, 2001. IEA the projection bij IEA, 2000. LBL the projections bij Sintiun and Fridley, 2000. SCM the projection by Sunds and Kejun, 2001 and AIM the work of the AIM model)

jection of Sinton and Fridley (2000). Both scenarios tend to be slightly high compared to other scenarios in 2050, reflecting the storylines of the two scenarios (high energy demand in A1b-C and reliance on domestic coal resources in B2-C).

4.4 Mitigation scenarios for China

4.4.1. Policy needs for China

In the previous section we saw that baseline developments are likely to lead to considerable increases in emissions of carbon dioxide and thus will also lead to impacts on the global climate. Although developing countries have no obligations so far, the required reductions to prevent severe climate impacts need, in the long-run, participation from both developed and developing countries. In the next section we will attempt to explore the possible policy options for GHG emission reduction by matching sustainable development paths in China and their effects.

4.4.2. The context for and content of climate change policies in China

China is presently in a stage of rapid industrialization, with rising incomes, increasing urbanization and a decline in the share of the agricultural sector in the economy. Although these societal changes can be associated with a more general process of “modernization”, there are also various circumstances that are specific for China. Hence, we have to carefully investigate the energy and associated systems in China, if policies to reduce GHG emissions are to be recommended. Increasingly, the need for a more sustainable development pattern than the one taken by presently industrialized countries is felt in the less industrialized regions of the world. This is as much a consequence of the perceived local environmental threats as of the possible global consequences of unsustainable practices. China has recognised the necessity of climate change abatement action in response to UNFCCC, which was ratified by China in 1992. In fact, climate change could be an important factor for the Chinese government in designing future environmental development in the framework of sustainable development, a long-term strategy set up by government. Many elements of climate policy can support such a longer-term strategy in the form of co- or ancillary benefits.

For the sake of convenience, we distinguish the following components of climate policies:

- (Climate change) policies: any action which interferes with the development path in the baseline scenario under discussion;
- Measures: the physical changes within the energy system (in fuel use, technology, reduction of energy demand, emission control, etc.) which influence the GHG emissions;
- (Policy) instruments: the political actions and mechanisms (such as subsidies, low-interest loan provision and educational campaigns) that are instrumental in implementing and realising the policy measures. The set of policy instruments can be subdivided into several clusters, including economic instruments, regulation, technology support and the so-called “social instruments” (e.g. information campaigns).

in each of the scenarios outlined in the previous section, there is a range of possible options and measures for GHG emission reduction that could be part of a longer-term climate change mitigation plan or strategy. Some of such options and measures are conceivable within both scenarios from the perspective of economic, political and societal feasibility and desirability. Others are not, in the sense that they will be attractive in the one scenario and unattractive, ineffective or hard to imagine in the other. However, in the development of global mitigation scenarios, the “SRES” modelling teams used the quantitative emission pathways of the various storylines at the start of their analysis, but hardly use the storylines to constrain the possible set of measures and/or policies that could be applied (Morita et al., 2000; IPCC, 2001). Here, we have followed a similar approach, but Table 4.2 still indicates the applicability of the various policy options, measures and instruments explored by us with the TIMER energy model within the context of the two baseline scenarios. In other words, for each instrument, we indicated how likely we considered the implementation of this instrument under each of the scenarios; however, in our quantitative exercises we considered all options.

A few important features of these simulations with the TIMER model should be noted:

- Population and economic activity trajectories are exogenous; these are taken from the baseline scenarios without any feedback from the energy system being taken into consideration.
- The TIMER model is not an optimization model, but simulates a complex interplay of decisions within the energy system. Hence, the analysis is often based on expert

judgement about which policy options and measures are interesting to explore, separately or in combination. The evaluation of the results is not in terms of an objective function but of various relevant system variables such as (changes in) investments, user costs and emission reduction.

- TIMER includes endogenous technology dynamics that have important cost-reducing effects if a technology is pushed by subsidies, demonstration projects and/or standards. For instance, use of energy efficiency measures lowers the cost of such energy -saving measures through learning-by-doing from accumulated energy-efficiency investments.
- As for all models, the quantification of policies is constrained by the characteristics of the TIMER model. Many of the complex, region-specific social dimensions of the determinants of GHG are absent so one has to rely on proxy variables and on storyline-related interpretations.
- A method to induce different abatement measures in TIMER is to attach a price to carbon emissions (by means of carbon levy or tax). Such a price generates a range of responses, such as investments in energy efficiency, fuel substitution and investments in non-fossil options. In TIMER, such a tax does not have any impact on the economic activity trajectory.

It should be kept in mind that these policy options and measures have to be introduced and implemented in a large field of competing policy interests. Sometimes, such other policies—for instance, population, employment, or health—have large impacts on the GHG emission path and are, as such, part of the baseline storyline and scenario.

4.5 Results for policy scenarios

This study dealt with three types of model experiments:

1. Exploring the system response by introducing a carbon tax during a certain period and at various levels.
2. Exploring the system sensitivity for specific options and measures.
3. Exploring a mitigation scenario by calculating the carbon emission reduction for an increasingly extensive package of the policy options and measures mentioned under point 2.

4.5.1. Responses to a carbon tax

One of the policy instruments that could be used to reduce carbon emissions is a carbon tax. Many studies have indicated that attaching a price to carbon emissions (e.g. carbon taxation) could be a very cost-effective instrument for inducing a series of measures to be taken in the energy system. The use of a tax allows for a large flexibility among end-users and investors in the choice of the actual measures taken. In models, applying a carbon tax in the system is often also used to obtain an indication of the possibilities of other instruments.

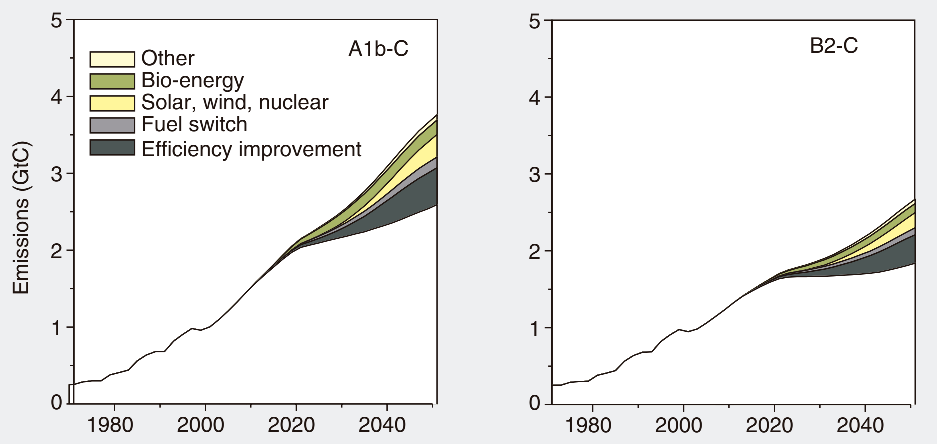

Figure 4.9 Attribution of carbon savings induced by US$30 per tC carbon tax in baseline scenarios.

Figure 4.9 shows that a carbon tax, gradually introduced from 2015 and reaching a maximum value of US$30/tC up to 2030, reduces the Chinese carbon dioxide emissions by 30% in both scenarios. To show the contribution of various reduction measures, we have allocated all avoided carbon emissions to four different clusters: the effects of energy-efficiency improvement, the effects of additional use of modern biofuels, the effects of additional use of non-thermal electricity (in particular, solar and wind) and the effects of fuel switching among fossil fuels[iv]

In the first 15 years after the introduction of the tax in the A1b-C scenarios, reductions are dominated by a fuel switch from coal to other fossil fuels; to a slightly lesser extent this is also the case in the B2-C scenario. However, after this period the role of the tax declines rapidly as fossil fuels, including natural gas, are replaced by non-fossil options. Over the whole period 2015–2050, energy savings contribute most to avoided carbon dioxide emission. From 2030, the effect of renewable mitigation options starts to become more and more important. Other indirect impacts of the carbon tax are discussed further in this chapter.

We can obtain some idea of the marginal abatement costs of emission reductions in China by exploring the system"s response to different levels of carbon tax. Figure 4.10 shows the response in two regions (China and Western Europe) for a hypothetical carbon tax introduced in 2000 for two different years, 2010 and 2030, within the A1b-C scenario. The figure shows that significant emission reductions can be achieved in China at relatively low taxes—certainly in comparison to Western Europe. The fig-

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[iv] It should be noted that the allocation, particularly the order, will depend somewhat on the methodology chosen. Here, first energy savings have been allocated first, then biofuels and non-thermal electricity and, finally, fuel-switch. Because of the sequence chosen, the effects of the latter are limited only to the changes in the remaining use of fossil fuels, after energy savings and additional non-fossil options have been accounted for.

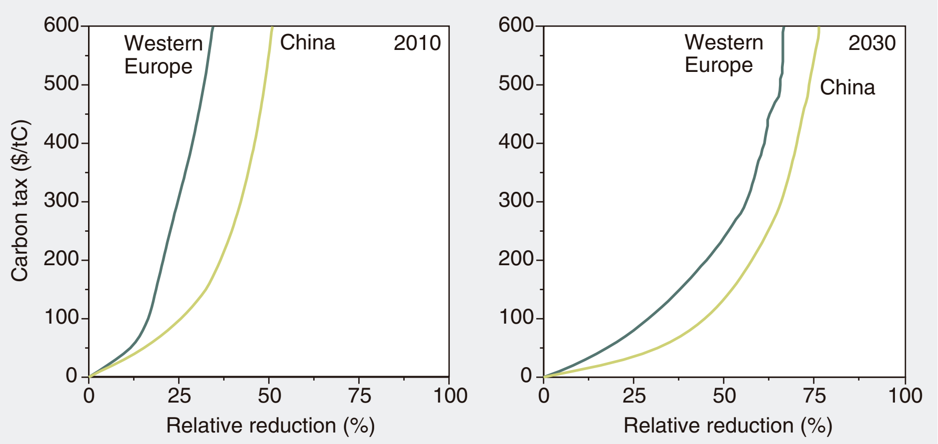

Figure 4.10 Relative emission reduction as a function of carbon tax applied for 2010 and 2030 in scenario A1b-C.

ure also shows that significantly larger emission reductions can be achieved in 2030 with the same energy tax (introduced in 2000) as in 2010. This is a function of two important mechanisms within TIMER. First of all, delays within the systems in terms of capital turnover and response time prevent the system from responding immediately to price pressure. Secondly, action taken in response to the tax is assumed to accelerate technology development by means of learning-by-doing, which enlarges the potential for reduction in later periods.

The comparison of the carbon tax response curve of the two regions gives us some idea of the potential for use of the Clean Development Mechanism to meet the required emission reductions of Annex-I countries through actual reductions in non-Annex-I countries. Under the Kyoto Protocol, Western Europe has to reduce its emissions by 8% compared to 1990; this is estimated to be in the order of 20–30% compared to the baseline (e.g. RIVM et al., 2001). Originally, studies expected that the final carbon price could be around US$50 per tC (e.g. RIVM et al., 2001) – but after the Marrakech accords and especially the decision of the USA not to ratify the Kyoto Protocol, price estimates are generally around US$10 per tC (see den Elzen and de Moor, 2001). Still, when we using the higher price as a benchmark of future climate agreements, in China, projects corresponding to a carbon price of US$50 per tC could reduce emissions by 15–20% compared to its baseline— or in other words reduce emissions by 0.2–0.3 GtC. This is an enormous potential for emissions reduction making China potentially very attractive for CDM projects.

4.5.2. Carbon emission reduction: policy options and measures

To get a better idea of the potential impacts of different policies between 2000 and 2050 in China, we implemented a series of modelling experiments. In most cases we chose measures that we regard as “moderate” since they are based on energy policies that are under discussion for the coming decade(s) in Western Europe. The measures

Table 4.2. Overview of policy options/measures, instruments and applicability

Policy measure	Possible policy instruments	Applicability		Implementation explored in the modelling experiment
		A1b-C	B2-C	
1. Incentives for energy-efficiency investments	• taxes/subsidies • low/zero-interest loans • information campaigns • appliance labels/ standards • investment in public transport systems • voluntary agreements with industry	+/- + - + + ++	++ ++ ++ +++ ++ ++	Reducing the gap in final energy intensity between Western Europe and China in 2050 by another 30% beyond the baseline.
2. Energy taxation inducing a series of responses	• tax on gasoline/kerosene as part of “greening tax” policy	+	+++	Adding an energy tax –equal for all fuel types – for industry and transport equal to current Western European tax levels for oil and gas
3. Influencing market penetration of secondary energy carriers	• taxes/subsidies, e.g. on natural gas or biofuels • emission standards	+/- +	+ +++	Reducing the use of coal in the building sector to zero
4. High-efficiency, gas-fired Combined-Cycle (CC) in central electric power generation	• technology and emission standards • institutional reforms • RD&D projects • Investments	++	++	In 2050, 15-20% of all electricity is generated by gas-fired combined cycle.
5. Advanced Clean Coal (ACC) options including Integrated Gasification Combined Cycle		++	++	All new coal power plants from 2010 onwards is highly efficient.
6. Reducing transmission losses		++	++	Losses in distribution and transmission of electricity are reduced in 2050 to the level of OECD countries (8%).
7. Increasing the share of nuclear power generation	• technology and emission standards • portfolio standards / renewable energy obligation • institutional reforms • RD&D projects • investments	++	+	Use of nuclear power is increased from 10% (A1b-C) and 7% (B2-C) to 20% of all electricity generated.
8. Increasing the share of renewables such as solar and wind in electric power		++	++	Use of new renewables in electric power generation is increased from 7% (both A1b-C and B2-C) to 20% of all electricity generated. In 2020, the required share is 10%.
9. Increasing the share of hydropower generation		++	+	Use of hydropower is increased from 68% to 90% of maximum potential of 378 GW.
10. Accelerating the penetration of biomass-derived fuels	• RD&D projects • tax exemption / subsidies to farmers • low/zero-interest loans • portfolio standards / renewable energy obligation	+	+++	Overruling of market dynamics with expansion targets; 10% market share in oil/gas market 2020, 20% market share in 2050
11. Carbon taxation inducing a series of responses	• carbon tax on fuel use in all sectors	++	++	Implementation of a US$30 carbon tax.

+++: very well applicable, ++ well applicable; + applicable; +/- might be applicable; - poorly applicable.

explored are discussed in Table 4.2, with the exact implementation in the model indicated in Appendix 4.2.

Table 4.3a and 4.3b show the mitigation effectiveness and cost aspects of these 11 policy options and measures, for the A1b-C and the B2-C baseline scenarios. Each policy option/measure can evaluated on four criteria: 1) effectiveness, 2) financial feasibility, 3) political feasibility and 4) strategic consequences. Here, we used the following indicators:

1. effectiveness: emissions reduction with respect to baseline;
2. financial feasibility: increase in energy system investments;
3. political feasibility: additional user costs;
4. strategic consequences: changes in total net costs of imported fuels.

Highly efficient power plants such as combined cycle and IGCC are able to considerably reduce emissions in China. This is particularly the case for IGCC if coal remains the dominant fuel in electric power. The strategy to develop coal-based clean technology could have both environmental and economic benefits, especially if China becomes a leader on this technology. It should be noted that improvement of electricity distribution can further reduce emissions by 1%.

In China alternatives for fossil fuel in the power sector up to 2050 are likely to remain poor competitors of thermal power plants with large supplies of very cheap coal. Thus, policies aiming to bring down the costs of these alternatives (either nuclear, wind or

Table 4.3a Introducing policy options/measures in China using the A1b-C baseline scenario

Measure/ Instrument (compare Table 4.2/Appendix 4.2)	Carbon emissions (compared to baseline)		Energy in-vestments (compared to baseline)		User costs (compared to baseline)		Fuel balance of trade (compared to baseline)	
	2020	2050	2020	2050	2020	2050	2020	2050
Demand side								
1. Energy efficiency	-6.2%	-10.8%	6%	9%	2%	3%	-15%	-28%
2. Energy taxation.	-2.0%	-3.8%	2%	1%	11%	15%	4%	5%
3. No coal use in buildings	-1.4%	-0.4%	1%	0%	3%	1%	7%	3%
Fossil-based electricity								
4. Combined cycle	-0.5%	-4.9%	0%	2%	0%	2%	2%	10%
5. IGCC	-5.3%	-9.4%	4%	8%	1%	3%	0%	0%
6. Improved distribution	-1.0%	-1.0%					0%	0%
Non-fossil fuels								
7. Nuclear	-0.4%	-9.6%	1%	6%	0%	2%	0%	-4%
8. Solar /wind	-2.3%	-6.2%	7%	4%	2%	2%	0%	-2%
9. Hydro	-2.8%	-2.9%	-1%	-1%	0%	0%	-1%	-2%
10. Biofuels	-0.2%	-0.7%	0%	-1%	0%	1%	0%	6%
Carbon tax								
11. 30 US$ per tC	-6.5%	-30.6%	6%	16%	20%	20%	28%	30%

Note: IGCC = Integrated Gasification Combined Cycle; furthermore, numbers cannot simply be added up as they relate to individual model experiments.

Table 4.3b Introducing policy options/measures in China using the B2-C baseline scenario

Measure/ Instrument (compare Table 4.2/Appendix 4.2)	Carbon emissions (compared to baseline)		Energy investments (compared to baseline)		User costs (compared to baseline)		Fuel balance of trade (compared to baseline)	
	2020	2050	2020	2050	2020	2050	2020	2050
Demand side								
1. Energy efficiency	-7.6%	-14.4%	7%	12%	2%	1%	-17%	-28%
2. Energy taxation.	-2.0%	-3.6%	1%	3%	15%	20%	4%	0%
3. No coal use in buildings	-0.9%	-0.5%	1%	1%	2%	1%	5%	1%
Fossil-based electricity								
4. Combined cycle	-0.3%	-4.5%	0%	1%	0%	1%	0%	5%
5. IGCC	-3.7%	-9.3%	4%	9%	2%	2%	1%	-1%
6. Improved distribution	-1.0%	-1.0%					0%	-1%
Non-fossil fuels								
7. Nuclear	-0.4%	-7.1%	1%	5%	0%	1%	0%	-5%
8. Solar /wind	-2.2%	-5.0%	7%	4%	1%	1%	0%	-3%
9. Hydro	-2.4%	-1.9%	-1%	0%	0%	0%	-1%	-2%
10. Biofuels	-0.3%	-2.0%	-1%	-1%	1%	2%	3%	9%
Carbon tax								
11. 30 US$ per tC	-6.7%	-29.8%	4%	16%	21%	15%	31%	18%

Note: IGCC = Integrated Gasification Combined Cycle; furthermore, numbers cannot be simply added up as they relate to individual model experiments.

solar) to improve their competitive position are unlikely to be very successful. Additional measures are required, such as long-standing renewable energy obligations or a combination of policies to promote non-fossil based alternatives and carbon taxes. The relatively modest policies explored here can reduce emissions by 5–10% for both nuclear and solar/wind power. The contribution of additional hydropower is modest as most of the existing resources are already used in the baselines. Biofuels (as an alternative to natural gas and oil) can reduce emissions to some extent—but will probably need to be imported.

Finally, as indicated earlier, a carbon tax of US$30 per tonne carbon introduced slowly in the 2015–2030 period induces a set of measures, which combined, reduce emissions by 30% in both scenarios. Such a strategy requires considerable additional investments to be made and increases user costs. As the funds raised by the tax itself can, in principle, be recycled, the net increase of user costs is 10 to 15%. As the carbon tax induces a large shift from coal to oil and natural gas use, the tax increases the fuel import costs by 20–30%.

4.5.3. Combining different measures into mitigation scenarios

The energy system is complex and there is a difference between the effectiveness and costs of a single option/ measure in isolation or the same option/measure in combina-

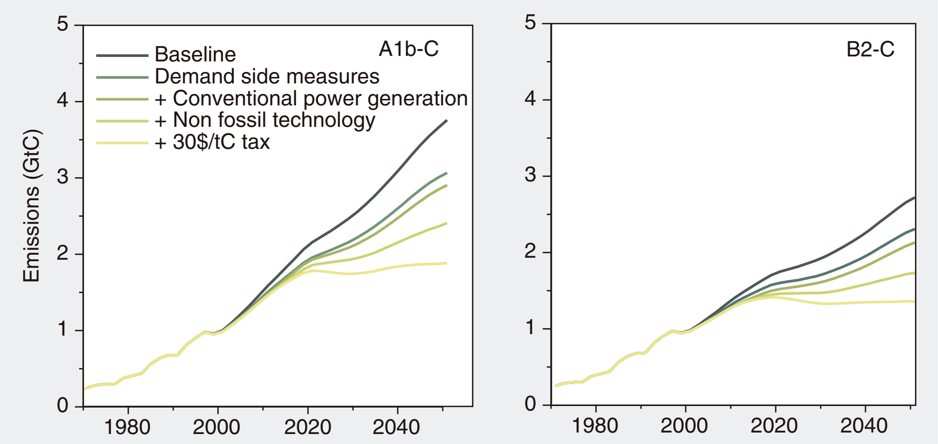

Figure 4.11 Carbon emission reductions achieved by a combination of policy measures.

tion with others. Here, we will present the results of a mitigation scenario based on a combination of the policy options discussed in the previous section. We have grouped them into four different categories: (1) demand-side measures, (2) measures for fossil-based electricity, (3) non-fossil technologies and (4) a carbon tax of US$30 per tC, fully effective after 2030.

Figure 4.11 (left) shows the carbon emission profile for the sequence of these different options starting from the A1b-C baseline. Demand-side measures form a very important part of the emission reductions obtained in these scenarios. If all options/measures are implemented, emissions are reduced by 50%—leading to a level of 2 GtC in 2050. The type of policies explored should certainly be regarded as feasible. Figure 4.11 (right) shows the same results, but now with the B2-C scenario as the baseline. Here, too, carbon emissions can be reduced by around 50%—and the final emissions come to about 1.3 GtC per year (stabilization after 2020/30). A large potential for GHG emission reduction was also identified in other studies (e.g. Jiang et al., 1998).

4.5.4 Kaya-factor accounting

The results can also be expressed in terms of the so-called Kaya identity. Figure 4.12 shows the changes in carbon emissions for 1970–1995, 1995–2020 and 2020–2045 for the baseline and the combined mitigation scenario (black bars). The stacked bars on the left of the black bars also indicate which factors have contributed to these changes ("Kaya" factors). The figure shows that not only in the mitigation scenario, but also in the baseline scenario, several factors contribute to emission reductions. Between 1970 and 1995, emissions would have increased by a factor of 8, driven by population and economic growth, and a shift towards commercial fuels, if not for a strong improvement in energy efficiency. Taking this improvement into account, the net increase is slightly less than a factor of 4. Reduction of energy intensity—based either on deliberate policies to improve energy efficiency or autonomous changes—will continue in the future to be an important force preventing the Chinese emissions from doubling or

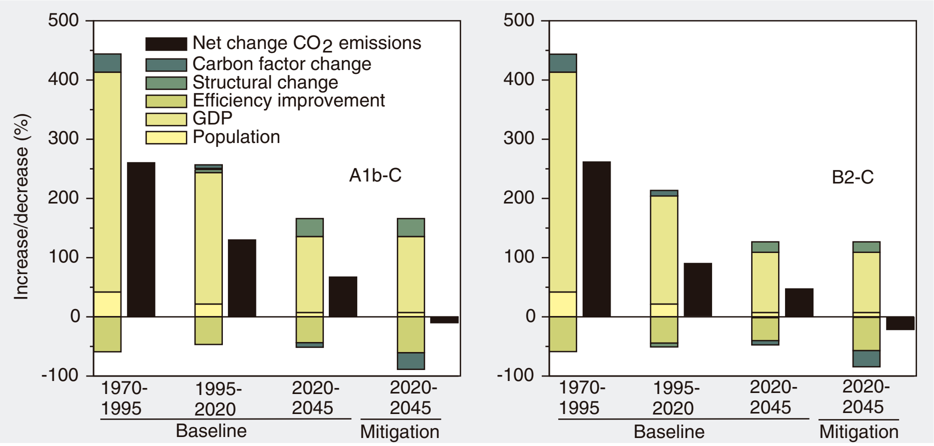

Figure 4.12 Changes in carbon emissions in 25 year periods and allocation of these changes to changes in Kaya factors.

even quadrupling in 25 year periods. Structural change represents overall an upward factor on emissions due to fast growth of the transport sector. Reduction in the carbon factor caused by shifts from coal to natural gas in residential areas also plays an important role in this. The mitigation scenarios push the contribution of these factors considerably further. In both the A1b-C and B2C scenarios, the mitigation scenario is successful in actually stabilizing emissions after 2030.

4.6 Conclusions and suggestions

4.6.1. Conclusions from the scenario analysis

Our scenario analyses suggest a number of trends and options with regard to future GHG emissions in China. Given economic and population growth scenarios, carbon emissions can be expected to increase by a factor of 3–4 in the first half of the century. In absolute terms, the increase will be largest in electric power generation and industrial production. The high growth in electricity demand and the competitive position of Chinese coal in this sector make electricity generation the fastest growing and, from 2015 onwards, largest carbon-emitting activity. Industry is also expected to rely heavily on coal for the first decades of the century, but the increasing market share of oil and gas, in combination with a decline in the energy-intensity of new industries, may well lead to stabilization in industrial carbon emission before 2040. The fastest growth in energy use is in the transport sector; however, it remains rather small in absolute terms and will rely mainly on oil and natural gas with a lower carbon content. Consequently, the sector is one of the driving forces behind rapidly growing oil and gas imports. In the residential and services sector, a phase-out of traditional fuels and, especially in urban regions, of coal, can be expected. Carbon emissions are expected to grow only slowly in these sectors.

Given these trends, China, with coal remaining the dominant energy carrier, will contribute an even larger part to global carbon emissions—becoming the largest emitter in the third decade of the century. The IMAGE 2.2 model indicates that both scenarios are expected to lead to an increase in global temperature of about 3–41C by the end of the century (IMAGE-team, 2001). China is expected to experience temperature increases similar to this overall global increase.

Longer-term carbon emission trends, in the second half of the century, will be largely determined by— uncertain—developments in the economic and social feasibility of non-carbon options such as solar/wind and biomass-derived fuels. It is also in the longer term that the difference between the various scenarios—in terms of sustainable development orientation, openness to fuel trade and the like—starts to make a large difference. For instance, by 2100 primary energy demand may differ up to a factor of 4 and carbon emissions up to a factor of 8. An important dynamic factor here is the assumed learning-by-doing which induces important cost decreases for non-carbon options as result of R&D and investment programmes in the sustainable development-oriented future. However, our analyses clearly indicate the large benefits of an orientation on sustainable development, especially in the longer term, for both China—lower urban air pollution, for instance—and the world.

Our exploration of emission reduction options suggests a large potential, at costs which are low compared to international standards. Not all options will be equally attractive and feasible across the various scenarios. In the first decades, a strengthening of energy conservation policies is most beneficial and cost-effective. However, energy efficiency improvements are often confronted most with institutional and financial barriers, especially in rapid growth periods in low-income countries.

Under both baselines, coal is expected to remain a dominant fuel in electricity generation. There are several specific measures to reduce GHG emissions in the electric power sector. First of all, introduction of clean coal use techniques (highly efficient IGCC, for instance) and an accelerated substitution away from coal to natural gas (with concomitant rise in gas imports) can be key options in the electricity sector (see also Zhang, 1998). Accelerated expansion of hydropower has only a marginal reduction potential—some 2% by 2050. Other non-fossil fuels, such as nuclear, wind and solar energy can be important for reducing carbon dioxide emissions further, certainly in the longer term. However, in view of the strong competitive position of coal, these fuels can only play an important role when they are supported by a lasting policy-guided effort (e.g. renewable energy obligation targets or carbon taxes). In all cases, the required investment fluxes may pose the largest challenge.

The analyses also show important trade-offs between the different options in terms of investments, increase of user costs and impacts on the balance of trade and emissions. For instance, policies that rely on a fuel switch from coal to oil might be cheap in terms of required investments but increase the costs of fuel imports.

Finally, it was also found that, in view of the differences in costs with Annex-I regions, there could be a considerable potential for CDM projects that could lower some of the financial barriers (see also Li, 2000; Sands and Kejun, 2001).

4.6.2 Suggestions for policy implementation

These policy measures discussed above need to be implemented in the context of existing (environmental) policies and development strategies in China. Below, we will make some suggestions how this could be done based on knowledge of the Chinese situation, international experience and the results of our analysis.

First of all, policy to reduce GHG emissions could be combined with existing plans, in particular, a domestic sustainable development strategy and the national energy development plan. Sustainable development is already recognized as an important factor for both short- and long-term plans. Agenda 21 for China, announced by the Chinese government in 1994, addresses the sustainable path into the future, which covers many energy activities. Policy options assessed in this study, such as clean energy utilization (including natural gas and non-fossil based energy) could well match the targets described in these national plans (Zongxin and Zhihong, 1997).

Secondly, it will be important to focus on non-regret opportunities. Much of the potential emission reductions discussed above can be implemented even with finding benefits larger than costs, certainly when taking into account the co-benefits (reduction of air pollution) (Wang and Smith, 1999). International technology collaboration to respond to climate change could provide an essential basis for developing countries to reach their sustainable development goal, such as CDM and technology transfer (see also Jiang et al., 1999).

In terms of instruments, many options are available. International cooperation could focus on GHG emission reduction and domestic sustainable development, thereby helping to reduce some of the political and financial barriers to GHG mitigation in China. Tax reform in China started 10 years ago: energy subsidies have been reduced and a fuel tax for transport will be established soon. In most OECD countries, energy taxation was originally implemented for revenue considerations. Now that the time period is different, it may be wise for China to consider not only revenue but also environmental concerns in its current tax reforms. Such taxes (either carbon tax or a mixed energy tax) could discourage the use of environmentally harmful energy types and cover so-called externalities. For other issues, a focus on physical planning and performance standards can be more effective than economic instruments.

To conclude, in this chapter we have seen that the emissions of carbon dioxide are expected to grow rapidly under different assumptions for the baseline scenario. The rate of increase is determined by several factors, such as economic growth, energy efficiency but also by the focus on environment and sustainable development values. We have also indicated the potential for emission reduction as being considerable and often low cost. Most options have important trade-offs between different types of policies in terms of investments, user costs, import costs and environmental effectiveness.

Acknowledgements

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Appendix 4.1 Major assumptions within the baseline scenarios

	A1b-C	B2-C	A1F	B1
Demand				
Population	In all scenarios, we have assumed population to increase to 1.6 billion in 2050 and afterwards to decrease to 1.5 billion in 2100.			
GDP growth	Very fast (2050: 10230 US$/cap; 5.3% p.a. 1995-2050)	Strong (2050: 7490 US$/ cap; 4.8% p.a. 1995-2050)	Very fast (2050: 10230 US$/cap; 5.3% p.a. 1995-2050)	Fast (2050: 10230 US$/cap; 5.3% p.a. 1995-2050)
Lifestyle	Material – intensive lifestyles (relevant parameter reaches a value of 50% above default)	Moderate trend to dematerialization (relevant parameter reaches a value 10% above default)	Material – intensive lifestyles (relevant parameter reaches a value 50% above default)	Strong dematerialization (relevant parameter reaches a value 20% below default)
Autonomous efficiency improvement	Fast efficiency development, pushed by private investment	Normal efficiency improvement	Fast efficiency development, pushed by private investment	Fast efficiency development, pushed by private investment and technology transfer
Price-induced efficiency improvement (accepted pay-back times)	Accepted pay-back times reach current OECD levels (e.g. 3 years in industry)	In between A1b-C/A1f and B1.	Accepted pay-back times reach current OECD levels (e.g. 3 years in industry)	Accepted pay-back times reach levels of twice current OECD levels (e.g. 6 years in industry)
Fossil fuel resources	In all scenarios, we have assumed extensive fossil fuel resources in China – with both resources and production costs based on Rogner (1997). These resources also cover undiscovered and unconventional types such as methane hydrates and unconventional oil.			
Energy taxes	Energy end-use taxes converge to current USA levels in 2100 (e.g., 4-6 US$4-6 per GJ in transport)	In 2100, end-use taxes reach a level in between the final B1 level and the current regional level	Energy end-use taxes converge to current USA levels in 2100 (e.g., 4-6 US$/GJ in transport)	Energy end-use taxes converge to current Western European levels in 2100 (e.g., 14-16 US$/GJ in transport)
Preference levels for end-use fuels	Strong aversion to use of coal for health, convenience and environmental reasons	Very strong aversion to use of coal for environmental reasons	Modest aversion from use of coal; problems related to coal use are solved differently	Very strong aversion from use of coal for environmental reasons
Electricity				
Efficiency of thermal power	Increases to 0.47-0.49 for coal, 0.51-0.54 for oil and 0.56-0.58 for natural gas	Increases to 0.44-0.48 for coal, 0.49-0.53 for oil and 0.53-0.57 for natural gas	Increases to 0.48-0.50 for coal, 0.52-0.55 for oil and 0.57-0.59 for natural gas	Increases to 0.44-0.48 for coal, 0.49-0.53 for oil and 0.53-0.57 for natural gas
Preference levels for fossil fuels	No preferences or aversion to any fuel in 2100	No preferences or aversion to any fuel in 2100; only small add-on cost for clean coal.	No preferences or aversion for any fuel in 2100	Very strong aversion from use of coal for environmental reasons
Preference levels for types of production	Indifferent	Indifferent	Indifferent	Preference for renewable electricity production; modest aversion towards nuclear; strong aversion towards fossil

Fuel supply				
Technology development for fossil fuels	Default (0.90)	Default (0.90)	Fast (0.87)	Default (0.90)
Technology development for renewables	Strong till 2040 (around 0.8-0.87), default from 2040 onwards (0.90)	Strong till 2040 (around 0.8-0.87), default from 2040-2060, 2060-2100 slower (0.92)	Slow to very slow (0.92-0.95)	Strong till 2040 (around 0.8-0.87), modestly strong from 2040 onwards (0.88-0.90)
Trade	No trade constraints	Trade between global regions is limited	No trade constraints	No trade constraints

Appendix 4.2 Translation of the policy options into system variables

This annex indicates how the policy options discussed in the main text have been translated into changes in model parameters.

Policy option/measure	Implementation explored in modelling experiment	Changes in model parameters
1. Incentives for energy-efficiency investments:	Reducing the gap in final energy intensity between Western Europe and China in 2050 by another 30% beyond the baseline.	Increase the accepted payback time for energy efficiency investments in such a way that the required energy intensity is reached
2. Energy taxation inducing a series of responses	Adding an energy tax –equal for all fuel types – for industry and transport equal to current Western European tax levels for oil and gas.	Increase the tax on fuels in these sectors to reach the Western European level by 2020.
3. Influencing market penetration of secondary energy carriers	Reducing the use of coal in the building sector to zero.	Introduce a premium factor for coal to phase coal out of the residential and service sector by 2020, for example.
4. High-efficiency, gas-fired Combined-Cycle (CC) in central electric power generation	In 2050, 15-20% of all electricity is generated by gas-fired combined cycle	Change the premium factor for natural gas for electricity generation and change its efficiency.
5. Advanced Clean Coal (ACC) option, including Integrated Gasification Combined Cycle	All new coal power plants from 2010 onwards are highly efficient.	Change efficiency of coal power plants.
6. Reducing transmission losses	Losses in distribution and transmission of electricity are reduced in 2050 to the level of OECD countries (8%).	Change distribution and transmission losses
7. Increasing the share of nuclear power generation	Use of nuclear power is increased from 10% (A1b-C) and 7% (B2-C) to 20% of all electricity generated.	Forced expansion
8. Increasing the share of renewables such as solar and wind in electric power	Use of new renewables in electric power generation is increased from 7% (both A1b-C and B2-C) to 20% of all electricity generated. In 2020, the required share is 10%.	forced expansion.
9. Increasing the share of hydropower generation	Use of hydropower is increased from 68% to 90% of maximum implementable potential.of 378 GW.	Accelerate hydropower by forced expansion as to reach 350 GWe installed capacity by 2050.
10. Accelerating the penetration of biomass-derived fuels	Overrule market dynamics with expansion targets; 10% market share in oil/gas market 2020, 20% market share in 2050.	Forced expansion.
11. Carbon taxation inducing a series of responses	Implementation of a US$30 carbon tax.	Implementation of a US$30 carbon tax, slowly building up from 2020 onwards.

5. UNCERTAINTY RANGES FOR THE IPCC SRES SCENARIOS: PROBABILISTIC ESTIMATES CONDITIONAL TO THE STORYLINE

Detlef van Vuuren, Bert de Vries, Arthur Beusen, Peter Heuberger

Abstract. The conditional probablisitic scenario analysis that is applied in this chapter combines statistical methods of uncertainty analysis at parameter level, while recognizing the deep uncertainty that exists for several underlying trends. The model calculations indicate that cumulative 21st century emissions could range from 800-2500 GtC in the absence of climate policy. This range originates partly from the underlying storylines, and partly from the probabilistic analysis. The latter causes about a 40% uncertainty range for each clearly defined storyline. Among the most important parameters contributing to the uncertainty range are uncertainty in income growth, population growth, parameters determining energy demand, oil resources and fuel preferences. While the quantitative results are shown to be reasonably consistent with both storyline and fully probabilistic methods, the current method adds to existing work by: 1) indicating consistent storylines that could lead to either high or low emission pathways, and 2) identifying the most important parameter contributing to uncertainty ranges. The latter is also shown to be scenario-dependent.

5.1 Introduction

Indications of possible long-term trends in the global energy system provide very essential information for policy makers. The energy system is by far the single most important driver of anthropogenic climate change, and also plays an important role in connection with several other sustainability problems such as regional air pollution and resource depletion. The future of the energy system is, however, beset with uncertainty, as it is the product of complex dynamic processes and factors, including demographic and economic development, technological change, energy policies and resource availability. Various development patterns for each of them could introduce very different futures for the energy system as a whole. Scenarios are tools used in the assessment of future developments of these complex systems that are either inherently unpredictable or characterized by large scientific uncertainties. In exploring future development of energy systems and climate change, uncertainty management needs to be a constant companion of scientists and decision-makers (Hulme and Carter, 1999). Uncertainty has various causes, varying from stochastic randomness to limitations in knowledge, and ignorance and human anticipation. Uncertainty can occur on different scales: model parameters, models structure and/or complete disagreement in conceptualization among experts (see next section). The question how to deal with uncertainty in model projections has, in recent years, been given considerable attention (Grübler and Nakicenovic, 2001; Schneider, 2001; Schneider, 2002; Webster et al., 2002; Patt and Dessai, 2005; Dessai et al., 2007). Two approaches were most prominent in the debate on handling uncertainty in the context of climate and (energy) emissions scenarios: *(storyline-based) alternative scenarios* and *fully probabilistic scenarios*.

The *alternative scenarios approach* is founded on the premise that many factors determining the future can vary over a large and partly unknown range. These ranges are only partly bound by relationships among variables (so-called stylized facts[i]). Usually (energy) models endogenize a limited number of these relationships as they may be too complex to incorporate and/or lack quantitative evidence (Rotmans and de Vries, 1997). In the scenario approach, such relationships are expressed in a "storyline"; this storyline represents a kind of underlying logic of the scenario and its main assumptions. This way of providing consistency to the complex parts of the real-world developments forces modelers (and users) to think in a more creative way about possible future developments.

The *fully probabilistic approach* to uncertainties expresses the most important model inputs in terms of probability estimates and uses statistical sampling techniques to create a range of emission pathways defined by a median value and various probability intervals. This approach is easily applicable to systems that are clearly defined and for which input parameters can be meaningfully expressed in terms of likelihood. The approach has also been applied to more complex systems, as in the modeling of future greenhouse gas trajectories (Webster et al., 2002; Webster et al., 2003). It operates from the positivist engineering/control paradigm, whereas the alternative scenario approach positions itself more in a constructivist social science tradition.

The ongoing discussion between proponents of the individual approaches has revealed strengths and weaknesses of both approaches (see Section 5.2.1). The methods can, in our view, best be seen as complementary, not exclusive. In fact, one could also combine the two methods by simultaneously accepting ignorance for some aspects of future development, while at the same time bringing in elements of formal uncertainty analysis. O'Neill (2004; 2005) introduced such a "*conditional probability approach*" for population scenarios, with as rationale that is more meaningful to make judgments about the likelihood of future trends in the context of a particular development path, than about the likelihood of this path itself. While O'Neill applied this approach successfully in population scenarios, hardly any attempt has, so far, been made to use a similar approach for the total energy system.

The main focus of this chapter is to explore what kind of information can be provided by a conditional probabilistic approach to uncertainty. For this purpose we have applied such an analysis using statistically sampled simulations of the TIMER energy model (van Vuuren et al., 2006b) conditional to the storylines of the IPCC SRES scenarios. We focus here, in particular, on one crucial output variable of this model, i.e. global CO_2 emissions.

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[i] The term "stylized facts" refers to stable patterns that emerge from many different sources of empirical data.

The aim was to provide insight into the following questions:

1. What range of emissions would result from a probabilistic approach to uncertainty?
2. What elements of uncertainty contribute most to these emission ranges?
3. How do results of a conditional probabilistic approach compare to other approaches of uncertainty?

Obviously, the answers to these questions depend on the modeling tool applied. A more complete account of uncertainties would be achieved by including more than one model (Nakicenovic and Swart, 2000; van Vuuren et al., 2006c). However, even then, some of the uncertainties will not be captured by any of the models.

5.2 Methods

5.2.1 Sources of uncertainty and earlier applications of uncertainty methods in scenario approaches

Uncertainty originates from various causes and can be classified in different ways (Rotmans and de Vries, 1997; Moss and Schneider, 2000; Dessai and Hulme, 2001; Van der Sluijs et al., 2003; Dessai and Hulme, 2004; Patt and Dessai, 2005). One classification is based on the nature of the uncertainty. *Ontic uncertainty* (a) refers to natural randomness, which can generally be expressed in mean estimates and their ranges of likelihood (for instance, uncertainty originating from chaotic behavior in complex systems). A key characteristic is that this type of uncertainty can not be easily reduced. Its influence can sometimes be empirically determined (e.g. distribution of extreme weather events), although there is no guarantee that the same distribution will hold in the future. *Epistemic uncertainty* (b), in contrast, comes from incomplete knowledge (for instance, ultimately available oil resources). In the case of energy scenarios, an important part of the uncertainty originates from not knowing how the techno-economic and socio-cultural context of the energy systems evolves. There are various subcategories of epistemic uncertainty based on the way it is handled: (mostly subjective) statistical expressions (b1); conditional statements (b2) or recognized ignorance (b3). A special form of epistemic uncertainty comes from c) *disagreements among experts* (Patt, 2007). The latter may also come from value pluralism of experts (Rotmans and de Vries, 1997). Together, the ucertainties may result in total *ignorance or deep uncertainty*. Here, there is no agreement on the description of the system, the probability distribution of important drivers of the system or the value system used to rank alternatives (Lempert et al., 2004). Finally, a special category (with ontic and epistemic elements) is *human reflexive uncertainty* (d) originating from unknowns in human response to and anticipation of changes (Dessai and Hulme, 2004). Here, statistical analysis is often meaningless. Even when historical analysis suggests certain estimates by comparison and analogy, there is no guarantee that such an approach is valid for the time to come.

Other classifications of uncertainty can also be made: one refers to scale and distinguishes uncertainty in *model parameters* (1), uncertainty about *model structure* (2) and uncertainties that arise from 3) *disagreements conceptual theories on an even larger scale*.

As indicated, various methods have been introduced to deal with uncertainty in scenario development. In the field of greenhouse gas emission scenarios, focus was originally on "business-as-usual" emission trajectories, with simple variations for the main driving forces (e.g. Leggett et al., 1992). The most prominent approaches today, the *alternative scenario approach* and the *fully probabilistic approach*, can both be seen as an improvement to these early projections. The *alternative scenario* approach emphasizes the need for consistent assumptions and the handling of ignorance (cat. b2, b3, c, d), while the *probability approach* places the variations in the framework of a more structural assessment of plausible futures (cat. a, b1).

The IPCC SRES scenarios, as most well-known application of the *alternative scenario approach*, map out a range of possible emission trajectories based on the wide variation in assumptions structured around four main storylines. Consistent with the basic premise of the approach, Nakicenovic and Swart (2000) indicate that it is not meaningful to assign probability estimates to these scenarios based on ignorance and the influence of societal choice (deep uncertainty). The SRES scenarios, however, formed the start of a lively debate. Schneider (2001; 2002) and Webster et al. (2002) argued that policy analysts and decision-makers need probability estimates to assess the risks of climate change impacts resulting from these scenarios; this is to decide how to respond to these risks. These decisions cannot be made on the basis of indicating "potential consequences" alone. Even when probability estimates are subjective, researchers (experts) are better equipped to make an assessment than the users (non-experts) of these scenarios. A counter argument from the SRES team (Grübler and Nakicenovic, 2001) that social systems (important in emission scenarios) are fundamentally different from natural science systems is dismissed by their critics: not only in social science but often in natural science too, conditional probability estimates need to be made for systems that cannot be measured (as they form a part of the future) (Schneider, 2002). The absence of probability assignments in the SRES scenarios also resulted in other ambiguities. Wigley and Raper (2001), for instance, interpreted the scenarios as equally likely and derived probabilistic statements on temperature change from the scenarios. However, given the fact that the SRES scenario provides no indication of likelihood, temperature could easily be outside the range reported by Wigley and Raper.

Several studies have applied the contrasting *probabilistic approach* to emission scenarios (Manne and Richels, 1994; Nordhaus and Popp, 1997; Scott et al., 1999; Webster et al., 2002; Webster et al., 2003; Richels et al., 2004; Kouvaritakis and Panos, 2005; Pepper et al., 2005; Sweeney et al., 2006). An important critique formulated against this approach is that attempts to assign subjective probabilities in a situation of ignorance forms a dismissal of uncertainty in favor of spuriously constructed expert opinion (Grübler and Nakicenovic, 2001; Grübler et al., 2006). Moreover, it is also argued that while the fully probabilistic approach provides more (seemingly) readily useable information, the alternative scenario approach provokes creative thinking of decision-makers about possible futures and strategic choices. Finally, uncoupled sampling within distribution ranges of input parameters may result in inconsistent combinations. Clearly, the handling of uncertainty and the appropriateness of assigning subjective probabilities to scenarios is a matter of lively debate and an important, unresolved, challenge in the application of climate scenarios (Dessai et al., 2007; Groves and Lempert, 2007).

5.2.2 Uncertainty approach used in this chapter

This chapter applies the conditional probabilistic approach, as indicated in the introduction, which is a combination of the scenario approach with formal uncertainty analysis. The approach attempts to combine the strength of the scenario approach in providing consistent descriptions of various uncertainties; and to handle ignorance with the strengths of the formal uncertainty approach in making/using explicit probability statements. The rationale is that the reduction of the uncertainty space, with help of divergent storylines, will make uncertainties more suitable for a formal uncertainty method. For example, it is difficult, if not impossible, to assign meaningful probabilities to the rate of per capita economic growth over the coming decades (as this depends on fundamentally uncertain parameters such as trends in globalization). However, if one restricts the set of possible futures that must be considered to only those in which globalization proceeds rapidly and trade barriers are reduced, the probability distribution of future economic growth rates may narrow down and gain confidence. This reasoning can be extended to many different factors that are included in storylines about the future. As such, it also responds to do justice to the cause of uncertainty in the analysis (Patt, 2007). The approach was applied earlier to population scenarios by O'Neill (2004; 2005).

In the conditional probabilistic approach, we based our analysis on the IPCC SRES scenarios (Figure 5.1). These scenarios are described in Section 5.2.3. The scenarios and storylines considered in this chapter all represent so-called baseline scenarios; i.e. we assume no climate policy in line with the original mandate given to SRES by the IPCC (Nakicenovic and Swart, 2000). Uncertainties with respect to technologies, which are only relevant in a world that includes climate policies such as carbon capture and sequestration (CCS), are therefore not included in the analysis. We also consider only greenhouse gas emissions from energy use; emissions and uptake from forestry and land use are not included. Our conditional probabilistic analysis consisted of the following four steps:

1. Identification of parameters subject to uncertainty analysis;
2. Assessment of the conditional probability ranges associated with these parameters;
3. Use of Monte-Carlo sampling to calculate uncertainty results and TIMER model runs;

4. Identification of ranges for model outcomes and of determinants adding to model uncertainty.

For step 1, we used the results of an earlier uncertainty analysis on the TIMER energy model that was based on the NUSAP method (van der Sluijs et al., 2002). This analysis used several techniques to identify elements of uncertainty in TIMER, including a formal sensitivity analysis, a 2-day expert elicitation workshop, and model comparison and interview techniques with different model developers. Based on this study, we identified the most relevant model parameters to include in a formal uncertainty analysis (either based on relevance or sensitivity). Step 2 was to quantify the probability functions of those model parameters conditional to the scenario storyline of the model. As explained in Section 5.2.5, the parameter ranges assigned to each parameter conditional to the storyline are often derived from information on the unconditional (full) uncertainty ranges as mentioned in the literature. Next (step 3), we applied Monte-Carlo sampling of input data for 750 model runs and estimated (step 4) the probability range for outcome parameters, and the contribution of the uncertainty ranges assigned to different parameters (see Section 5.2.6).

5.2.3 The TIMER energy model

In this analysis we used the TIMER 2 energy model (Chapter 2). TIMER is a system-dynamics simulation model at an intermediate level of aggregation: 17 world regions, 5 energy-demand sectors (industry, transport, residential, services and other) and around 10 different energy carriers. TIMER is a simulation model: it does not optimize scenario results on the basis of perfect foresight, but simulates year-to-year investment decisions based on specific rules about investment behavior, fuel substitution and technology. The time horizon in the present analysis is the period from 2000 to 2100, while model calibration is performed on the basis of historical data for the 1971–2000 period.

In the model, first energy demand is calculated on the basis of changes in sectoral value-added and GDP, population, income elasticities, autonomous-energy efficiency improvement (AEEI) and price-induced efficiency improvement (PIEEI) (See Figure 5.2).

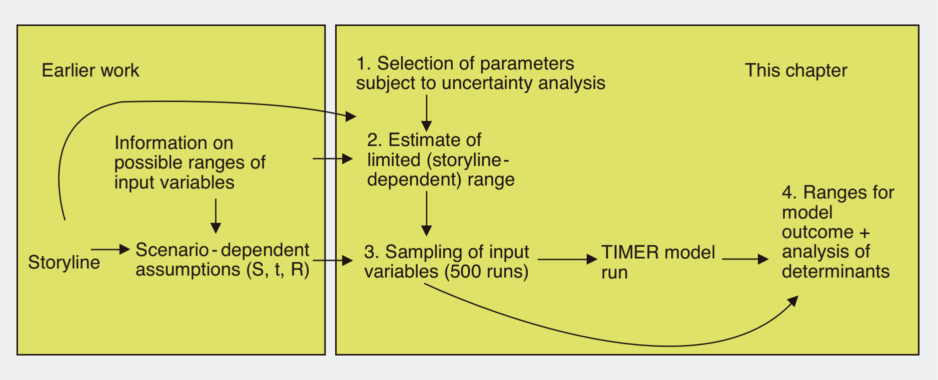

Figure 5.1 Overview of the analysis.

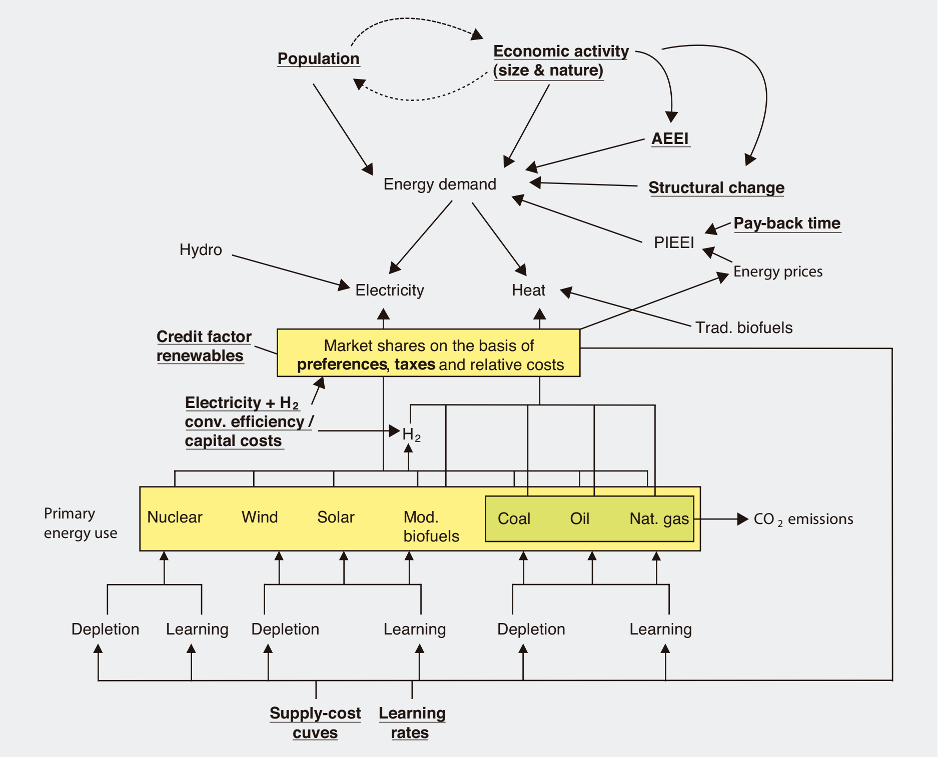

Figure 5.2 Representation of the TIMER model, indicating important model connections (factors included in the uncertainty analysis are "underlined", while important output variables are in "italic").

Market shares of various energy carriers in each sector are then determined by means of multi-nomial logit equations, taking into account price changes and/or changes in subscribed fuel preferences. Demand for electricity and hydrogen are forwarded to submodels that simulate investments in various technological options to produce these final energy carriers. These include fossil-fuel and bio-energy based options and non-fuel-based technologies (hydropower, nuclear, wind and solar PV). The decisions on investments and fuel use are derived from the relative (perceived) costs of each option, according to a multinomial logit formulation. Demand for primary energy carriers (fossil fuels and bio-energy) are finally fed into different production models that simulate their production and trade. The costs of energy carriers in TIMER result from an interplay between depletion and learning dynamics. Depletion leads to increasing production costs, as a function of cumulative production of fossil fuels or of the ratio between actual and maximum potential in the case of renewables. Learning-by-doing leads to a decrease in production costs.

5.2.4 Storylines of the IPCC SRES scenarios

Nakicenovic and Swart (2000) provide a detailed description of the SRES scenarios, organized around the two major uncertainties in the direction that the world could evolve. These are globalization versus regionalization, and economic orientation versus orientation towards social development and environmental protection (resulting in four scenario families A1, A2, B1 and B2). Obviously, other dimensions are crucial too; these are considered to be implicitly or explicitly related to these two dimensions, for instance, technology and governance. While the total set is considered to represent a wide range of outcomes, this does not mean that the four families represent all possible outcomes.

The storyline of the A1 scenario is based on an assumed continuation of globalization trends and a focus on market processes and economic objectives. Within the logic of the storyline, economic growth is assumed to be high. As this could spur on the demographic transition, population growth in turn is low. In terms of the energy system, the scenario is characterized by rapid technology development but also by energy-intensive lifestyles. Within the A1 storyline, there are three variants based on the emphasis in technology development: 1) balanced (A1b), 2) fossil-intensive (A1FI) and 3) focused on renewable technology (A1T). The A2 storyline, in contrast, emphasizes regional (energy) security and cultural identity. Here, it is assumed that trade protectionism and other economic and cultural barriers between world regions will slow down technical innovations and economic growth, which will, in turn, tend to slow down the demographic transition in low-income regions. The B1 storyline describes a convergent world with emphasis on global solutions to environmental and social sustainability, including concerted efforts towards reduction of economic inequity, less energy- and material-intensive products and lifestyles ("dematerialization") and strict controls on air and water pollution. Finally, on the basis of its position with respect to the major uncertainties, the B2 storyline emphasizes regional sustainable development. However, for practical reasons this scenario is mainly implemented as a combination of medium assumptions for several trends.

Although the SRES scenarios as originally implemented are still broadly consistent with the literature, new insights have emerged for some parameters (van Vuuren and O'Neill, 2006). For instance, current expectations for population and economic growth for low-income regions are now generally lower than assumed in SRES. Against this background, a set of updated scenarios was recently developed using the Integrated Model to Assess the Global Environment (IMAGE), the integrated assessment modeling framework of which TIMER forms the energy model (van Vuuren et al., 2007) (see Figure 5.3). These scenarios form the starting point of the analysis presented here.

We will look explicitly at the four main storylines (A1, A2, B1 and B2). We have decided to comply with the tradition of sometimes placing the B2 storyline in the middle of the three other, more explicitly focused, storylines. We assume that the alternative variants in the A1 world (A1B, A1FI and A1T) can be generated in the analysis by vary-

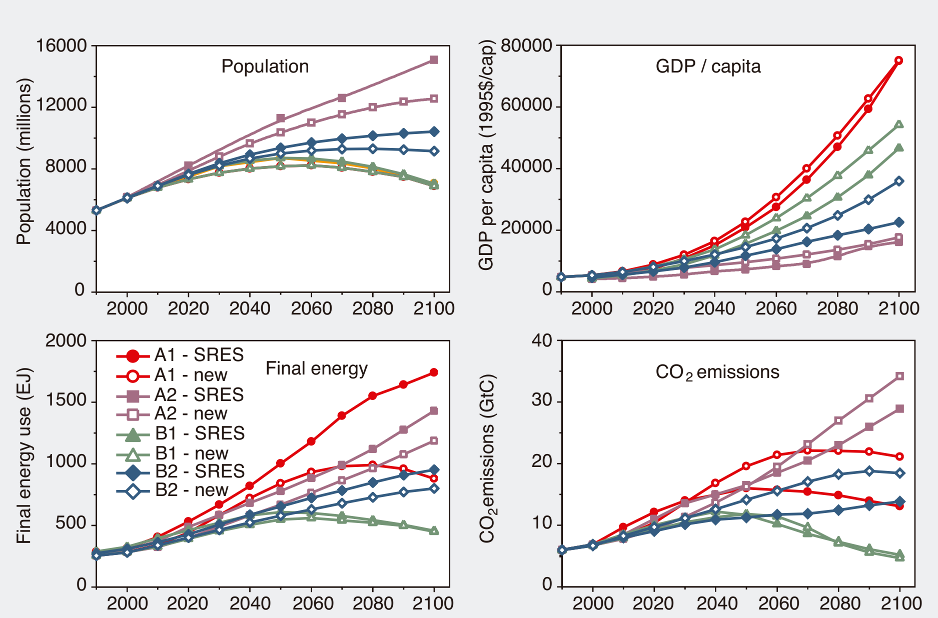

Figure 5.3 Driving forces and fossil fuel CO_2 emissions in the IMAGE 2.3 SRES scenarios compared to the IPCC SRES Marker scenarios (Nakicenovic and Swart, 2000) (see also www.ipcc.ch).

ing technology parameters on the basis of statistical uncertainty analysis in the A1 storyline – and thus need not to be specified explicitly.

5.2.5 Parameter values and their ranges

Earlier van der Sluijs et al. (2002) used several methods to perform a sensitivity and qualitative uncertainty analysis for the TIMER model[ii]. We have used their selection of the most sensitivity parameters as starting point for selecting uncertainty parameters considered in this study. Moreover, the expert elicitation was used in the specification of useful parameter ranges. The list of input parameters is given in Table 5.1 (see also Figure 5.2).

For all input variables, assumptions for our uncertainty analysis were made on a global scale, unless additional information was available that allowed regional specification. Webster and Cho (2006) recently analyzed the historical level of correlation in regional economic growth rates, and found that regional growth was far from perfectly correlated. Sampling growth rates in regions more independently (only bound by the empirically observed level of correlation) in an updated analysis of the original work of Webster et al. (2002) (which assumed full regional correlation) led to a considerably reduced range of outcomes for CO_2 emissions. As a result, one may assume that the full

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[ii] Some parameters (technology assumptions for H_2, wind/PV resources and capacity credit) were added later in association with model additions made more recently.

Table 5.1 Input parameters included in uncertainty analysis

Parameter category	Parameter	Central value	Sampling range around central value
Driving forces	Population	Scen, Reg	Scen, Reg
	GDP	Scen, Reg	Scen, Reg
	Size of industry sector	Scen, Reg	Indep.
Energy demand	AEEI	Scen, Reg	Indep.
	Pay-back time	Scen, Reg	Indep.
	Structural change	Scen, Reg	Indep.
Technology change	Fossil fuels	Scen, Reg	Indep.
	Renewables (electric power)	Scen, Reg	Indep.
	Nuclear power	Scen, Reg	Indep.
	Bio-energy	Scen, Reg	Indep.
	Energy demand	Scen, Reg	Indep.
	Hydrogen technologies	Scen, Reg	Indep.
	Thermal power plants	Scen, Reg	Indep.
Resources	Oil resources	Reg	Indep.
	Gas resources	Reg	Indep.
	Coal resources	Reg	Indep.
	Wind resource	Reg	Indep.
	Biomass resource	Scen, Reg	Indep.
	PV resource	Reg	Indep.
Other	Fuel preferences	Scen, Reg	Indep.
	Credit factor for renewables	Reg	Indep.
	Taxes	Scen, Reg	Indep.
	Short-term price uncertainty oil and gas	Reg	Indep.

Scen: indicates that either the central value or the sampling range around this value is scenario-dependent.
Reg: indicates that either the central parameter value or the sampling range around this value is region-dependent.
Indep.: indicates that the sampling range is scenario- and region-independent (thus a constant sampling range around a central value).

correlation assumed in this analysis is also likely to result in broader ranges in output variables than in the situation where no perfect correlation has been assumed.

For each parameter we use as main value the assumptions of the recent TIMER elaboration of the IPCC SRES scenarios (van Vuuren et al., 2007). The sampling ranges around these values have, as far as possible, been based on ranges indicated in the literature, such as historical fluctuations or explicit statements on their distribution (see Appendix 5.1). As indicated in Table 5.1, for most parameters, the sampling range is set the same for all scenarios and regions. The sampling for population and economic growth forms an exception, as here the sampling ranges are also scenario- and region-dependent. The resource estimates form another exception as no scenario dependency has been assumed.

Estimating the sampling range is complicated by the fact that if ranges (or even probability distribution functions, pdf) are found in the literature, these often refer to unconstrained situations (i.e. not depending on certain storylines). Only population pdfs conditional to the IPCC storyline were directly available (O'Neill, 2004). This introduces

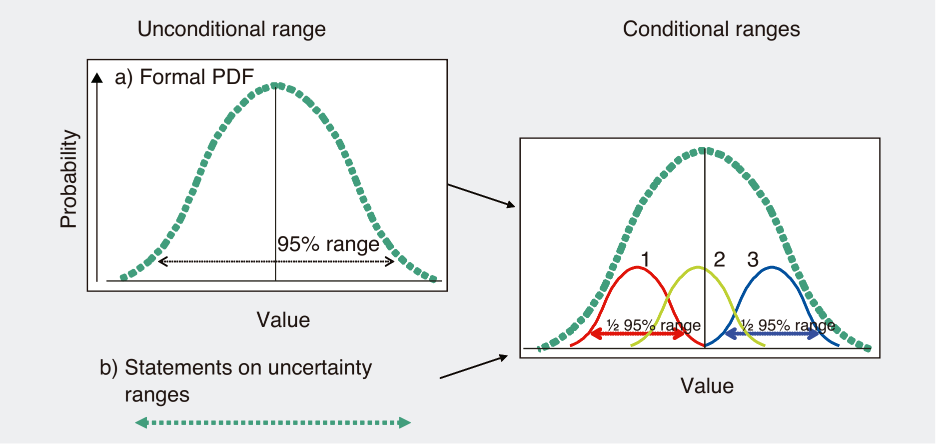

Figure 5.4 Scheme used in interpretation process showing derivation of conditional ranges.

Note: Conditional ranges are derived by assigning half the range of the unconditional distribution around the central storyline-based value. This example is given for technology change, where A2 is characterized by slow technology development, B2 by medium and A1 by high technology development.

another element of arbitrariness as the unconditional ranges/pdfs need to be interpreted in the context of our storylines. Although expert elicitation would be a preferred instrument to do this, for the sake of simplicity and time, the ranges here were only partly based on expert elicitation (van der Sluijs et al., 2002) and partly by interpretation of available literature by the authors of this chapter . The overall scheme used in this interpretation process is shown in Figure 5.4., As an example, an unconditional range is shown on the left-hand side for a selected input variable as found in the literature (e.g. a 95% interval). For those parameters for which such pdfs could be found (progress ratios, population), the shape was mostly comparable to a normal distribution. On this basis, we have (again for the sake of simplicity) assumed all parameters to be normally distributed. Next, storyline descriptions were used to choose a specific range within the unconditional pdf for each scenario. As most storyline statements are described as “high”, “low” or “medium”, a standard interpretation was made. We assumed that these statements generally refer to values above, below or near the median value, respectively, thus assigning a corresponding half of unconditional 95% interval to each scenario (see Figure 5.4). On the right-hand side, three different conditional distributions are shown, representing low, medium and high values. This implies that, unless more specific information had been available, our conditional distribution was characterized by main value, based on the existing scenario implementation of van Vuuren et al. (2007), with an uncertainty range equal to half the unconditional range.

The pdfs of different parameters are not unrelated. Relationships may exist in the form of interactions outside the scope of the model or in the form of the scenario storyline. For instance, the A1 storyline emphasizes that its high economic growth is likely to spur on the demographic transition leading to low population growth. Or, in another example, the relatively slow rate of technological change in the A2 scenario is considered to be in line with the low economic growth rate, which, in turn, is an assumed consequence of trade protectionism. As our approach captures the original implementation of the scenarios and only samples around these “median” values, the existing qualitative relationships between model parameters are arguably preserved.

5.2.6 Parameter sampling and analysis

In order to limit computational load we use the Latin Hypercube Sampling (LHS) technique. LHS can be used in combination with linear regression to quantify the sensitivity and uncertainty contributions of the input parameters to the model outputs (Saltelli et al., 2000; Saltelli et al., 2004). On this basis, 750 runs are made for each scenario, sampling values for each of the 26 input values (X_i). In the analysis of the output data, the values for each output variable Y (e.g. CO_2 emissions) are approximated by a linear function of the inputs $X_{i,}$ expressed by:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 \ldots + \beta_n X_n + e \tag{5.1}$$

where β_i is the so-called ordinary regression coefficient and e the error of the approximation. The quality of the regression model is expressed by the coefficient of determination (R^2) representing the amount of variation in Y explained $Y - e$. Next, we use the standardized regression coefficient (*SRC*), which is a relative sensitivity measure obtained by rescaling the regression equation on the basis of the standard deviations σ_Y and σ_{Xi}:

$$SRC = \beta_i \frac{\sigma_{X_i}}{\sigma_Y} \tag{5.2}$$

*SRC*s can take values between -1 and 1. SRC is the relative change $\Delta y/\sigma_y$ of Y due to the relative change $\Delta x_i/\sigma_{xi}$ of the parameter X_i considered (both with respect to their standard deviation σ). Hence, *SRC* is independent of the units, scale and size of the parameters. Its value is indicative of the contribution of the uncertainty in X_i in the uncertainty of Y. The sum of squares of *SRC* values of all parameters equals the coefficient of determination, which for a perfect fit equals 1. An absolute *SRC* value above 0.2 (contributing more than 4%) is indicative of a strong relationship, provided that its contribution is also significant. Testing whether *SRC* is significant is done with the student t-statistic (Saltelli et al., 2000). The *SRC* is significantly different from zero if the absolute value of the student t-statistic exceeds 2. It is important to note here that any conclusions drawn from the regression model are only valid if the R^2 is indeed close to 1, i.e. the regression model is indeed a fair approximation. Commonly, a value above 0.8 is considered acceptable. Furthermore, any statements about the *SRC*s are made under the assumption that the input parameters are uncorrelated.

5.3 Results

We use the so-called Kaya identity as a framework for discussion of our results. The Kaya is presented below:

$$CO_2emis = Pop * \frac{GDP}{Pop} * \frac{EnergyCons}{GDP} * \frac{CO_2emis}{EnergyCons} \tag{5.3}$$

where CO_2emis stands for emissions of CO_2, *Pop* for population size , *GDP* for economic output, and *EnergyCons* for primary energy consumption. The factor *EnergyCons/GDP* (energy intensity) is a function of energy efficiency improvement and changes in the structure of the economy. The factor $CO_2emis/EnergyCons$ (carbon factor) is a function of the mix of primary energy carriers. While section 5.3.2 focuses on developments in energy intensity and in the carbon factor, section 5.3.3 looks into changes in the mix of primary energy carriers.

Table 5.2 summarizes the information found on the standardized regression coefficient (SRC), which shows the relationship between the input variables and the main output variables discussed here. The table shows the average value over the 2000-2100 period of SRC. Results of Table 5.2 are included in the discussion of the results further on in this chapter .

5.3.1 Trends in CO_2 emissions

The CO_2 emissions calculated by the TIMER model on the basis of these scenarios covers a broad interval (4 to 40 GtC in 2100) (Figure 5.5). The emission trajectories are not surprising: for each scenario the median values follow a pattern consistent with the marker IPCC scenarios. In the case of A1, rapid economic growth results in a sharp increase in emissions in the first half of the century, but emissions level off after 2050, mainly as a result of a stabilizing population. Under A2, emissions grow only slightly in the first decades (as a result of slow economic growth), but continue to grow in the second half of the century, driven by further population growth and an increasing share of coal use (see further on). The B2 scenario shows an intermediate pattern throughout the century, while the B1 scenario follows a pathway that clearly differentiates from other scenarios, peaking already around 2050. Here, the assumed (normative) "pro-active" assumption with respect to fuel choice and the fast technology change lead to very different results than other scenarios after 2050.

Of importance here are not so much the median values, but the formalized uncertainty ranges. Figure 5.5 shows a relatively strong overlap between the 95% interval ranges of the A1, B2 and A2 storylines, and of B1 up to 2040. Before 2050, the A1 scenarios full range lies above the range of other scenarios as a result of high economic growth assumptions, but results are more widespread in the second half of the century, overlapping almost completely with the B2 range (around 15-25 GtC).

Table 5. 2 Contribution of input variables to the uncertainty in selected output variables (average SRC in the 2000-2100 period)

Section	5.3.1		5.3.2				5.3.3											
Output parameters Input parameters	CO$_2$		En/GDP		CO$_2$/En		Coal		Oil		Natural gas		Modern bio-energy		Nuclear power		Renew. energy	
Driving forces																		
Population	0.29	0.26	0.01	0.01	0.04	0.11	0.19	0.16	0.18	0.22	0.17	0.22	0.11	0.16	0.2	0.18	0.19	0.23
	0.81	0.37	0.06	0.04	0.22	0.05	0.66	0.3	0.65	0.25	0.55	0.2	0.32	0.16	0.62	0.28	0.41	0.19
GDP	0.58	0.63	0.74	0.66	0.11	0.14	0.19	0.21	0.4	0.48	0.2	0.26	0.16	0.14	0.29	0.31	0.15	0.13
	0.5	0.69	0.59	0.66	0.21	0.2	0.34	0.35	0.43	0.45	0.28	0.25	0.19	0.2	0.37	0.49	0.23	0.19
Size of industry sector	0.07	0.07	0.1	0.11	0.02	0.02	0.04	0.03	0.05	0.08	0.03	0.04	0.03	0.03	0.02	0.02	0.03	0.04
	0.05	0.07	0.13	0.11	0.01	0.01	0.05	0.05	0.03	0.05	0.02	0.03	0.03	0.03	0.03	0.03	0.02	0.03
Energy demand factors																		
AEEI	0.53	0.4	0.57	0.55	0.14	0.16	0.34	0.27	0.19	0.17	0.29	0.3	0.23	0.22	0.37	0.28	0.25	0.27
	0.21	0.41	0.52	0.59	0.18	0.16	0.21	0.36	0.14	0.16	0.16	0.21	0.11	0.21	0.2	0.36	0.09	0.16
Pay-back time	0.07	0.07	0.09	0.11	0.01	0.02	0.03	0.03	0.06	0.06	0.04	0.05	0.02	0.04	0.04	0.03	0.04	0.05
	0.04	0.06	0.12	0.1	0.01	0.01	0.03	0.04	0.06	0.05	0.03	0.03	0.03	0.03	0.03	0.04	0.03	0.03
Structural change	0.21	0.29	0.24	0.39	0.05	0.09	0.11	0.15	0.09	0.13	0.11	0.18	0.09	0.15	0.13	0.16	0.11	0.18
	0.21	0.29	0.53	0.42	0.15	0.09	0.18	0.2	0.17	0.14	0.15	0.14	0.11	0.14	0.18	0.22	0.11	0.13
Technology dev. rates																		
Fossil fuels	0.02	0.06	0.03	0.03	0.05	0.1	0.28	0.2	0.18	0.13	0.35	0.26	0.3	0.22	0.2	0.2	0.11	0.09
	0	0.01	0.03	0.03	0.08	0.11	0.12	0.19	0.12	0.16	0.21	0.26	0.18	0.25	0.12	0.14	0.05	0.06
Renewables (power)	0.09	0.13	0.03	0.05	0.19	0.2	0.12	0.19	0.02	0.02	0.06	0.08	0.05	0.03	0.25	0.42	0.74	0.72
	0.04	0.11	0.04	0.05	0.24	0.29	0.08	0.17	0.02	0.02	0.04	0.06	0.03	0.03	0.15	0.16	0.73	0.83
Nuclear power	0.03	0	0.01	0	0.07	0.01	0.04	0.01	0.01	0.01	0.02	0.01	0.03	0.01	0.38	0.18	0.02	0.01
	0.01	0.01	0.03	0.01	0.14	0.03	0.04	0.02	0.01	0.01	0.02	0	0.04	0.02	0.26	0.29	0.03	0.01
Bio-energy	0.04	0.08	0.01	0.01	0.17	0.17	0.06	0.02	0.04	0.14	0.05	0.08	0.27	0.28	0.01	0.02	0.02	0.01
	0.02	0.03	0.01	0.01	0.14	0.16	0.01	0.04	0.08	0.08	0.02	0.05	0.37	0.26	0.01	0.02	0.01	0.01
Energy demand	0.11	0.1	0.13	0.14	0.02	0.03	0.06	0.05	0.07	0.07	0.06	0.07	0.05	0.07	0.08	0.07	0.06	0.08
	0.05	0.08	0.13	0.13	0.02	0.02	0.04	0.06	0.06	0.06	0.04	0.04	0.03	0.05	0.05	0.07	0.03	0.04
Hydrogen technologies	0.01	0.01	0	0	0.02	0.01	0.03	0.01	0.03	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0
	0	0	0	0	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0	0
Thermal power plants	0.03	0.03	0.03	0.03	0.02	0.03	0.05	0.05	0.01	0.01	0.02	0.01	0.02	0.01	0.04	0.05	0.03	0.02
	0.02	0.03	0.04	0.03	0.03	0.03	0.03	0.05	0.01	0.01	0.01	0.02	0.01	0.01	0.04	0.05	0.02	0.02
Resources																		
Oil resources	0.09	0.11	0.04	0.03	0.19	0.19	0.13	0.1	0.6	0.49	0.25	0.21	0.19	0.19	0.06	0.08	0.03	0.04
	0.03	0.06	0.04	0.03	0.12	0.2	0.08	0.1	0.37	0.52	0.2	0.25	0.2	0.2	0.03	0.05	0.02	0.03
Gas resources	0.04	0.02	0.01	0.01	0.14	0.04	0.25	0.21	0.14	0.11	0.46	0.41	0.26	0.19	0.21	0.2	0.15	0.12
	0.05	0.05	0.02	0.01	0.25	0.2	0.17	0.22	0.08	0.17	0.44	0.48	0.15	0.21	0.16	0.14	0.11	0.1
Coal Resources	0.01	0	0	0	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0	0	0
	0	0.01	0.01	0	0.07	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.03	0.03	0.03	0.01	0.02	0.01
Nuclear resources	0	0	0	0	0.01	0.01	0	0	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01
	0	0	0	0	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.02	0.01
Wind resource	0.03	0.03	0.01	0.01	0.06	0.04	0.03	0.05	0.02	0.01	0.01	0.01	0.01	0.01	0.05	0.07	0.21	0.18
	0.01	0.02	0.01	0.01	0.04	0.05	0.01	0.03	0.01	0.02	0.01	0.01	0.01	0.01	0.02	0.03	0.1	0.14
PV resource	0	0	0	0	0.01	0	0	0	0	0	0	0.01	0.01	0	0.01	0.01	0.01	0.01
	0	0	0	0	0	0.01	0	0	0	0.01	0	0	0.01	0	0.01	0.01	0.01	0.01
Residues resource	0.01	0.01	0	0	0.05	0.04	0.02	0.01	0.01	0.01	0.01	0.02	0.14	0.11	0.01	0.02	0.01	0.01
	0.01	0.01	0	0	0.08	0.06	0.01	0.02	0	0.01	0.01	0.01	0.21	0.14	0.02	0.01	0.01	0.01
Biomass resource	0.02	0.04	0.01	0.01	0.08	0.16	0.03	0.03	0.01	0.07	0.03	0.08	0.11	0.23	0.01	0.03	0.01	0.02
	0.01	0.01	0	0.01	0.08	0.04	0	0.01	0.03	0.01	0.01	0.02	0.16	0.06	0	0.01	0.01	0.01
Other																		
Fuel preferences	0.29	0.35	0.07	0.08	0.71	0.68	0.59	0.71	0.04	0.12	0.24	0.34	0.34	0.36	0.29	0.43	0.16	0.18
	0.12	0.21	0.08	0.07	0.56	0.59	0.3	0.45	0.03	0.05	0.17	0.2	0.21	0.34	0.24	0.27	0.12	0.14
Credit factor for renewables	0.01	0.01	0	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.06	0.08
	0	0.01	0	0.01	0.01	0.02	0.01	0.01	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.05
Taxes	0.02	0.05	0.03	0.05	0.03	0.05	0.02	0.01	0.02	0.07	0.03	0.02	0.02	0.06	0.02	0.01	0.03	0.03
	0.01	0.02	0.04	0.03	0.01	0.02	0.01	0.01	0.02	0.01	0.01	0.01	0.02	0.03	0.02	0.02	0.02	0.02
ST price uncertainty	0.03	0.02	0.04	0.04	0.13	0.1	0.14	0.14	0.03	0.04	0.16	0.17	0.19	0.17	0.14	0.14	0.11	0.09
	0.03	0.05	0.04	0.04	0.24	0.22	0.21	0.22	0.06	0.07	0.2	0.27	0.22	0.22	0.15	0.16	0.12	0.12
Trade	0.02	0.02	0.01	0.01	0.07	0.05	0.07	0.07	0.02	0.01	0.06	0.06	0.07	0.05	0.08	0.1	0.07	0.04
	0	0.03	0.02	0.01	0.08	0.09	0.09	0.07	0.07	0.04	0.08	0.11	0.14	0.07	0.12	0.08	0.08	0.05

Colour coding indicates the level of contribution (categories are SRC > 0.5, SRC 0.25-0.5, SRC 0.05-0.25 and SRC > 0.05).

Note: Every possible relationship is indicated separately for the A1, A2,and B1 and B2 scenarios (left upper corner, left lower corner, right upper corner, right lower corner). See also Figure 2 for the position of different variables.

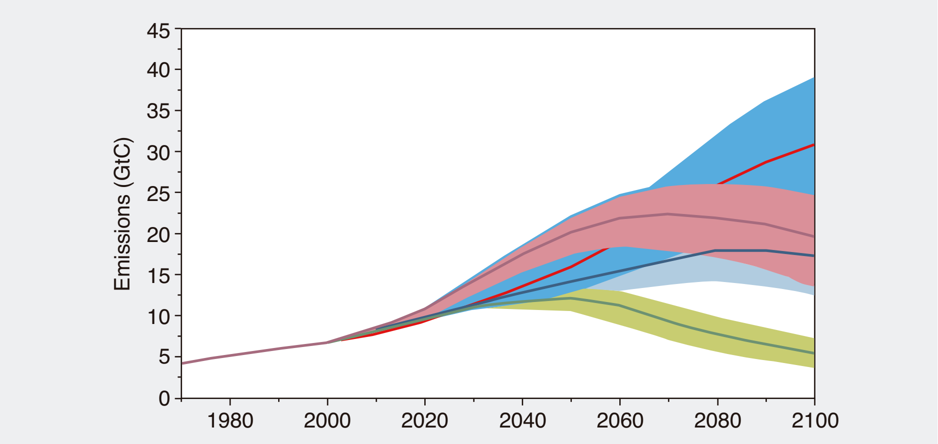

Figure 5.5 CO_2 emission as a function of time.

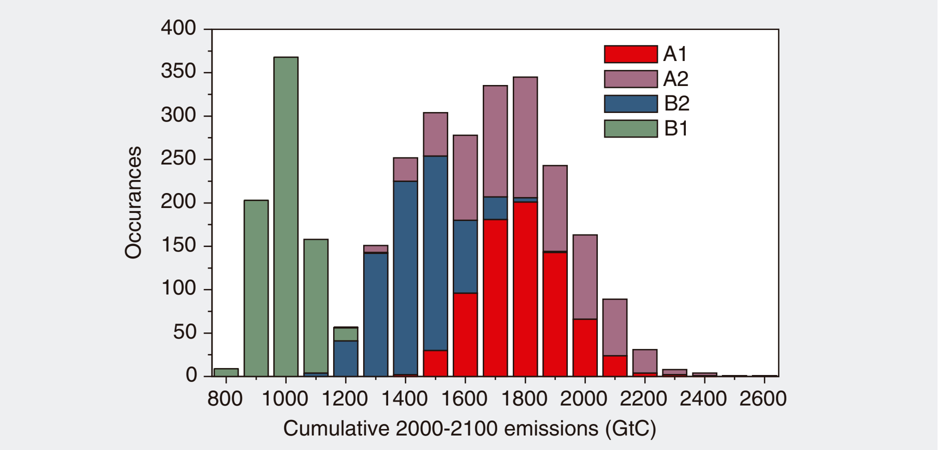

Figure 5.6 Frequency distribution of cumulative emissions 2000-2100.

The 2000-2100 cumulative emissions (Figure 5.6) range from an annual average of 800-1200 GtC for B1 to 1200-2500 GtC for the other scenarios. The “medium-assumption” scenario B2 range overlaps with the low-end range of “high growth” A1 and “fragmentation scenario” A2. The A2 shows the widest range of all three scenarios, extending both on the lower and upper sides beyond the A1 range. The peaks in the pdfs for the A1, A2 and B2 scenarios are in close proximity to each other, with an average annual value of 1500-2000 GtC.

Table 5.2 shows that the most important determinants of global carbon emissions are the input factors that determine energy demand: income, population, efficiency improvement and structural change. Other factors that play a role are uncertainty in fuel preferences, technology improvement rates for renewables and energy demand and oil resources. In fact, the results indicate that cumulated carbon emission can almost completely be described as a linear combination of these input variables, although at a specific moment in time and for different storylines other factors are important. For instance, population is relatively important in A2, autonomous efficiency improvement in A1 and fuel preferences in A1 and B1. These observations are consistent with the original storyline – and confirm added value of the conditional approach.

5.3.2 Energy intensity and the carbon factor

The trajectories for energy intensity and the carbon factor are shown in Figure 5.7. For energy intensity, all scenarios show a distinct improvement (consistent with the historical trend): most progress occurs in B1 and the least improvement in A2. The uncertainty range around the development path of B1, A1 and B2 partly overlap. The development pattern occurring in the A2 scenario is clearly distinct (slow), and its range has no overlap with the other scenarios (as a result of the relatively slow development of GDP and unfavorable technology assumptions). The uncertainties determining the energy intensity improvement (see Table 5.2) are GDP, autonomous energy efficiency improvement, structural change (both between and within sectors), the oil resource and fuel preferences. Short-term uncertainty in energy prices also plays a role (not shown). The influence of the first three factors can be readily understood from assumed model relationships (GDP drives AEEI and structural change), while other factors operate via price-induced efficiency improvements.

A very wide range of results is found for development of the carbon factor (CO_2 emissions per unit of energy) strongly related to the storylines. In contrast to energy intensity, the carbon factor has been nearly constant over the last 30 years (indicating a relatively constant energy mix). This trend is continued in the full range of “medium” B2 scenarios – although by the end of the century, depletion of fossil fuels results in a distinct drop. The A2 range follows a similar trajectory in the first 50 years, followed

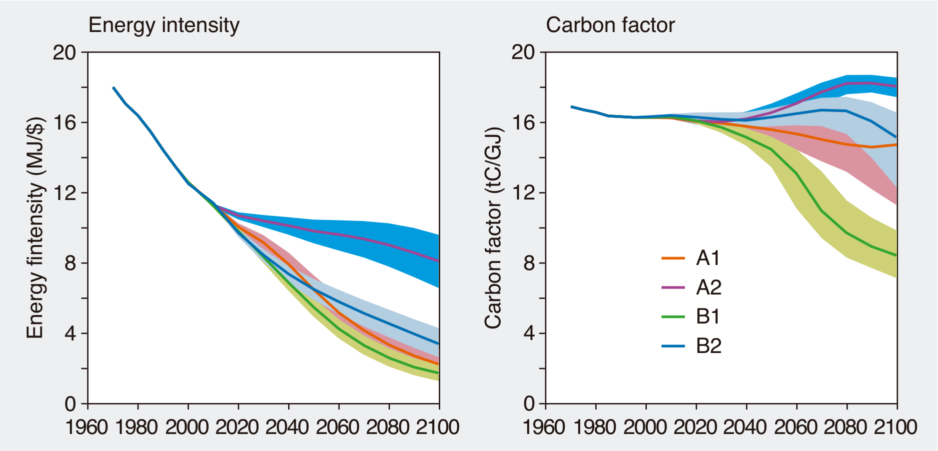

Figure 5.7 Development of the Kaya indicators.

by an increase in carbon factor as a result of a move towards coal (see further). The A1 scenario range also originally follows a trajectory similar to the B2 scenario, with some decrease due to optimistic technology assumptions (important for the penetration of non-fossil-based technologies).

Finally, the carbon factor for B1 rapidly declines – driven by the focus on renewable resources. The uncertainty ranges are larger for B2 and A1 than in the other two scenarios. This can be understood on the basis that the storyline for these two scenarios is less binding for fuel choice (B1 focuses on renewable sources, while A2 is forced into coal use due to trade restrictions). In addition to the factors that impact energy demand, the uncertainties in fuel preferences and several resource and technology parameters contribute to the ranges found for the carbon factor. Again, the contribution of the different factors depends on the storyline. Uncertainty in GDP growth is relatively important for the uncertainty in energy intensity in the A1 scenario; while the uncertainty in structural change is relatively important in B1 and B2. For the carbon factor uncertainty, population and gas resources stand out in A2 (both influencing depletion dynamics in this scenario) and technology development for renewables in B1.

5.3.3 Fuel mix

The use of fossil fuels obviously directly determines the emissions associated with each scenario. Figure 5.8 shows the global consumption of coal, oil, natural gas and renewables in each of the scenarios. As can be seen in Figure 5.2, these fuels are substitutes. This means that given energy demand, low consumption levels of some fuels lead to higher consumption levels of others. Three factors play a major role in substitution: fuel preferences, technology change and depletion.

The availability of extractable fossil fuel, in particular oil, makes resources a current subject of debate (Witze, 2007). Some believe that the world has already reached a maximum rate at which oil can physically be produced. As half the ultimately extractable oil has been depleted, further depletion will force world oil consumption to decline (this vision has been brought forward by the so-called proponents of the peak-oil hypothesis). Others, however, claim that there will not be real limits on oil production for the next 30 years. Here, we have based the uncertainty ranges for conventional resources on the probabilistic statements of USGS (as summarized in TNO, 2006). On the low side, the USGS estimates coincide reasonably with those of peak-oil proponents (Laherre and Cambell, 1999; Deffeyes, 2006). On the high side, the USGS estimates are consistent with claims that there will be abundant oil resources available in the next decades (Witze, 2007).

A crucial uncertainty factor in energy futures is “whom to trust”. For unconventional fossil resources the situation is even more complicated as probabilistic estimates of resource availability have not been established and estimates vary from hardly any extractable reserves to nearly unlimited supplies. In this study, we vary unconventional

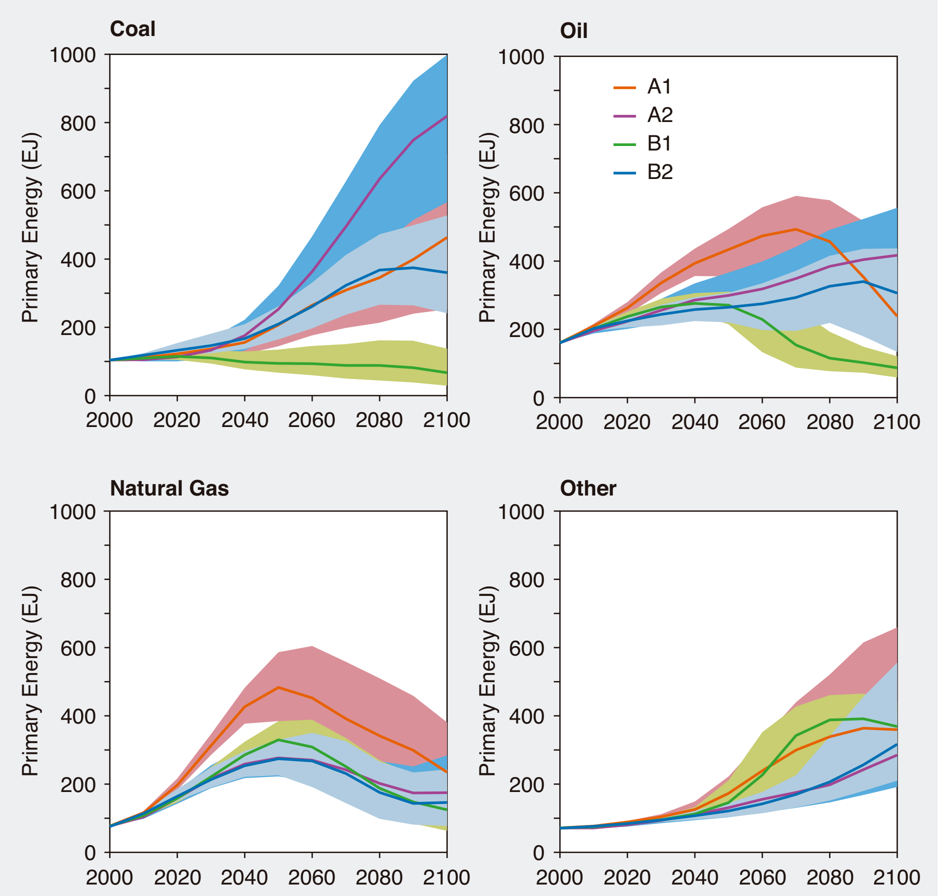

Figure 5.8 Development of global primary energy consumption (coal, oil, natural gas and other fuels).

fossil fuel estimates over a wide range, but based on the large estimates of these resources, their availability continues to dominate supply as indicated in Figure 5.9[iii].

The results in our calculations show that for oil a clear peak in consumption levels occurs in about half of the scenarios. However, such a peak occurs in different periods, at different levels and for different reasons. In fact, even for high resource estimates (in each of the storylines) oil use is likely to peak as a result of saturating energy demand (driven, for example, by a stabilizing world population) in combination with slowly rising prices. This results in the high and median pathways that are depicted for the various scenarios. Low-resource assumptions in combination with competitive alterna-

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[iii] In this chapter, we applied a factor 2 variation, upwards and downwards, in unconventional resources. This range, however, is not wide enough to fully capture the very low reserve estimates of oil-peak proponents, nor does it capture a deliberate choice to refrain from developing these resources for environmental reasons.

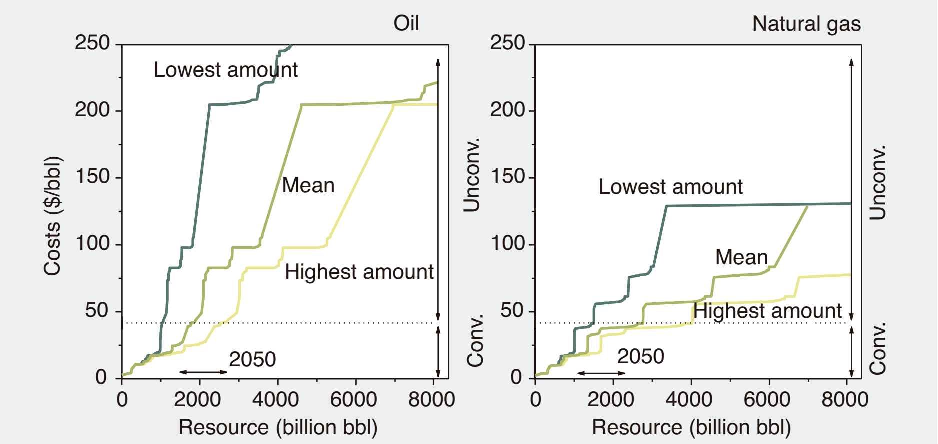

Figure 5.9 Oil and gas long-term oil supply-cost curve (no technology change included). The supply-cost curves show the two extreme assumptions (high and low) and the mean values. The figure indicates both convention and unconventional resources. The vertical arrow indicates 2050 cumulative consumption levels in the scenarios.

tives show a peak in oil use before 2040. In the calculations here, the expectations of the most extreme proponent of the peak-oil theory (an oil peak before 2010) cannot be reproduced given: 1) assumed inertia, 2) availability of large unconventional resources and 3) the fact that no explicit model relationship exists between the extraction rate and the degree of depletion (this relationship forms part of the peak-oil hypothesis). Table 5.2 shows that the range of oil consumption pathways is determined by energy demand, the size of the oil resource and the technology factors for fossil fuel production. In addition, also the assumed potential of oil's main competitor, bio-energy plays a role (both resource size and technology development).

Figure 5.9 compares the long-term supply-cost curves under the low, medium and high resource estimates. Sampling is done in between these three extremes. For the complete simulation, depletion occurs along these curves. The curve only changes by moving to the left along the x-axis as a result of technology development. In the figure, resource availability is compared to 2050 and 2100 cumulative consumption levels. As shown, under the medium assumptions, conventional oil is more-or-less depleted around 2050. However, the large amounts of unconventional resources are still available for exploitation. If supply of conventional oil is only 1000 billion barrels, all resources are likely to be depleted by 2050, along with the most accessible unconventional resources. At the other end of the range, high estimates (2500 billion barrels) imply that even by 2050, conventional resources have only been exploited by about two-thirds. Given these trends, 2100 cumulative consumption levels vary from 3000-5000 billion bbls, in which the majority of consumption comprises non-conventional resources under each set of assumptions. Clearly, such scenarios imply a transition to unconventional oil resources, something that deserves further attention, given the uncertainty in production costs, the associated impacts on the environment, but also the gross greenhouse gas emissions.

Uncertainty in natural gas use is determined (Table 5.2), apart from demand factors, by gas resources, short-term fuel price uncertainty, technology development for fossil fuels, oil resources (as substitute) and fuel preferences. Figure 5.9 shows that at similar cost levels, more natural gas than oil is available. Correspondingly, natural gas use grows more rapidly than oil use. It should be noted that the TIMER model does not simulate infrastructure. In reality, infrastructure investment could be an important constraint to rapid natural gas introduction. Natural gas use continues to grow up to 2040-2060, after which gas use peaks in all scenarios. The main reason is that resource depletion results in higher natural gas prices and, given the flexibility of fuel choice in the power sector, leads to relatively easy substitution away from natural gas.

For coal use, a distinct difference is found between the B1 scenario and the other three scenarios (Figure 5.8). The assumed preferences in B1 for clean fuels leads to declining coal production levels. In all other scenarios, coal consumption in the absence of climate policy is likely to increase. Coal use in 2100 ranges from 30 EJ to a staggering 1000 EJ. On the high side, the A2 scenario dominates the overall range. The uncertainty in coal use is determined by similar factors to those for natural gas use, although here too, the uncertainty in renewables in the power sector plays an important role.

Finally, the trajectories for other energy carriers (renewables and nuclear) show a rapid expansion in all cases. The highest values are found for the B1 and A1 scenario (in B1, rapid technology development and a preference for clean fuels are major drivers; in A1, a major driver is rapid technology development in combination with high energy demand). As the A1 range is wider than the B1 range, the highest values are, in fact, found under the A1 storyline. The lowest values are found under the A2 and B2 scenarios, with comparable medium values and ranges.

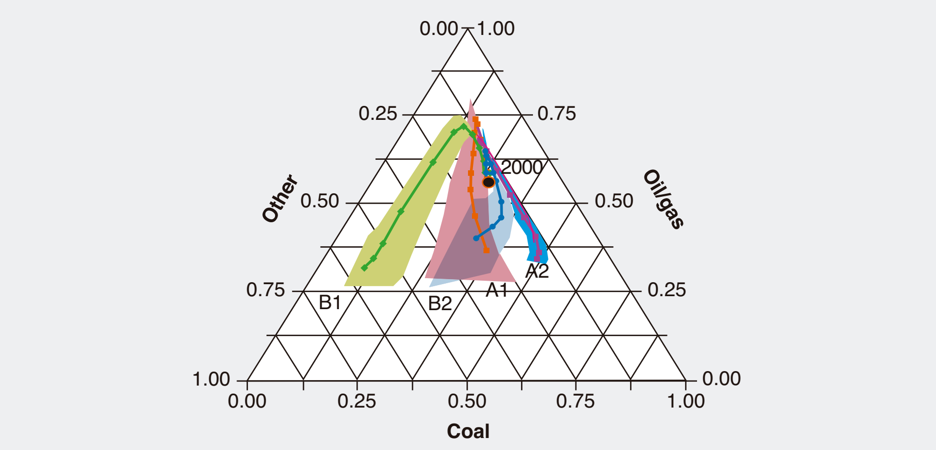

Figure 5.10 Primary energy expressed in the contribution of 3 main categories: coal, oil/gas and other (bio-energy and non fossil-based electric power). The corners of the triangle indicate 100% other (left-bottom), 100% coal (right-bottom) and 100% oil/gas (top).

Table 5.3 Fossil fuel prices

	Oil prices			Gas prices			Coal prices		
	2000	2050	2100	2000	2050	2100	2000	2050	2100
	$/GJ	$/GJ	$/GJ	$/GJ	$/GJ	$/GJ	$/GJ	$/GJ	$/GJ
A1	3.7	6.6-9	8.7-11.3	2.2	5.4-8.0	7.4-9.9	1.1	1.4-1.5	1.9-2.3
A2	3.7	7.4-10.0	10.6-14.9	2.2	4.7-5.9	8.5-10.8	1.1	1.3-1.4	2.3-3.2
B1	3.7	6.1-8.7	7.7-10.0	2.2	4.3-6.3	7.1-9.2	1.1	1.3-1.4	1.6-1.8
B2	3.7	5.9-8.6	8.3-10.8	2.2	4.2-6.1	7.7-9.9	1.1	1.4-1.5	2.0-2.3

The trends as discussed here are also depicted in Figure 5.10, which shows that originally all scenarios move in the direction of increasing shares of oil/gas. (It should be noted that this figure shows shares in total consumption; scenarios have very different overall consumption levels.) However, after a few decades the share of oil/gas in all scenarios decreases as a result of increasing prices (thus reducing competitiveness with other forms of energy). In the B1 scenario, the response is to go in the direction of an energy system consisting of primarily renewable energy (consistent with the storyline assumption of both rapid technology development and preference for clear energy sources). There is a clear uncertainty associated with the B1 scenario – but still the scenario results seem to be distinct from those of the other scenarios. The A2 scenario responds differently to increasing oil/gas prices by moving in the direction of coal. The uncertainty range surrounding this scenario is smaller.

Underlying the fuel choice in the model are the trend energy prices (in TIMER closely related to production costs). As indicated in Figure 5.2, production costs are a function of depletion and learning-by-doing; both are driven by cumulative production. These costs are shown for fossil fuels in Table 5.3. Interestingly, the differences between the scenarios are rather small – given the feedbacks in the model: scenarios with relatively abundant resources or rapid technology development lead to high exploitation rates and thus, indirectly, to higher prices. For oil, the scenarios indicate a 2-3.5-fold increase in oil prices across the century. For gas, an even higher increase is found. In contrast, coal prices increase only modestly (certainly in absolute numbers).

In terms of the contribution of uncertainty in input factors to the uncertainty in output factors, again the influence of storyline is clearly noted. Population is relatively more important in A2 for most output factors, while fuel preferences play a more important role in B1.

5.4 Discussion and comparison to other approaches

In the introduction, we have already indicated that uncertainty can be classified in different ways (a-d, 1-3). Obviously, the source or type of uncertainty has important consequences for the way it needs to be managed in scenarios. Different methods were applied in the literature to deal with uncertainty. In addition to the already discussed methods (alternative scenarios and full probabilistic approach), other methods from the literature have been applied to deal with uncertainty in scenarios: model comparison (e.g. 2006) and the NUSAP method (van der Sluijs et al., 2002). In our discussion here, we include the former, considering that quantitatively comparable results are available. For the NUSAP method, where more qualitative assessments of uncertainty are also added, readers are referred to van der Sluijs et al.(2002). Each of the uncertainty methods relate in a different way to the sources of errors indicated above. With respect to sources of uncertainty, *formal probability analysis,* in particular, addresses ontic uncertainty and statistical representations of epistemic uncertainty (a-b1) by expressing uncertainty ranges in pdf of input variables. In terms of scale, the uncertainty addressed by this method occurs mostly at the level of parameters (1). The *alternative scenario method*, in contrast, addresses epistemic or human reflexive uncertainty (b2, c, d), in particular, by varying values of input parameters across the scenarios. In terms of scale, the scenario method focuses on the level of parameters (1), but by adding storylines outside the model on more conceptual issues (3). *Model comparison* as a method to deal with uncertainty is particularly relevant for uncertainty originating from value pluralism and ignorance on model relationships (c, 2). By comparing different models some model-based biases can be made explicit (although collective bias will not be detected).

Some earlier scenario studies used the methods discussed above (or combinations of them) as shown in Figure 5.11. The studies of Webster et al. (2002), Sweeney et al (2006) and Kouvaritakis (2005) can be interpreted as applications of the fully probabilistic approach. The study of Richels et al. (2004) is to some degree an application of a more conditional probabilistic approach – as their results are made conditional to one major unknown, technology change (two sets of scenarios, one with optimistic technology change assumptions and one with pessimistic assumptions). The EMF-21 modeling study (Weyant et al., 2006) is an example of an application of the model

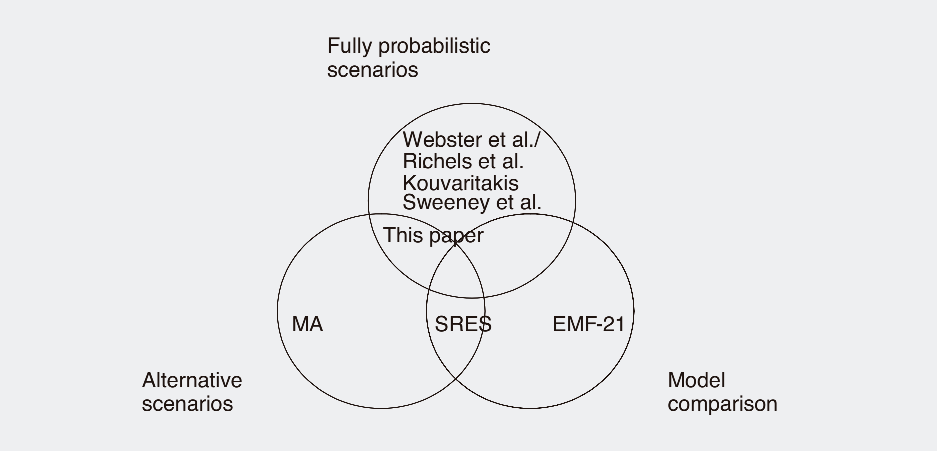

Figure 5.11 Overview of earlier studies in comparison to the different methods for dealing with uncertainty in scenario analysis.

comparison method to gain insight into uncertainty. The Millennium Assessment scenarios (MA) provide an example of the pure alternative scenario approach as based on a diverging storyline implemented by only one model for each topic these scenarios looked at (Carpenter and Pingali, 2006). The SRES report (Nakicenovic and Swart, 2000) combined two approaches: development of 4/6 different storylines, but also comparison of the results of six different models.

5.4.1 Comparison with results of other studies

Figure 5.12 presents the outcomes of the studies indicated above for the cumulative and annual CO_2 emissions in 2050 and 2100. The results, first of all, indicate that uncertainty increases in time in every single study. The ranges for each of the SRES scenarios in the original SRES report seem to be somewhat wider than the range developed here, using the conditional probabilistic approach with a single model (particularly for B1 and A1). There are two main explanations for this. First of all, the SRES range originates from the use of different models and hence also reflects model differences. For the A2 scenario, for instance, the high end of the range in SRES is represented by the ASF model that always shows relatively high coal consumption levels relative to other models, while the MARIA model shows high penetration rates of nuclear power resulting in relatively low emission levels (van der Sluijs et al., 2002). A second reason for the wider SRES range in the full range results of the A1 scenario is the explicit attention to the role of technology (A1T versus A1FI) (Nakicenovic and Swart, 2000). Although the sampling here allows for wide ranges of technology development rates and technology preferences, the resulting range still does not capture the one from the more explicit storyline approach taken in SRES.

On average, the scenarios of this study show slightly higher emissions than the corresponding IPCC-SRES scenarios. The reason for this is not obvious: new insights into population and income development, into fossil fuel resources and into 1995-2005 emission trajectories and model bias may all play a role. Only for B2, it is clear that some of the original SRES models have paid more attention to the “environmental orientation” of the original storyline, while here B2 has been purely interpreted as a “medium/dynamics as usual” scenario. A model comparison study would be needed to gain more insight into the reason for higher CO_2 emissions in this study vis-à-vis SRES for the other scenarios.

Comparing the results of this study to the fully probabilistic studies shows that the latter give both broader (Webster et al., 2002) and smaller range of outcomes (Richels et al., 2004; Sweeney et al., 2006) compared to the overall range of this study. The former is somewhat unexpected given the expectation that purely probability-based approaches may suffer from a bias towards one central set of assumptions. It should be noted, however, that the EPPA model used by Webster (a general equilibrium economic model) seems to be less constrained by inertia than TIMER: the lowest trajectories of Webster et al. (2002) show very low emissions in the first part of the century as a direct model response to certain assumptions. Webster et al. (2002) concluded earlier that their results were reasonably consistent with the IPCC SRES range (which can be seen in Figure 5.12), but that SRES was somewhat biased to the lower end of the range (which is only the case for 2100 annual emissions). More recently, Webster and Cho (2006) concluded that the assumption of perfect correlation in economic growth rates among regions is also causing wider ranges in their analysis compared to a case where historically observed levels of correlation were accounted for.

The combination of the two ranges identified by Richels et al. (2004) is considerably lower. It roughly coincides with the range found here for the central B2 storyline. It should be noted that Richels et al. (2004) only vary a limited set of parameters in their analysis (population, GDP and technology assumptions) resulting in a narrower

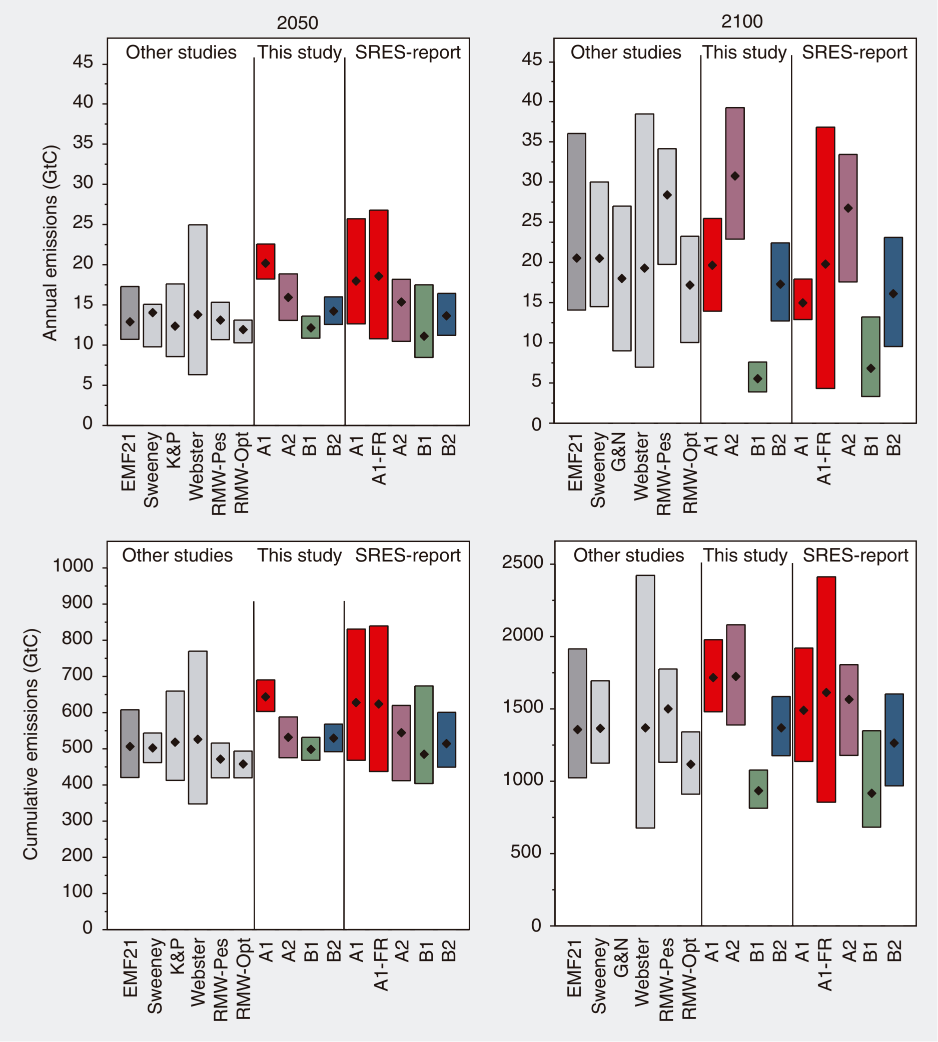

Figure 5.12 Cumulative emissions in the 2000-2100 period according to different studies. addressing uncertainty.

range. Comparison with the Sweeney et al. (2006) range leads to comparable outcomes – while the range of the modeling effort by Kouvaritakis (2005) (for 2050 only) shows the results of scenarios in this study to overlap well with their unconditional range.

Finally, we compare our results to the outcome of the EMF-21 study. The modelers participating in that study were all asked to contribute one single, modeler's preference baseline. In most cases, these baselines can be interpreted as the central-estimate scenarios of different modelers/models. The range across the EMF-21 outcomes coincides reasonably with the B2 range of this study, with some overlap of the A1 range as well. The range is considerably narrower than the whole across all four scenarios of this study: neither the B1, nor the A2 range is represented, indicating that most modelers would not regard them as central baselines[iv].

The comparison of the studies as a whole provides some insight into the importance of different forms of uncertainty:

1 Uncertainty analysis within one particular model, done here using the conditional probability approach but also the probability approach of Webster et al. (2002) may result in a similar range of outcomes, as generated by a multitude of models (such as EMF-21).
2 Fully probabilistic uncertainty analysis may result in ranges that are broader than those derived by storyline-based methods (Webster et al., 2002), but also result in more narrow ranges (2004). The differences between these studies show the role of subjective choices.
3 The uncertainty ranges generated by TIMER around the different storylines compare well to the ranges that are obtained by the other uncertainty studies.

An intriguing question remaining is what can be said about the probability of the development of the 2000-2100 carbon emissions, without making these conditional to different storylines (the focus on this indicator comes from its relevance for long-term climate change). Some observations can be made on the basis of Figure 5.12:

1 there is an overlap in the ranges of the A2, B2 and A1 scenarios in this study (between 1400-1600 GtC) despite the differences in storyline.
2 the fully probabilistic studies seem to show the strongest overlap in the 1100-1700 GtC range (with the highest probabilities around 1400 GtC).
3 the modeler's preference baselines of EMF-21 range from 1000-1800 GtC – with a central value of 1400 GtC.

Combined, these results seem to suggest that modelers appear to obtain a majority of their results within a much more confined range than the total uncertainty range across all the different storylines. The question, however, remains: is this caused by collectively biased expectations with respect to the future – or does "the balance of

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[iv] The EMF-21 study covers mainly economic models from the USA, Europe and Japan, possibly providing some bias in expectations.

evidence" suggest an indication of likely emission levels, despite fundamental uncertainties? One should note that the full range of the B1 outcomes – and part of the A2 range – is outside the ranges suggested here.

The analysis here is constrained to baseline (no climate policy) scenarios. A similar analysis can be done for mitigation scenarios, 1) either to identify probabilistic outcomes of scenarios conditional on both storyline and stabilization target (compare Webster et al. (2003) for a comparable analysis in the fully probabilistic approach), 2) or to identify strategies robust under different storylines (Groves and Lempert, 2007).

5.4.2 Overall assessment of the different methods

Based on the results of the analysis, and the deliberations that were made earlier, Table 5.4 represents an attempt to summarize some of the strengths and weaknesses of the various approaches.

5.4.3. Implications of the suggestion that crucial model outcomes can be described by a small number of variables

The model results discussed in Section 5.4 also show that in most cases specific model outcomes can be described by a linear combination of only a few model inputs (Equation 5.1). For estimating the cumulative 21st century emissions, for instance, the outcomes indicate that only 10 model inputs at most (even less in some of the scenarios) are sufficient to reproduce the full range of model outcomes. Does this mean that the complete TIMER model can be replaced by a simplified representation? The answer is "no", for two reasons:

Table 5.4 Comparison of methods

Uncertainty method	Strengths and weaknesses	Type of uncertainties typically addressed
Full probabilistic analysis	- Formal methodology, but subjective - Very suitable for dealing with statistical uncertainty	a, b1, 1
Storyline-based alternative scenarios	- Subjective, but very flexible method - Very suitable for dealing with uncertainties originating from societal choice, value interpretation and uncertainty or ignorance in relationships	b2, b3, c, d, 1, 3
Model comparison	- Formal methodology - Suitable for comparing uncertainty in formalized relationships or for detecting model bias	b, 2
Conditional probabilistic method	- See probabilistic and storyline-based method	a, b, c, d, 1, 3
NUSAP	- Able to capture non-quantitative aspects of uncertainty	b, c, d, 1-3

1) the simplified model can only be derived on the basis of the more complex model, as no information is available beforehand on how different model dynamics work out;
2) models have several outputs and, as shown in Table 5.2, different factors contribute to different model outcomes.

However, the results may still be used as an indication of the priority that should be given to resolving uncertainty (if possible) for each model input parameter.

5.5 Conclusions

- ***Conditional probabilistic scenario analysis can be used as a way to introduce statistical methods of uncertainty analysis, while recognizing deep uncertainties.*** Uncertainties represent a crucial element of scenario analysis. Two main methods are often presented as options for uncertainty analysis: the scenario approach and the fully probabilistic approach. This chapter shows that it is possible to combine the two approaches (conditional probability analysis) in a way that allows formal analysis of those elements where meaningful probability estimates can be established, while still retaining the strong elements of a storyline approach to uncertainty. Storylines are a device for structured thinking about a future with deep uncertainty. They are also a means of making projections more useful to users. Assumptions regarding the reasoning behind the choice of driving forces, parameter values, and modeling approaches are made more explicit. The added value of the conditional probabilistic approach compared to a non-conditional approach can also be observed from the analysis of most relevant uncertainties. These are shown to be a function of the storyline.

- ***The model calculations suggest that 21st century cumulative emissions range from around 800 to 2500 GtC in the absence of climate policy. The low end of the range originates in a different storyline than the high end of the range.*** The results indicate that CO_2 emissions from the energy system may develop in very different directions, with emissions ranging from 4-40 GtC in 2100 or in terms of cumulative 2000-2100 emissions, 800-2500 GtC. The reason for this wide range results partly from the fundamentally different way the 21st century society could develop. The range found in this study is consistent with the range found in the SRES scenario study (from which the storylines used here are derived), but also with the range found in the fully probabilistic study of Webster al. (2002). The smaller uncertainty ranges suggested by some other studies all coincide with the uncertainty range identified here for the so-called B2 world, based on a more-or-less business-as-usual type of storyline. As such, the conditional probabilistic approach can give one a sense of whether existing emissions scenarios are biased in a particular direction.

- ***Emissions for a clearly defined storyline could still include an uncertainty range of more than 40%.*** These ranges originate from stochastic uncertainty and existing ambiguity in each storyline. Important variables contributing to this uncertainty are uncertainty in the development of driving forces such as population and income, uncertainty in energy efficiency improvement, oil resources, fuel preferences and technology development of biofuels and renewables. There seems to be a dominance of “energy demand”-related factors as causes of uncertainty. However, one needs to realize that in TIMER (just as in most other energy-system models) the supply sector is described with considerably more detail than the demand sector, and as a result the effects of single parameter values are smaller.

- ***There is considerable overlap in the uncertainty ranges identified for the A2, A1 and B2 storylines. The results for B1 stand out.*** Especially, the interpretation of the B2 scenario as a “medium” pathway, and the A1 storyline, results in a clear overlap of outcome ranges for several parameters. The B1 storyline, a normative choice for sustainable development and away from fossil fuels, produces very different results.

- ***The storylines explored here are deficient in many ways – and are therefore not likely to come true.*** For instance, all scenarios here assume “no climate policy”. However, given the current focus on climate change, this assumption is highly unlikely. Moreover, the feedbacks of climate change to the drivers have not been considered. Similarly, the TIMER model also does not capture the possible feedbacks of the energy system on the economic drivers (e.g. of very high fossil fuels as a result of depletion). Finally, the scenarios are derived from caricature storylines that are continued over 100 years without surprises. Surprises, however, may occur, such as technology breakthroughs (fusion) or major wars. Furthermore, societies may shift from “one storyline to another”.

APPENDIX 5.1 STORYLINE ASSUMPTIONS AND ASSUMED PARAMETER RANGES

Table 5A.1 Main storyline assumptions underlying the SRES scenarios[v]

	A1			A2	B1	B2
Storyline	Globalization; liberalization;			Heterogeneous world; self-reliance; fragmentation	Globalization; orientation on social and environmental sustainability ;	Local solutions to sustainability ; regional emphasis
Population	Low			High	Low	Medium
Economic growth	Very high			Low in developing countries; medium in industrialized countries	High	Medium
Attitude towards environmental protection	Reactive			Reactive	Proactive	Proactive
Main goal for the energy system	Reliable, cheap energy for everybody			Security of energy supply	Energy services within sustainable limits	Combination of different goals
Primary energy use	Very high			High	Low	Medium
Technology development	Rapid			Slow	Rapid	Medium
Type of technology development	Balanced (A1B)	Primarily fossil fuels (A1FI)	Primarily non-fossil energy (A1T)	Balanced	Primarily energy efficiency and non-fossil energy	Balanced

Assumed ranges for driving forces

The main (exogenous) driving forces of energy demand in TIMER are GDP growth, economic structure (here represented by share of industry in GDP) and population growth.

1 GDP (Gross Domestic Product). In the model, energy demand for five sectors is driven by GDP or sectoral value added (see below).

2 Share of industry (% of GDP). Energy demand in the industry sector is driven by industry value-added, in the service sector by service value-added. As energy intensity is generally lower in the service sector than in the industry sector, a shift in sectoral composition of GDP will influences energy demand.

3 Population. Population drives energy demand in all sectors.

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[v] It should also be mentioned here that the idea that one particular logic, and its associated interpretations and values, prevails for the full 100-year period is rather unrealistic (De Vries 2006). The uncertainty resulting from a dynamic switching between the scenarios is not explicitly considered here.

We have analyzed the regional growth rates of four large global regions (as used in the IPCC SRES report) for economic growth in the 1890-2000 period (based on 10 year averages in the 1890-1970 period on the basis of HYDE data). Furthermore, we studied the five-year moving average for the 1970-2000 period, based on the World Bank Development Indicators). For the OECD region, a normal distribution was found – with an average per capita growth of 2.2% and a 95% range from 1.2-3%. The other three regions (Central Europe and the Former Soviet Union (REF), Asia (ASIA) and Africa–Latin America–Middle East region (ALM)) had much wider historical ranges with distinct temporal patterns. For Asia, growth rates were found mostly in a 0-1% range during the 1890-1970 period and a 4-6% range in the 1970-2000 period (after the “take-off” phase of some of Asia’s economies). A broad range was also found in the ALM region, but with almost an opposite temporal distribution.

Based on the historical distributions, we could propose regionally defined economic growth rates and their distributions for each region, depending on the four storylines - with the mean values roughly consistent with the IMAGE 2.3 implementation of the IPCC scenarios (see Table 5A.2). It should be noted that using the 5-10 year growth values as indicative for the uncertainty in long-term growth pattern, the resulting 100 year growth level for the highest (A1) and lowest (A2) storylines are considerable higher and lower, respectively, than the growth rates that have actually occurred in the past over such a long time period.

Table 5A.2 Description of sampling ranges for driving forces

	A1	A2	B1	B2	Rationale
GDP (% growth in constant$ in the 2000-2100 period)					
Default values	2.7	1.2	2.3	2.2	Here global values are shown. However, in reality we use regionally defined growth rates consistent with the IMAGE 2.3 implementation of the IPCC SRES scenarios.
Sample ranges	2.4-3.2	1.0-1.5	2.0-2.7	1.6-2.4	Regionally defined ranges based on the historically founded values.
Share industry (% of GDP in 2100)					
Default values (% of total GDP)	0.36	0.35	0.27	0.37	Based on the IMAGE 2.3 implementation of the SRES scenarios and underlying WorldScan calculations (IMAGE-team, 2001).
Sample ranges	0.32-0.40	0.31-0.39	0.24-0.31	0.33-0.41	0.04 used on the basis of current variation among OECD regions (15% range in total).
Population in 2050 and 2100 (billion)					
Default values	8.2/6.9	10.4/12.5	8.2/6.9	9.0/9.1	Both default values and ranges are based on O’Neill (2004).
Sample ranges	7.6-8.6/ 5.6-8.2	8.5-13.7 9.2-16.0	7.6-8.6/ 5.8-8.0	8.3-10 7.5-10.8	

For economic structure, the size of the industrial sector plays an important role as it is the most energy intensive sector. The central values (by region as a function of time) were set on the basis of the IMAGE implementation of the IPCC-SRES scenarios (IMAGE-team, 2001), in turn, based on the runs of Bollen (2004). Analysis shows the current variation among OECD regions for the relative size of the industry sector (compared to GDP) to be around 15%. On this basis a conditional sampling range of 8% (4% above and below the central value) was assumed.

Finally, for population O'Neill (2004) published a set of scenarios conditional to the SRES storylines. We took the 95% intervals from this publication, and sampled within these ranges, assuming normal distribution. The assumption of normal distribution is reasonably consistent with the distributions reported by O'Neill.

Assumed ranges for factors determining energy demand

In addition to the driving forces discussed above, several other factors determine energy demand: these include autonomous energy efficiency improvement (AEEI), price-induced efficiency improvement (PIEEI) and structural change (SC) within sectors.

1 AEEI captures forms of efficiency improvement not caused by price changes but general technology improvement. For example, the presence of more efficient boilers at the time an old boiler is replaced.
2 PIEEI: this factor describes the impact of increasing prices on energy efficiency.
3 SC: this factor describes the energy intensity development within sectors independent of efficiency improvement (e.g. transport modes).

In TIMER, AEEI is assumed to relate to GDP growth in a similar way as described by Richels (2004), although we also assume that this percentage declines over time as a result of (slowly) approaching thermodynamic limits. Interpreting the variation (unconditional range) applied by Webster et al. (2002) (0.25-1.5% annually for OECD countries) means that he samples mostly 25% in either direction relative to his economic growth rates. Given no other inputs on this parameter, we have assumed these numbers to form the basis of our ranges.

The contribution of price-induced energy efficiency improvement in TIMER depends mainly on the assumed pay-back time. We applied a variation of 15% to these values – based on the default assumptions made in each scenario and the requirement to keep the scenarios sufficiently distinct.

Finally, structural change by TIMER captures changes in the type of activities over time within each sector (e.g. shifts from heavy to light industry). The TIMER description assumes a long-term saturation of energy demand per sector (in terms of GJ per capita). In the scenarios, one factor is used to scale this saturation up/downward as a function of time based on the storyline of the scenario. This factor reflects the emphasis on energy-intensive services in the scenario and is used here for uncertainty analysis. To assess its potential range, we analyzed the differences in per capita energy consumption of the different representations of the SRES scenario per storyline (Nakicenovic

Table 5A.3 Description of sampling ranges for parameters determining energy demand

	A1	A2	B1	B2	Rationale
AEEI (as % of GDP per capita growth)					
Default values	0.28-0.44% of GDP per capita growth (depending on region and sector)				
Sample ranges	±25%	±25%	±25%	±25%	Based on the variation applied by Webster et al.
Accepted pay-back times (years)					
Default values	3.4	2.8	6	3.2	Industry sector; similar trends for other sectors
Sample ranges	±15%	±15%	±15%	±15%	Based on the assumed default values
Structural change (2100 multiplication on energy demand compared to standard TIMER setting)					
Default values	1.75	1.50	0.85	1.25	A1 is representative of a saturation of per capita energy use (at high income and temperate zones) of 20-30% above US levels; B1 is found 30% below US levels.
Sample ranges	±15%	±15%	±15%	±15%	The proposed range complies with the general rule assuming that the B1-A1 range is representative of the full uncertainty range. The range between differences per capita energy use of the same scenario as reported by different models in SRES report is also around 30-50%..

and Swart, 2000). Values of 30-50% variation among the central values were generally found for different model representations of the same storyline. Assuming this to a reasonable indication of the uncertainty range, we used a sampling range of 15% upwards and downwards.

Technology change

Technology is represented in TIMER both by learning curves (progress as a function of cumulative experience) and time-dependent exogenous inputs. We have clustered the technology variables into different groups: learning curves for 1) fossil fuel production, 2) renewables in the power sector, 3) nuclear power, 4) bio-energy and 5) energy demand, 6) hydrogen technologies and time-dependent assumptions for 7) thermal power plants. The learning curves are a function of the so-called *progress ratio*.

- Progress ratio: A measure of improvement for a doubling of experience, where a value of 0.8 indicates a 20% improvement for each doubling

Assessments of the historical pdf have been made for technology in general (Argotte and Epple, 1990) and energy technology in particular (McDonald and Schrattenholzer 2002). The results of these studies tend to reveal wide ranges – with most values found between 0.7 and 1.0. Progress ratios in TIMER are dependent on technology, time and scenario. Taking the conditional range to be half the unconditional uncertainty range (0.3), we have samples for each scenario with a value of 0.07 above and below

Table 5A.4 Description of sampling ranges for parameters determining technology progress

	A1	A2	B1	B2	Rationale
Progress ratios					
Default values	0.7-1.05	0.7-1.05	0.7-1.05	0.7-1.05	Range captures all values as function of time, technology and storyline
Sample ranges	±0.07	±0.07	±0.07	±0.07	This represents about 25% of the unconditional range in p-values found in the literature (Argotte and Epple, 1990; McDonald and Schrattenholzer 2002).
Efficiency of thermal power plants					
Sample ranges	±0.04	±0.04	±0.04	±0.04	Sampling based on the assumed variation across the differences scenarios

the default values. Sampling was done independently for the clusters of technologies mentioned above. For thermal power technologies, upward and downward sampling of 4% was applied on the basis of the variation across the different scenarios.

Resources

For fossil fuel resources, standard values in TIMER are based on those reported by TNO (2006) using the methodology of Rogner (Rogner, 1997). For each fossil fuel, Rogner provides different categories varying in production costs and probability of occurrence (each category assumed to have higher production costs than the previous). Together, these categories form a long-term supply-cost curve for oil, natural gas and coal. For conventional resources of oil and gas, the TNO numbers (categories1-4) are based on the USGS estimates for the reserves and resources, with a different likelihood of occurrence (costs estimates added by Rogner).

1. Resources of fossil fuels: Available amounts of oil, natural gas and coal per costs category.
2. Renewable resources: Maximum use by category of renewable energy; in TIMER the form of the supply cost curve is kept constant.

In our analysis, we assumed these estimates to be independent of the storyline and were able to assign probability values to each of these categories in such way that the total probability of these categories collectively again reflected the original USGS probability estimate for total conventional oil and gas resources. This results in a range of conventional oil resources of 7-17 ZJ. Interestingly, the lower end of this range equals estimates provided by the proponents of the “end-of-cheap-oil” hypothesis (Laherre and Cambell, 1999). In other words, in most of our probabilistic runs we included substantially higher resource estimates than the peak-oil proponents but our runs do not preclude their estimates.

For unconventional resources of oil and gas and for coal, probability ranges are much harder to derive as no concrete ranges were found in the literature. For unconventional gas resources, for instance, ranges provided in the literature seem to have more relevance for geology than for energy production. In contrast to conventional resources, the values provided by Rogner do not represent the upper range, but best-guess estimates. Therefore for unconventional oil, we assumed a rather arbitrary range of 50% around Rogner's estimates, while for gas, we assumed a range of 70% relative to Rogner's estimates. The higher number for natural gas comes from the fact that here unconventional resources represent mainly gas hydrates, an enormous source of potential energy but characterized by a huge uncertainty with respect to the potential use of natural gas. For coal, Rogner's estimates represent best-guess values for each category. We applied a sampling range, both upwards and downwards, of around 25%.

A wide range of estimates for potentials can also be found for renewables. De Vries et al. (2007) recently provided an estimate of storyline-based long-term costs supply-cost curves that have also been used as input for the IMAGE 2.3 scenarios. De Vries et al. also provide estimates of uncertainty by varying main input assumptions per scenario – and comparing the results for reported potential of different scenarios. Based on their results, ranges of 50%, 40% and 50% for wind, biomass and PV resources, respectively, have been established – while it is assumed that the form of the supply cost curve itself is retained.

Other

There are a number of other factors that were identified as meaningful factors for uncertainty analysis:

1 Fuel preferences: in the model an additional value is put on top of prices to reflect fuel preferences (in particular, with respect to coal prices to reflect its reduced preference based on convenience and environmental impacts).
2 Trade: In the model, the openness to international trade is modeled by putting an additional value on top of transport costs.
3 Capacity credit: The capacity value assigned to renewables is assumed to decline with increasing renewable penetration. The shape of this curve can be influenced by the credit factor.
4 Energy taxes: Taxes on top of energy prices as function of sector and region.
5 Short-term uncertainty in oil/gas prices: a factor added to the model to reflect factors influencing oil and gas prices outside the scope of the model. This factor ensures that the oil price is set at a level of 50-60$/bbl in 2005.

The fuel preference values were varied in the analysis by 50% for each scenario. Since no external information was available, the range was based on the variation in values in the historical calibration and across different scenarios.

The added value on transport costs, reflecting trade barriers, were varied by 50% in either direction in our probabilistic modeling. Again, the range is based on their values in the original scenarios.

Table 5A.5 Description of sampling ranges for parameters determining resources

	A1	A2	B1	B2	Rationale
Fossil fuel resources					
Default values	Rogner, 1997 updated for oil and gas with new USGS figures				
Oil	900-2300 Gbbl for conventional oil; 3500-14000 Gbll for unconventional oil; (7-17 ZJ and 27-100 ZJ; respectively). The sum of all Rogner categories is 21 ZJ for conventional oil and 100 ZJ for unconventional oil.				Estimates based on the 5-95% interval from USGS (TNO, 2006) + assuming a 10% uncertainty in reserves and a 80% uncertainty in the enhanced recovery category. In this way, the lower range coincides with the maximum 1000 Gbl estimate of peak oil proponents (Laherre and Cambell, 1999). For unconventional oil, lower values for the lower range estimates are used. Cambell and Laherre provide an estimate of 700 Gbll of unconventional oil, to be produced between 1990 and 2050.
Gas	6-17 ZJ for conventional gas; 260-1600 ZJ for unconventional gas; The sum of all Rogner categories is 21 ZJ for conventional gas and 800 ZJ for unconventional gas				Based on uncertainty factors as applied for oil.
Coal	200-360 ZJ. The sum of all Rogner categories without attributing a likelihood is 300 ZJ .				
Renewable resources	De Vries et al.				
	Wind ±50%. Biomass ±40%, PV ±50%				De Vries et al. (2007)studied the sensitivity of technical and economic potential of renewables both as a function of scenarios and a one-by-one factor analysis. The proposed numbers reflect the average of these uncertainty ranges.

An important factor for the penetration of intermittent renewables into the electric power system is the assigned capacity credit as a function of penetration. On the basis of various curves published in the literature (see (Giebel, 2005)), we have shifted the curve used in TIMER with a factor of 2 upward and downward.

For secondary energy taxes, values in the scenarios were based on current values in different regions. In the uncertainty analysis these levels were varied by 50%, based on the existing differences between the scenarios and current regional variation.

Finally, present-day oil and natural gas prices in TIMER can only be represented by an assumption that other factors –long-term supply cost curves and simple price-setting equations – have a substantial influence on fossil fuel prices (the equilibrium price of oil in TIMER is around 25 US$/bbl). Important factors that currently contribute to high

Table 5A.6 Description of sampling ranges for other factor

	A1	A2	B1	B2	Rationale
Fuel preferences (added to prices)					
Default	Slight preference for clean fuels	No preferences	Preference for clean fuels	Slight preference for clean fuels	
Sample ranges	±50%	±50%	±50%	±50%	
Trade (added to transport costs)					
Default	Open	Closed	Open	Closed	
Sample ranges	50% up	50% up / down	50% up	50% up / down	Based on differences among the scenarios.
Credit Factor (capacity credit assigned to renewables)					
Default	Function depending on penetration rate.				
Sample ranges	Function multiplied by 0.5-2.0.				
Energy taxes					
Default	Avg. USA values	Current regional values and US values	Avg. OECD Europe values	Medium settings	
Sample ranges	50% variation				
Short-term uncertainty oil/gas prices					
Default	Prices return to normal levels in 2010				
Sample ranges	Prices return to normal levels from 2008-2050.				

oil prices and which are not represented in the model are lack of production capacity, speculation and supply insecurity. As it is uncertain how long these factors will continue to determine oil prices, the short- to medium-term price increase has been added as an additional uncertainty. This factor is defined by the year that prices return to equilibrium, assuming a linear decrease (varying from 2008 to 2050). The gas price is assumed to be coupled to the oil price.

6. MULTI-GAS SCENARIOS TO STABILIZE RADIATIVE FORCING

Abstract. Using the results of a recent model comparison study performed by the Energy Modeling Forum, we have shown in this chapter that including non-CO_2 gases in mitigation analysis is crucial to formulating a cost-effective response. In the absence of climate policies, the emissions of non-CO_2 greenhouse increase from 2.7 GtC-eq per year in 2000 to 5.1 GtC-eq per year in 2100 (averaged across all the models). A multi-gas reduction strategy stabilizing radiative forcing at 4.5 W/m^2 (compared to pre-industrial) reduces the emissions (on average) to 2.5 GtC-eq. Such an approach leads to a cost reduction of 30–40% compared to a CO_2-only reduction strategy for the same target. The choices of a target and how the gases are valued form an essential part of developing multi-gas strategies. Model results show that the use of IPCC global warming potentials (GWPs) as a basis for substitution has large consequences for the timing of methane reductions. In this context, an assessment on multi-gas metrics, going beyond the mere physical aspects, is important for both research and policy-making.

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6.1 Introduction

Of the set of gases that contribute to the enhanced greenhouse effect, carbon dioxide provides the largest contribution. Nevertheless, taken collectively, the non-CO_2 greenhouse gases contribute about 25% of current greenhouse gas emissions. In terms of equivalent emissions and using IPCC 100-year global warming potentials (GWPs), non-CO_2 greenhouse gases (NCGGs) comprise CH4, N_2O, PFCs, HFCs and SF_6. Despite this still appreciable contribution from NCGGs, most of the literature on mitigation scenarios has concentrated on CO_2. One reason for the limited number of so-called multi-gas studies is that consistent information on emission reduction costs for the NCGG gases has been lacking. Over the last few years, the number of studies that consider NCGGs as well as CO_2 abatement potential have been increasing. Such studies generally find that major cost reductions can be obtained through: (1) relatively cheap abatement options for some of the NCGGs (USEPA, 1999; Blok et al., 2001) and (2) an increase in flexibility in abatement options (Gielen and Kram, 1998; Hayhoe et al., 1999; Reilly et al., 1999; Tol, 1999; Jensen and Thelle, 2001; Manne and Richels, 2001; Van Vuuren et al., 2003b). Other studies report additional advantages of multi-gas strategies, such as in avoiding climate impacts by focusing on short-lived gases (Hansen et al., 2000). Interestingly, policy makers already acknowledged the potential benefits of a multi-gas approach in 1997 by formulating the Kyoto Protocol targets as strategy in terms of a basket or aggregation of greenhouse gases, thereby allowing substitution among these gases. At the time, this was mostly based on the theoretical understanding that increased flexibility leads to a reduction of costs. More recently, the U.S. Administration also choose a multi-gas approach for its climate policy aiming to meet a GHG intensity target.

Considering CO_2-only stabilization, a reasonable understanding of mitigation potential and the associated costs has been gained through a large range of studies covering a wide spectrum of climate targets, and based on a wide range of assumptions and modeling approaches (see Hourcade and Shukla, 2001). A similar situation for multi-gas stabilization did not exists, as the number of individual studies is still rather limited. Furthermore, methodologies have not been compared and studies have generally not assessed multiple stabilization targets. A large model comparison study and the data that has recently been collected on marginal abatement costs for NCGGs provide an opportunity to improve that situation. The study was conducted under Stanford University's Energy Modeling Forum (EMF-21; (Weyant et al., 2006))[i].

Here we will use the results of the EMF-21 scenarios to develop insights into the question of how multi-gas climate change mitigation strategies differ from CO_2-only mitigation strategies. We also compare these new multi-gas scenarios to the baseline scenarios employed earlier by IPCC in the Third Assessment Report (the SRES scenarios) (Nakicenovic and Swart, 2000) and compare the results of the different modeling groups. Finally, we use the results to discuss some crucial methodological issues with regard to multi-gas reduction strategies. In order to evaluate the trade-offs of reducing one gas instead of another, we need to make the climate impacts of each of the various gases and their associated reduction costs comparable. As shown in this chapter, the choice of such metrics is far from straightforward and can crucially change the resulting optimal reduction strategy.

Section 6.2 provides an introduction to the methodological questions that are addressed in this chapter, while Section 6.3 discusses the results for the scenarios without climate policy. Section 6.4 discusses the results for the mitigation scenarios. These results form the basis of a broader discussion in Section 6.5 on the metrics of multi-gas mitigation scenarios. Finally, conclusions are drawn in Section 6.6.

6.2 Methodological questions in multi-gas analysis

The main source of information used in this chapter comes from the EMF-21 study on multi-gas scenarios. In EMF-21, 18 modeling groups and 8 expert organizations on mitigation options collaborated in improving the current state of multi-gas modeling. The purpose of the exercise was twofold. The first was to perform a comprehensive assessment of modeling work to improve the understanding of including NCGGs and terrestrial carbon sequestration (sinks) into short- and long-term mitigation policies;

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[i] The authors acknowledge the contribution of the modeling teams, who provided input for the EMF-21 study. This input has served as the basis for analysis in this chapter.

second, the assessment would strengthen the collaboration between experts on NCGG, and sinks abatement options and modeling groups. The second purpose was felt necessary, as many groups had no representation of NCGG emissions or abatement at the beginning of the exercise. Table 6.1 provides a summary listing of the models and characteristics. Three main model categories can be identified for those participating in the EMF-21 study; we classify them as MultiSector Computable General Equilibrium models (MS-CGE), Aggregate Computable General Equilibrium models (A-CGE) and Integrated Structural Models (ISM). The first group consists of macro-economic models, with considerable sectoral detail. The second group consists of models that focus more on integrated assessment of the economy and climate change, include inter-temporal optimization, and in this context tend to reduce the amount of sectoral detail. The last group consists of models that focus more the structural (physical) processes underlying emissions. Obviously, these groups overlap, but as Table 6.1 shows, within these categories similar techniques are often used to include the non-CO_2 gases (see Table 6.1; and text further in this section).

Given the body of knowledge on CO_2 abatement, a crucial question is how our insights will have to change if multi-gas strategies are to be adopted. Models that are able to address such questions need to be able to deal with a set of rather obvious questions directly related to modeling NCGGs:

a. What activities cause emissions of NCGGs and how are these activities represented in the models?
b. What is the abatement potential of different sources of NCGGs and how can this information be included in the models?
c. How do implementation barriers influence the abatement potential that can be implemented at any point of time?
d. How will the abatement potential for NCGGs evolve over time; and be influenced by technological change and/or reductions of implementation barriers?

In the EMF-21 study, the first question was addressed by developing a dataset of current NCGG emissions in different regions and indicating their main economic driving forces. The way models include this information depends highly on the type of model being considered (see Table 6.1). Detailed integrated structural models generally couple emissions of NCGGs to activities explicitly included in the models (e.g. the number of farm animals). General equilibrium models, in contrast, usually include these gases by incorporating them in the production function of the model. To help answer the second question, this NCGG dataset was extended by including a set of abatement options that could be identified for 2000–2020.

Information on these abatement options has been made available in terms of the characteristics of individual measures, but also in the form of so-called marginal abatement cost curves (MACs). Again, the way models adopted this information differs, depending mostly on the type of model (including a description of individual reduction measures, use of MACs, or incorporating the information into the production functions). The last two questions (c and d) were left mainly to the individual modeling groups to address.

Table 6.1 Key characteristics of EMF 21 models

Model	Model type (a)	Representation of NCGG emission reduction options (b)	NCGG contribution method (c)	Solution concept (d)	Time horizon (e)	Group in this chapter (f)
AMIGA	MS-CGE	RFPF	GWPs	RD	2100	1
GTEM	MS-CGE	RFPF	GWPs	RD	2030	1
GEMINI-E3	MS-CGE	RFPF	GWPs	RD	2050	1
EU-PACE	MS-CGE	RFPF	GWPs	RD		1
EDGE	MS-CGE	RFPF	GWPs	RD	2030	1
EPPA	MS-CGE	RFPF	GWPs	RD	2100	1
IPAC	MS-CGE	RFPF	GWPs	RD	2100	1
SGM	MS-CGE	RFPF	GWPs	RD	2050	1
WIAGEM	MS-CGE	RFPF	GWPs	RD	2100	1
Combat	A-CGE	MAC	RF	INTOP	2100	2
FUND	A-CGE	MAC	RF	INTOP	2100	2
MERGE	A-CGE	MAC	RF	INTOP	2100	2
GRAPE	A-CGE	MAC	RF	INTOP	2100	2
IMAGE	ISM	MAC	GWPs	RD	2100	3
MESSAGE	ISM	SM	GWPs	RD	2100	3
AIM	ISM	SM	GWPs	RD	2100	3
MiniCAM	ISM	SM	GWPs	RD	2100	3
POLES/AgriPol	ISM	MAC	GWPs	RD	2030	3

NCGG: non-CO_2 GHG gases.
(a) MS-CGE: Multi-Sector Computable General Equilibrium; A-CGE: Aggregate Computable General Equilibrium; ISM: Integrated Structural Model, used here to indicate the group of models that include relatively detailed structural models of the sectors that emit non-CO_2 greenhouse gases; most of the models in this group can also be classified as Integrated Assessment Models.
(b) RFPF: Reduced Form Adjustment to Production Functions; MAC: (Reduced Form) Marginal Abatement Costs curves; SM2 indicates models that have included individual reduction measures.
(c) RF:Radiative Forcing; GWPs: Global Warming Potentials.
(d) RD: Recursive Dynamic; INTOP: Inter-temporal Optimization.
(e) Time horizon
(f) Groups used in this chapter, color coded to correspond to in the figures.

For recent work on the question of how potential can evolve over time (see Graus et al., 2004; Delhotal and Gallaher, 2005; Lucas et al., 2007).

In addition to the set of questions raised above, a second set of questions is needed to address multi-gas abatement strategies, which originate from the need to combine the contributions of the different gases, with their different lifetimes and different radiative properties. This second set of questions, as set out below, is also directly relevant to policy-making:

1. How to define a mitigation target for a multi-gas stabilization scenario?
2. How to allow for substitution among the different greenhouse gases and which metric is used to determine the value of each gas?

In response to the first question, the modeling teams in EMF-21 decided, as a group, that the appropriate target for a multi-gas, mitigation exercise would be radiative forcing as: (1) it was the most comparable to the concentration targets used earlier in CO_2-only studies, while (2) it allowed for substitution among different gases. In quantitative terms, the group decided to compare model runs that focused on stabilizing radiative forcing at 4.5 W/m^2 above pre-industrial levels. A radiative forcing target of 4.5 W/m^2 is more or less equal to a CO_2 concentration at 550 ppmv (the standard case in most earlier work), assuming 1 W/m^2 additional forcing for the NCGGs (a value based on the IPCC-SRES scenarios) (Wigley and Raper, 2001). For reference purposes, a 4.5 W/m^2 target also roughly corresponds to a 3 ^{8}C equilibrium temperature increase relative to pre-industrial times using a medium climate sensitivity. With respect to the second question (how to define substitution among gases over time) this was again left to the individual modeling groups to address. As Table 6.1 shows, two main methods were used: substitution based on the 100-year GWPs of the different gases and substitution based on inter-temporal optimization under the radiative forcing target[ii]. In both cases, the time horizon plays an important role. In the former case, alternatives for 30 or 500-year GWPs produce varied results; in the latter, results critically depend on the optimization year chosen (here 2100–2150). The common practice is to compare and aggregate emissions by using GWPs. Emissions of NCGGs are converted to a carbon dioxide equivalent basis using GWPs. GWPs used here are calculated over a 100-year period, and vary according to both the ability of the gases to trap heat and their atmospheric lifetime compared to an equivalent mass of CO_2.[iii] We return to the question of stabilization and substitution metrics (GWPs) in Section 6.5 with reference to the modeling results.

On the basis of all the considerations above, three main scenarios were run in each model:

1. a reference scenario without climate policy, based on the preferences of individual modeling teams;
2. a scenario that aims to stabilize radiative forcing at 4.5 W/m^2 (above pre-industrial) using a CO_2-only strategy and,
3. a scenario that aims to stabilize radiative forcing at 4.5 W/m^2 (above pre-industrial) using a full multi-gas strategy.

The first scenario aimed to give insight into NCGG emissions in the absence of climate policies. The second and third scenarios, taken collectively, aimed to give insight into the potential role of non-CO_2 gases in mitigation under a long-term stabilization target (and the methodological questions raised above). It should be noted that in both stabilization scenarios (2 and 3), no weight is given to short-term benefits of mitigation,

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[ii] For clarity, to determine the climate impact of emissions of different gases in any point of time, obviously a climate model is needed that is able to account for the properties of each gas. In this context, the two alternative approaches with regard to substitution can also be characterized as taking full account of the complex dynamics of the climate responses which can only be done through inter-temporal optimization, or instead using a more simple proxy (GWPs).

[iii] Although the GWPs have been updated by the IPCC in subsequent Assessment Reports, estimates of emissions in EMF21 use the GWPs from the Second Assessment Report, in order to be consistent with international reporting standards under the United Nations Framework Convention on Climate Change. The consequences of using this are small.

which critically influences results (see the discussion section). Formally, the EMF21 exercise also included a scenario in which a maximum rate of temperature change target was selected. However, too few models were run with this scenario to allow comparison of results. Finally, the stabilization scenarios did not allow for an overshoot of the radiative forcing target at any point of time.

6.3 Development of emissions without climate policies

All modeling groups provided a reference scenario that included projections of the emissions of the major greenhouse gases in the absence of climate policy. Figure 6.1 shows the pathways for GDP included in the baseline, while Table 6.2 and Figure 6.2 show the results for these reference cases for the emissions of four main categories of gases.

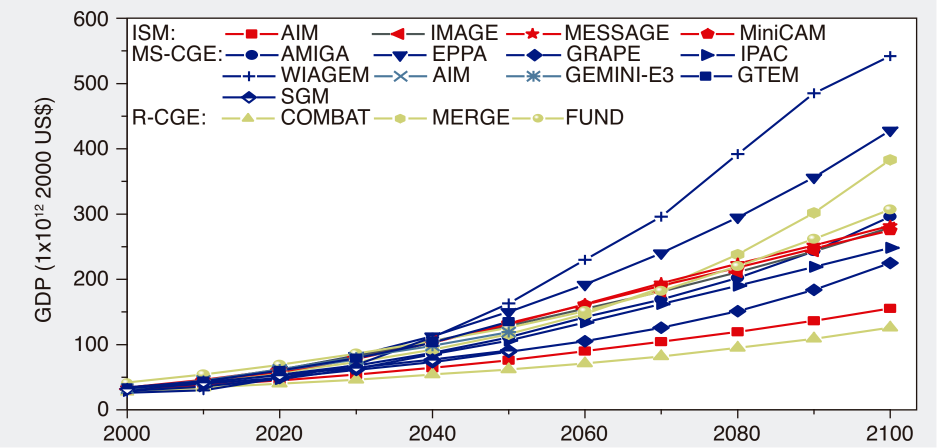

Figure 6.1 GDP trajectories in the EMF-21 scenarios.

Table 6.2 Results (in GtC-eq.) for reference scenarios averaged across the long-term models

	2000				2100				Growth rate		
	Mean	˜SD	+SD	Contribution (Mean) (%)	Mean	˜SD	+SD	Contribution (Mean) (%)	Avg. (%)	˜SD (%)	+SD (%)
CO_2	6.61	6.33	6.89	71.2	19.47	14.68	24.26	79.1	1.1	0.8	1.3
CH_4	1.73	1.57	1.89	18.6	3.07	2.10	4.79	12.5	0.6	0.2	1.0
N_2O	0.83	0.68	0.97	8.9	1.23	0.87	1.86	5.0	0.4	0.0	0.8
F-gases	0.13	0.11	0.14	1.4	0.83	0.49	1.17	3.4	1.9	1.4	2.3
Total	*9.29*	*8.69*	*9.89*		*24.62*	*18.93*	*30.32*		*1.0*	*0.7*	*1.2*

GtCeq: Gigaton Carbon equivalent; SD: Standard deviation. NCGGs are converted using GWPs from the IPCC Second Assessment Report.

The numbers include most of the long-term models with EMF-21 that have reported results. Two models, however, were not included in the average results reported here and elsewhere in this chapter, as their results were too different from the other models (particularly unlikely to comply to the 4.5 W/m² target). The results of these models are included in the graphs showing the individual results of the models.

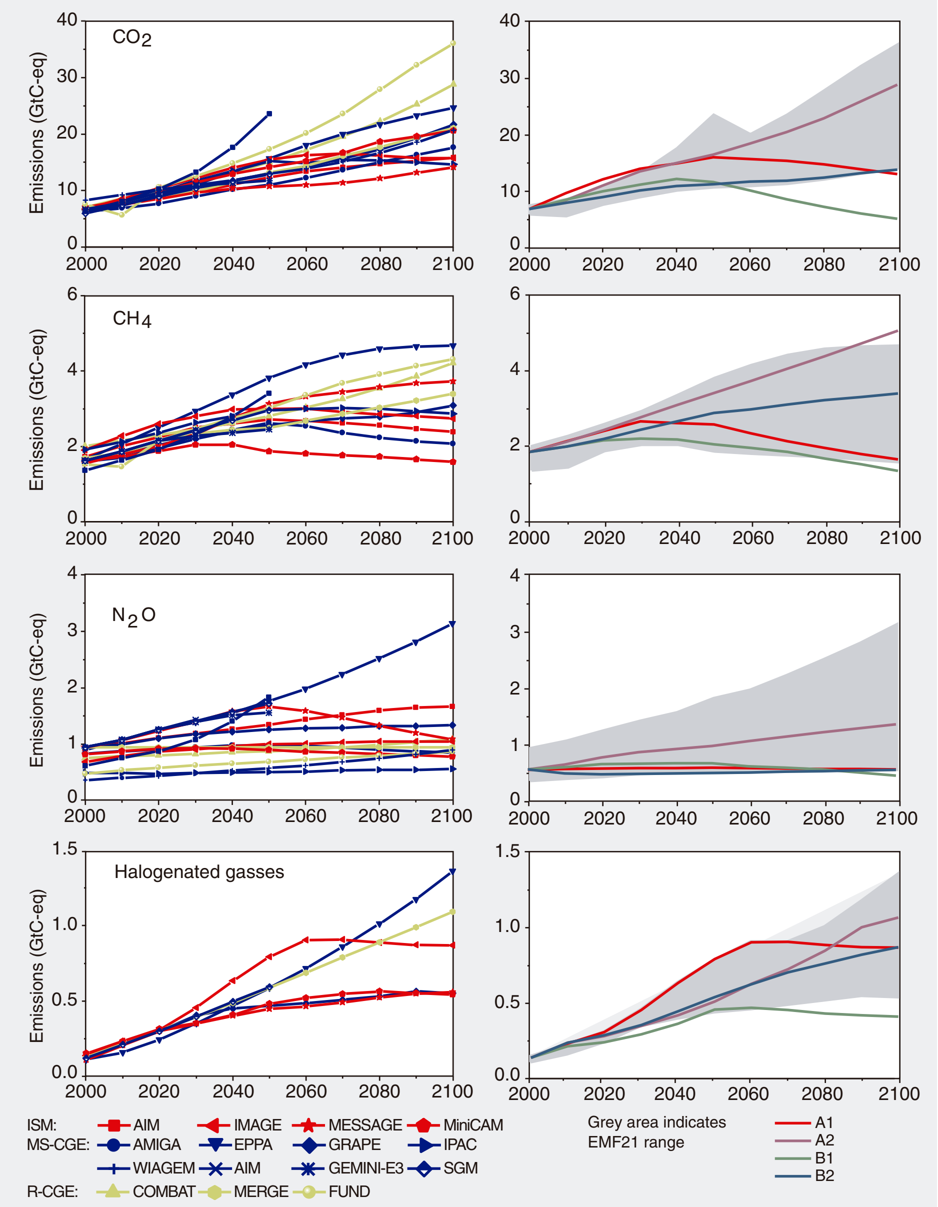

Figure 6.2 Baseline emission development in the EMF-21 scenarios (left) and comparison to the SRES marker scenarios (right).

On average, GDP (Figure 6.1) is expected to grow (across all models) by a factor 3.6 in the 2000–2050 period (2.6% annually) and 9.4 in the 2000–2100 period (2.2% annually). The spread across the models is considerable—with one model indicating a fivefold increase of GDP up to 2100 and another model a 20-fold increase. The MS-CGE as a group seems to show a somewhat higher GDP growth rate than the ISM and A-CGE group (but the difference is not statistically significant).

CO_2 emissions (Figure 6.2) are projected to increase in all models compared to 2000; however, the spread in model results is considerable, ranging from 14 to 36 GtC per year in 2100. CO_2 emissions (across the long-term models) increase on average by 1.1% per year during the 21st century (where results range (standard deviation) from 0.8% to 1.3% growth annually). A considerable part of the spread originates in the second part of the century – where some models show sustained emissions growth, while others show emission growth slowing down or even going negative (mostly due to assumptions on a stabilizing or declining global population). The substantially slower (or even negative) emission growth rate in the second half of the century occurs in most of the models included in the ISM and MS-CGE group. The A-CGE group, on average, seems to have higher CO_2 emission growth rates than the other models in this period. Comparison with Figure 6.1 shows that this difference does not originate from economic growth assumptions. Differences are likely to be related to assumptions on saturation of energy consumption in certain sectors or assumptions on fossil fuel depletion.

The projected increase in CH_4 emissions is considerably less than that for CO_2 for most models. Averaged across the different models, the annual emission increase amounts to 0.6% per year, leading to a decline in the CH_4 share in total emissions from 19% to 13%. The main reason for the slower growth of CH_4 compared to the CO_2 growth is that emissions mostly originate from the agriculture sector. Activities in this sector are expected to grow slower than the main driver of CO_2 emissions, energy consumption. Almost all models show signs of stabilizing and declining emissions in the second half of the century, except for those in the A-CGE group. One reason could be that this modeling group does not capture the saturation dynamics of the driving forces of methane emissions. The range of results for CH_4 is somewhat broader than for CO_2.

Averaged across all models, emissions of N_2O are projected to grow 0.4% annually in the 21st century (one standard deviation range from 0.0 to 0.8%). This is the slowest growth rate of the four groups of gases discussed here, and as a result, the share of N_2O in total emissions drops from 9% to 5%. Note that for N_2O, base year emissions of the different models differ substantially. Two factors may contribute to this. First of all, there are different definitions of what should be regarded as human-induced and natural emissions in the case of N_2O emissions from soils. Secondly, some models may not have included all emission sources.

In the last group, the fluorinated gases (F-gases: PFCs, HFCs and SF_6), emissions grow on average faster than CO_2 emissions (1.9% per year). As a result, the contribution of these gases in equivalent emissions increases from 1.4% to 3.4%, in some models even surpassing N_2O. It should be noted that only a limited subset of models included these gases into the simulations. Most, but not all, of the models project the most rapid increase to occur in the first half of the century.

In conclusion, without climate policies, the baseline scenarios project that emissions of NCGGs will grow significantly. At the same time, their share in total emissions will drop as CO_2 emissions are expected to grow faster than the most important NCGG emissions[iv].

Figure 6.2 also compares the EMF-21 results with the IPCC SRES scenarios (Nakicenovic and Swart, 2000). In general, the range of the EMF-21 emission projections coincides with those from SRES. Some difference is noted for CO_2, where, in the short term, two SRES scenarios are above the EMF-21 range; in the longer term, the B1 is clearly below the EMF-21 range. The latter is due to the deliberate assumption of radical energy efficiency improvement and penetration of renewable energy in B1. For N_2O, the comparison is slightly complicated by the spread of base year emissions in the EMF-21 set (see discussion above); however, in general, growth rates seem to be similar. The coincidence between the SRES and EMF-21 ranges bears further evaluation. First of all, it should be noted that the ranges in the EMF-21 and SRES study originate from very different causes. In the SRES study, deliberate assumptions to map out possible pathways (storylines) cause emissions to diverge across the different scenarios. In EMF-21, a very similar range results from the use of a multitude of models that were free to choose their own modeler's preference baseline scenario. In that sense, the correspondence between the EMF-21 and SRES sets is interesting as the ranges have different causes.

There is some overlap in the models included in the two studies, but the models that were also included in SRES do not represent a majority within the whole EMF-21 set (4 out of the 14 models that reported results: AIM, IMAGE, MESSAGE, MiniCAM). They do, in fact, very seldom form the EMF-21 range. With respect to the other modeling groups included, it is unlikely that simply reproducing SRES results has led to this result, given the independent status of the models, and the methodological differences between these models and most of the SRES models.

The total emission growth under these baseline scenarios implies a sharp increase in radiative forcing as indicated in Figure 6.3. Reported increases in radiative forcing projected by the model groups increase from (on average) 1.7 W/m^2 above pre-industrial today to 6–8 W/m^2 in 2100. This implies that none of the reference scenarios will comply with the 4.5 W/m^2 stabilization target without additional policies in place. The higher radiative forcing of FUND in 2000 is due to FUND not including the (negative) radiative forcing of aerosols (the reason for other differences is unknown).

[iv] For reporting purposes, overall emissions here are post-calculated on the basis of 100 year GWPs. As indicated in the main text, some of the models do not use GWPs as a basis for substitution, while other models do.

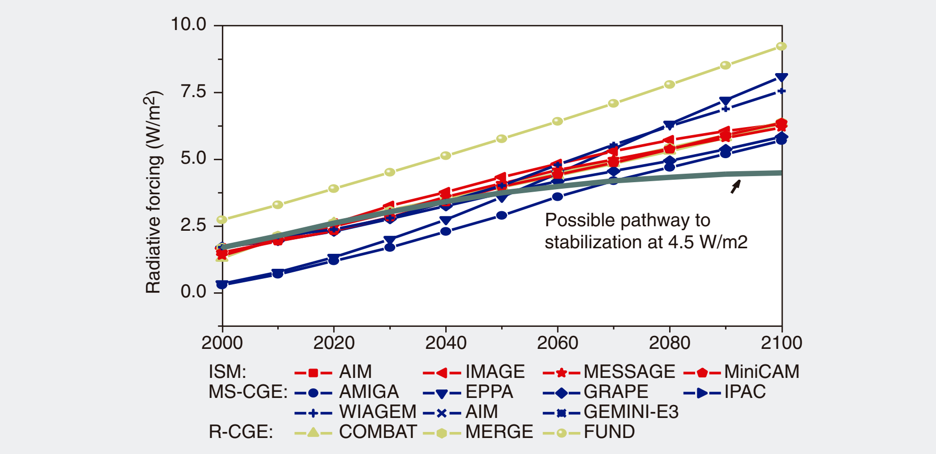

Figure 6.3 Increased radiative forcing under the reference scenarios (without climate policies). The thick black line indicates a possible pathway to the stabilization target of 4.5 W/m².

6.4 Stabilizing radiative forcing at 4.5 W/m²: multi-gas versus CO2-only

6.4.1 Emission reductions (total greenhouse gas reductions)

In order to stabilize greenhouse gas radiative forcing at 4.5 W/m², compared to pre-industrial levels, greenhouse gas emissions need to be reduced substantially in comparison to the baseline emissions. The exact numbers obviously differ depending on the baseline. The emission pathways, averaged across all models and including the standard deviation range, are shown in Figure 6.4. The emission reductions compared to baseline amount on average to about 10% in 2020 and to 35% in 2050 and 65% in

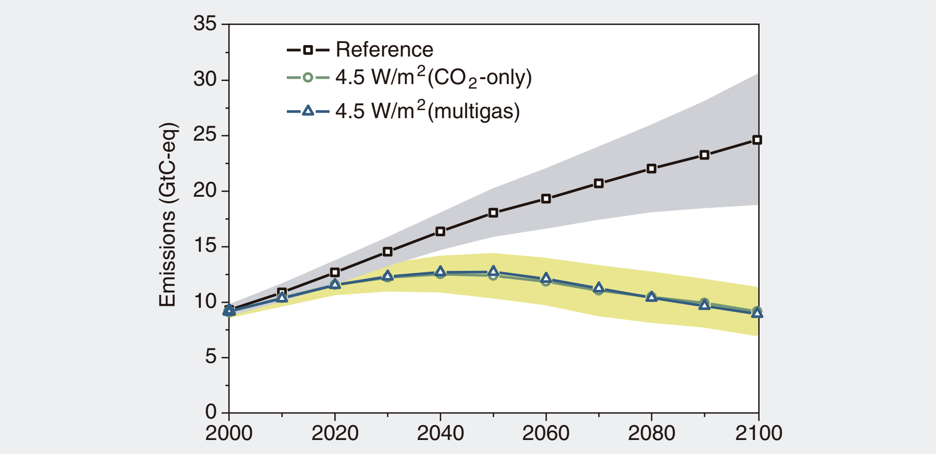

Figure 6.4 Total equivalent CO_2 emissions under the reference scenarios, and the stabilization scenarios (area indicates the standard deviation) averaged across all models).

2100. There is no significant difference between the total equivalent emission numbers of the multi-gas and CO_2-only strategy. As to be expected, the range across the models is reduced somewhat in going from the reference scenario to stabilization scenarios—caused by the (equal) additional constraint set on all models to stabilize radiative forcing.

6.4.2. Emission reductions (reductions by gas)

If we start untangling the contribution of the different gases, we can see that in the CO_2-only strategy the largest contribution in mitigation originates from reducing CO_2 emissions (by construction). CO_2 emissions are reduced by about 75% in 2100 compared to baseline. Nevertheless, as shown in Figure 6.5 and Table 6.3, a small number of the emission reductions, are, in fact, achieved through reductions in CH_4 and N_2O as systemic changes in the energy system; this is induced by putting a price on carbon, which also reduces these emissions. For instance, the reduction in fossil fuels use also reduces CH_4 emissions during production and transport of coal, oil and natural gas. On average, emissions of CH_4 are reduced by about 20% and N_2O by about 10%.

Compared to the CO_2-only strategy, a much larger share of the emission reductions occurs in the multi-gas strategy through reductions of non-CO_2 gases, and as a result smaller reductions of CO_2 are required. The emission reduction for CO_2 in 2100 drops (on average) as a result from 75% to 67%. This is still a fairly high percentage caused by the large share of CO_2 in total emissions (on average, 60% in 2100) and partly by the exhaustion of reduction options for the NCGGs. The reductions of CH_4 across the different models average around 50%, with remaining emissions coming from sources that are currently are considered to be difficult to abate, 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 F-gases, high reduction rates (about 75%) are found across the different models.

Several factors play a role in the differences among the different models. These include the total reduction burden (which depends strongly on projected baseline emissions), the distribution among different sources, the different methodologies used to represent technological change, and also the method chosen to determine substitution among the different gases.

It should be noted that although the contributions of different gases change sharply over time, there is considerable spread among the different models. This can be seen in Figure 6.5. Many models project relatively early reductions of both CH_4 and F-gases under the multi-gas case. However, the subset of models that does not use GWPs as substitution metric for the relative contributions of the different gases to the overall target – but that does assume inter-temporal optimization in minimizing abatement costs – does not start to reduce CH_4 emissions substantially until the end of the period.

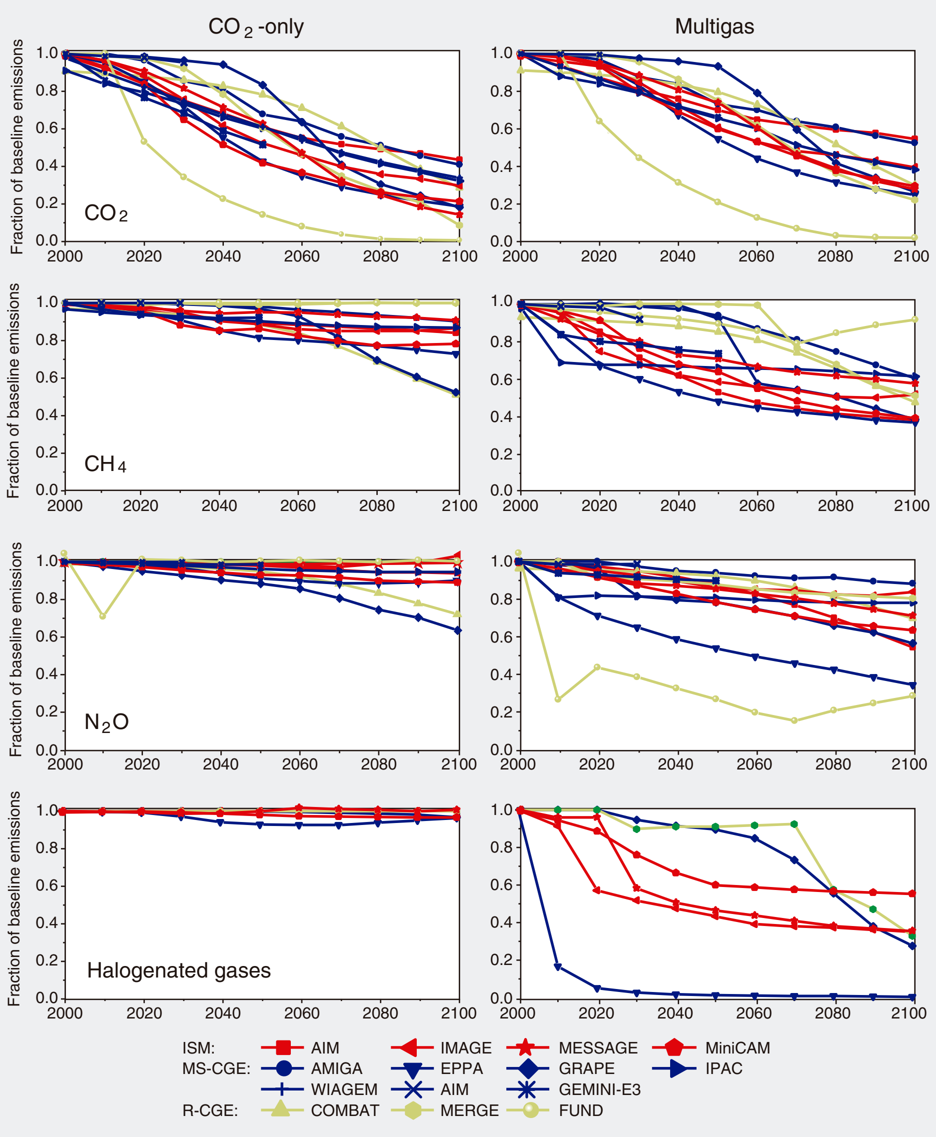

Figure 6.5 Reduction of emissions in the CO_2-only versus multi-gas strategies.

Table 6.3 Percentage reductions in greenhouse gases in CO_2-only and Multi-Gas strategies

	Reference	CO2-only				Multi-gas			
	2100	Avg.	-Std-Dev	+Std-Dev	Red.	Avg.	-Std-Dev	+Std-Dev	Red.
CO2	19.47	4.85	2.75	6.95	**75%**	6.49	4.71	8.27	**67%**
CH4	3.07	2.39	1.61	3.17	**22%**	1.48	0.99	1.97	**52%**
N2O	1.23	1.11	0.54	1.68	**10%**	0.77	0.60	0.93	**38%**
F-gases	0.83	0.82	0.49	1.17	**2%**	0.22	0.09	0.35	**73%**
Total	24.62	9.18	7.13	11.23	**63%**	8.95	7.22	10.68	**64%**

Emissions are reported in CO_2 equivalence using 100-year GWPs.

The reason for this result is that in aiming at the long-term target, it does not pay to engage in early CH4 emission reductions because CH_4 has a short atmospheric lifetime (about 10 years). In other words, since the benefits in reducing radiative forcing in the atmosphere are more immediately felt with CH4 mitigation, these models wait to reduce these emissions as the target approaches. In their calculations, there is not much benefit in reducing CH4 early in the simulation.

In the models that use GWPs as the basis for their substitution, however, CH_4 emission reductions are relatively attractive early-on (compared to CO_2 emission reductions) based on the availability of low-cost emission reduction options. It should be noted that for N_2O, reductions in the first few decades also seem to be substantial—and here the results do not differ among the different categories of models. Here, inter-temporal optimization and use of GWPs give the same results because N_2O and CO_2 have similar (medium-length) lifetimes in the atmosphere.

6.4.3 Costs of mitigation

In the EMF-21 study, two costs concepts were considered: the marginal costs of emission reduction and the reduction of GDP from a baseline scenario. The first concept can be calculated by all models, while the second concept can only be calculated if it somehow includes a description of the macro-economy. Figure 6.6 shows the ratio of marginal costs (i.e. the carbon tax used to induce the required emission reductions) in the multi-gas case to the CO_2-only case. While there are clear differences among the models and in time, the reduction in the marginal costs amounts, on average, to 30–60%. Almost all models show a much greater reduction in the first few decades; in this period a considerable part of the more expensive emission reductions are now being replaced by cheaper reductions in NCGG emissions. The average reduction in the carbon tax in the first few decades amounts to 50–60% across all models. In the second part of the century, the carbon tax is reduced by about 35–40% on average. Some models, however, again show an increasing cost benefit from the multi-gas strategy by the end of the scenario period since the higher flexibility avoids the steep cost increases involved in the deepest CO_2 emission reductions.

More or less the same results can be seen for the second cost indicator, GDP losses. The cost reduction here is about 30–40%, with again the largest benefits occurring in the first few decades of the scenario period. The slightly lower impact on GDP losses than on marginal reduction costs (carbon tax) is to be expected given the nature of the cost measures (the first measure deals with marginal costs, while the second measure integrates across the whole range of measures taken). The differences in results across the different models are larger in the case of GDP losses, which can be understood as these are influenced by a much wider range of uncertainties. In both cases, however, the impacts on costs of multi-gas strategies vis-à-vis CO_2-only strategies are very substantial—certainly in comparison to the smaller contribution of NCGGs to overall emissions.

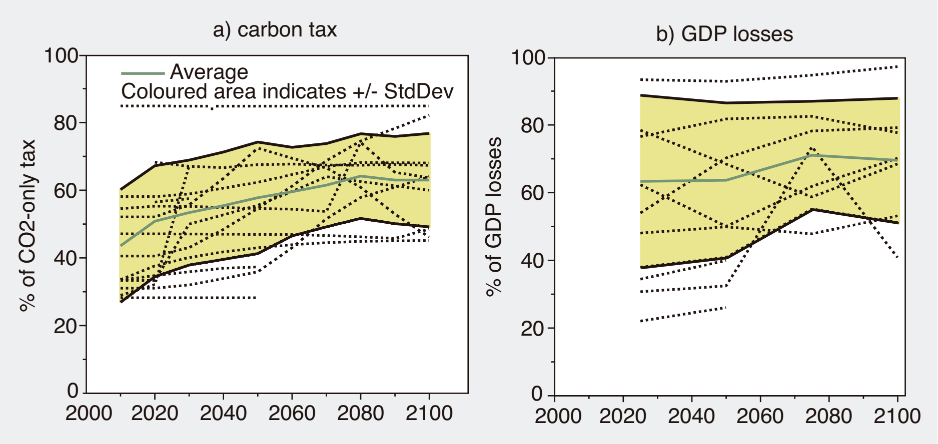

Figure 6.6 Costs of stabilizing radiative forcing at 4.5 W/m^2, ratio of costs in the multi-gas case to the CO_2-only case (grey area indicates standard deviation).

6.5 Discussion on the metrics of multi-gas scenarios

The previous sections have indicated the importance of considering multi-gas strategies as part of stabilization scenarios. In the introduction, however, we indicated that multi-gas strategies are more complicated than CO2-only strategies as they need metrics to compare the contribution of a set of gases with different lifetimes and different radiative properties. Such metrics are needed for two important issues (which some approaches combine into a single issue):

a. how to define the stabilization target for a multi-gas stabilization scenario and,
b. how to allow for substitution among the different greenhouse gases in a way that reflects their relative contributions to climate change.

In this section we will discuss some of the advantages and disadvantages of different targets and, where possible, use EMF-21 results to analyze them.

6.5.1 Definition of stabilization target

As the UNFCCC calls for a stabilization of greenhouse gas concentrations at a level that prevents dangerous anthropogenic interference, most mitigation studies have focused on stabilization scenarios. In models and studies that consider only CO_2 this meant stabilizing CO_2 concentration (the CO_2-only strategy as defined in this study is slightly different, as any increase in NCGG concentrations needs to be compensated by further CO_2 emission reductions). For multi-gas studies, one would need a similar long-term climate target but now integrating all of the NCGGs with CO_2.

In general, a target for climate policy can be chosen anywhere in the causal change of climate change, as indicated in Figure 6.7. Choosing a target early in the chain increases the certainty of required reduction measures (and thus costs), but decreases the certainty on climate impacts (see Figure 6.7 and Table 6.4). Selecting a climate target further down the cause–effect chain (e.g. temperature change, or even climate impacts avoided) increases certainty on impact reductions, but decreases certainty on required reduction measures (UNFCCC, 2002). Uncertainties increase most (either way) in the step from radiative forcing to temperature change due to the large uncertainty range for climate sensitivity (Matthews and van Ypersele, 2003). Analogy with the CO_2 concentration suggests formulating targets in terms of radiative forcing, which is equivalent to the concentrations of the different gases weighted by their radiative properties. The additional advantage of choosing radiative forcing targets over temperature targets is that in determining required emission reductions the uncertainty caused by the unknown climate sensitivity does not play a role. The downside is, of course, that a wide range of temperature impacts is possible for the same radiative

Table 6.4 Assessment of the main advantages of using different targets in modeling exercises, model comparison studies and assessment of available literature

Target	Advantages	Disadvantages
Impacts	Direct link to aspects climate policies aim to avoid (direct link to Article 2, UNFCCC)	Very large uncertainties in required emission reductions and costs
Global mean temperature	Metric is also used to organize impact literature, and has proven to be a reasonable proxy for impacts	Large uncertainty on required emission reduction (as result of the uncertainty in climate sensitivity) and thus costs
Radiative forcing	Relatively easy to translate to emission targets (thus does not include climate sensitivity in cost calculations) Allows for full flexibility in substitution among gases Connects up well to earlier work on CO_2 stabilization Allows for easy connection to work with GCMs/Climate models	Not as familiar as emissions or concentrations (but can be expressed in terms of CO_2-equivalent concentration) Cannot be directly observed or measured
Concentrations of separate greenhouse gases	Can be translated relatively easily into emission profiles (reducing uncertainty on costs)	Does not allow for substitution among gases (thus loses the opportunities of cost reduction of ‘What’ flexibility)
Emissions	Lower uncertainty on costs	Very large uncertainty on global mean temperature increase and impacts Either needs a different metric to allow for aggregating different gases (e.g. GWPs) or forfeits opportunity of substitution
Costs/activities	Low uncertainty on direct abatement costs; relatively low uncertainty on macro-economic costs	Very large uncertainty on global mean temperature increase and impacts
Rate of temperature increase	Related to some forms of ecological impacts	Very high uncertainty on costs and probably unrealistic in the first few decades

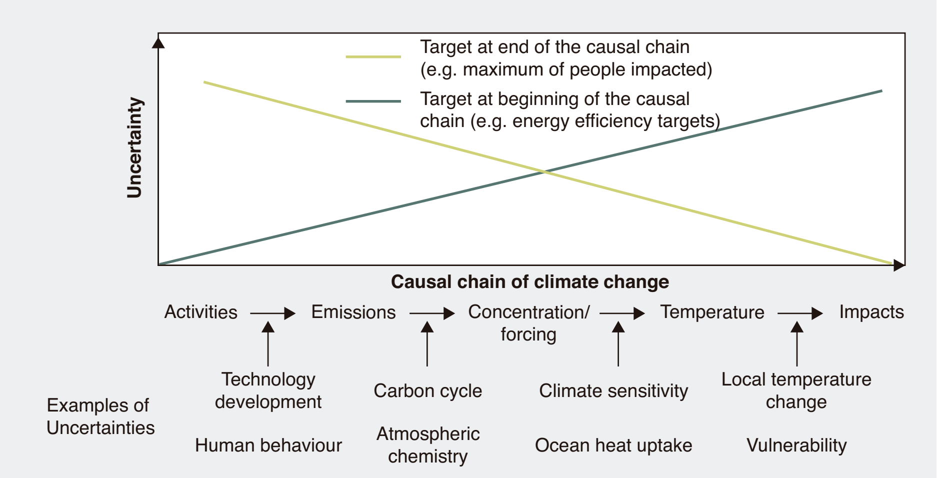

Figure 6.7 Simple representation of the cause-effect chain of climate change, illustrating the consequences for uncertainty from the choice of policy target within the chain.

forcing level. Temperature targets have an important advantage of being more easily associated with impacts (which can be related to global temperature increase – as argued in the Third Assessment Report (IPCC, 2001).

In addition to long-term targets, short-term targets may be also be chosen for climate policy (e.g. the maximum rate of temperature increase). The rationale for such targets is that climate impacts are also related to the rate of climate change if this rate is too fast for ecosystems or human systems to adapt to. However, the little modeling done in EMF-21 on these targets suggest that in the first few decades, stringent temperature rate targets can be difficult to comply with. In particular, MERGE calculations found that stringent temperature rate targets of 0.2°C per decade can lead to high abatement costs (Manne and Richels, 2006). Other models suggested similar results, by showing the high rate of temperature increase in their mitigation scenarios in the first few decades, partly due to reduction of sulfate cooling in this period (van Vuuren et al., 2006b). The implication is that if temperature rate targets are used, they need to be set carefully in the early decades.

The choice of different targets is not only relevant because it leads to a different interpretation of (the same) uncertainty ranges. It is also relevant because it can lead to different strategies and outcomes. The clearest is that for targets such as concentration and emission targets by gas, the opportunity of substitution among gases is forfeited (the advantage of allowing this substitution was shown in Section 6.4). But also the timing of emission reduction may depend on the stabilization target chosen. If the aim is to stabilize temperature, it often seems economically more attractive to peak radiative forcing in a certain year, and next, to further reduce emissions to decrease radiative forcing levels instead of stabilizing radiative forcing directly. The former strategy can avoid the (delayed) further warming associated with the radiative forcing peak level, while still delaying some of the emission reductions in time and thus reducing discounted costs (den Elzen and Meinshausen, 2005).

The discussion in Table 6.4 concentrates on the selection of one particular target (e.g. for model comparison). In policy-making, however, a set of related targets will generally be chosen (instead of one single target) and this set will be updated in due time. For instance, the EU and several European countries have, as an ultimate target, decided on a maximum increase in global mean temperature of 2°C compared to pre-industrial levels. This target is translated into related greenhouse gas concentration levels and then into emission reduction targets. In the course of time, new insights into costs, climate sensitivity and/or impacts are likely to lead to re-evaluation of these targets. In this way, some of the disadvantages of certain targets, as indicated in Table 6.4, can be avoided.

6.5.2 How to define substitution among gases

For the second methodological question, a measure is needed by which the emissions of different greenhouse gases with different atmospheric lifetimes and different radiative properties can be compared. Ideally, such a measure would allow for substitution among different gases (in order to achieve cost reductions) but ensures equivalence in climate impact. Fuglesvedt et al. (2003) provide a comprehensive overview of the different methods proposed, and the advantages and disadvantages of using them. In the modeling described in this chapter, two methods were used: 1) substitution based on GWPs and 2) inter-temporal optimization under a radiative forcing target.

The first method has been adopted in most current climate policies, such as the Kyoto Protocol and US climate policy (White-House, 2002). There has also been a continuous debate on their use for this purpose, based on both natural science and economic arguments (Wigley, 1998; Manne and Richels, 2001; Godal, 2003; O'Neill, 2003; Person et al., 2004). These arguments include the argument that GWPs do not account for the economic dimension of the problem and are based on rather arbitrary time horizons. Inter-temporal optimization models that include radiative forcing and climate change equations can, in fact, totally avoid the use of substitution metrics such as GWPs by simply optimizing across the different gases under the long-term target, as shown within EMF-21.

The question of how to substitute among different gases over time is not independent of the policy target discussed in the previous section. If only long-term targets are selected, the cost optimal strategies from the inter-temporal optimization models will early-on not focus on reducing short-lived gases. This is shown, for instance, by Manne and Richels (2001). The debate can be well illustrated by the comparison study performed in EMF-21. Figures 6.8 and 6.9 show the reduction rates over time again for methane, aiming at stabilization of radiative forcing at 4.5 W/m^2 using a multi-gas approach.

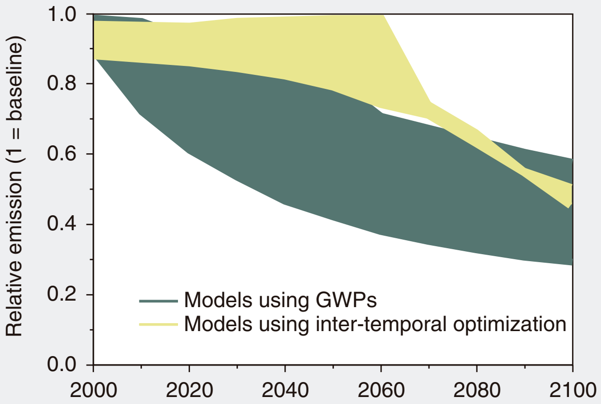

Figure 6.8 Reduction of methane for models that use year-by-year fixed (GWPs) or that base substitution on inter-temporal optimization.

While most models based substitution on using GWPs, four models based substitution on direct contributions to radiative forcing within a full inter-temporal economic optimization framework. The last four are indicated in Figure 6.8. While there are no clear differences among the two groups for most gases, there is a very clear difference for methane. For those models that base substitution on GWPs, the reduction of CH_4 emissions in the first three decades is already substantial. In contrast, models that do not use GWPs only start to reduce CH_4 substantially by the end of the period. The logic in the latter case is that aiming specifically on the long-term target set in the analysis, early CH_4 reduction does not pay off given its short lifetime. In the first group of models, however, CH_4 emissions are attractive on the basis of the available low-cost reduction options. This is illustrated too in Figure 6.9, where a direct comparison is seen between IMAGE (based on GWPs) and MERGE (based on contributions to radiative forcing within an inter-temporal cost optimization framework) results. In IMAGE, a very substantial share of reductions is obtained from CH_4 and the F-gases in the early periods. Their share declines over time (as cheap reduction options are exhausted). MERGE, in contrast, shows almost no reduction in methane emissions until 2070. N_2O, however, shows a major share of early reductions. Finally, by 2100 there is not much difference between the two approaches.

What do these results imply for policy-making? For policy-making purposes, a substitution metric should not only be operational in a modeling context, but also in the real world. The cost reductions from a multi-strategy shown in Section 6.4 can only be achieved if substitution metrics are available that are acceptable to a large group of actors involved in climate policy. As alternative to the GWPs that are now used as substitution metric, it is, in principle, possible to derive the exchange rates of different gases from model results of the cost-optimizing models, as shown by Manne and Richels (2001).

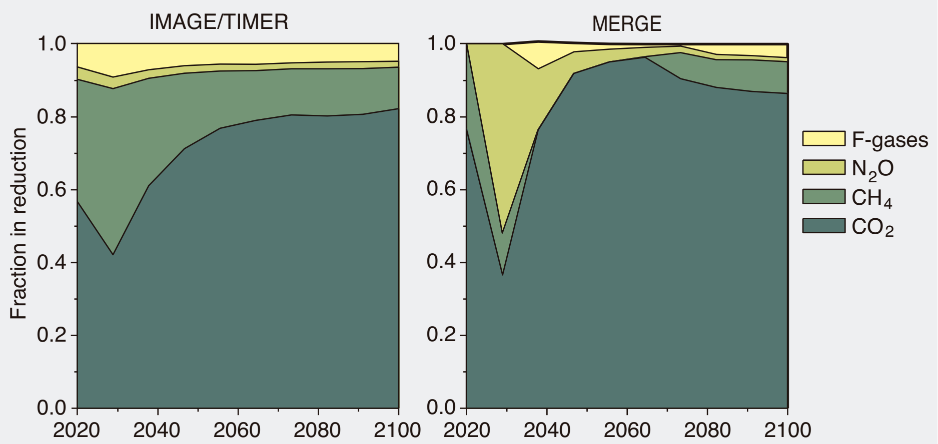

Figure 6.9 Contribution of different gases in overall reductions. Comparison of a model using GWPs as a basis for substitution (IMAGE) versus a model that uses inter-temporal optimization (MERGE)

However, there are two complications. First, these alternative metrics are model-dependent (for example, on the current insights into present and future mitigation costs) and (by definition) dependent on the target that is chosen in the analysis. As uncertainties on costs add to those on radiative forcing, these alternative exchange rates are more uncertain and require a debate on the correct economic model and mitigation potentials. The second complication is that for multi-gas emission reduction strategies and multi-gas trading markets to function correctly, the changes in the value of the exchange rate over time (if any) need to be predictable and smooth. Otherwise, the additional risk of changes in the exchange rate could prevent investors from making otherwise cost-optimal investments. Given the dependency on models and mitigation costs, fully cost-optimal metrics might not be able to pass this test. Relevant questions are therefore: (1) what are the additional costs of using GWPs versus not using them (are the costs with use of GWPs as metric close enough to the lowest costs achievable); and (2) can other real world metrics (that do comply with the considerations above) be developed that have a better performance. Several studies, (O'Neill, 2003; Person et al., 2004; Aaheim et al., 2006), have argued that the disadvantages of GWPs are likely to be outweighed by their advantages by showing that the cost difference between a multi-gas and CO2-only strategy is much larger than between a GWP-based multi-gas strategy and a cost-optimal strategy (thus suggesting that GWPs can achieve most of the cost savings).

One should also note that the cost-optimal results as discussed here are fully optimized under a long-term target, with no benefits assigned to short-term benefits, such as a lower rate of temperature change. This assumption leads to much more extreme differences between the cost optimization and GWP-based strategies than alternative analyses that would have valued short-term gains as well. As GWPs are calculated on the basis of the integral of radiative forcing throughout the century, they automatically lend some value to short-term benefits. Strategies with GWP-based substitution (or cost-optimal results based on temperature rate targets) lead to significantly less warming throughout the scenario period achieved by considerable reductions of CH4 early in the scenario period. Postponing this abatement (as suggested by flexible optimization) leads to higher rates of temperature in the first few decades. Thus, a relevant question on metric within the debate is whether climate policy should focus on long-term targets only, or also on short-term targets such as the rate of temperature change.

The discussion above indicates a debate on useful substitution metrics that is still open. It would seem very appropriate to reconsider the use of GWPs as a substitution metric in the light of the debate on costs and benefits (and not only in the light of their physical properties, which has been the focus of the debate on GWPs up to now). The results of such evaluation are not yet clear. They would focus on the costs of using GWPs versus ideal metrics, but also on their capacity to make a multi-gas strategy feasible in the real world.

6.6 Conclusions and the way forward

EMF-21 performed a multi-model comparison project on scenarios that not only include CO2, but also other major greenhouse gases. The analysis has shown the following results:

- **Under baseline conditions, emissions of non-CO2 gases are expected to grow considerably from around 2.7 GtC-eq. per year in 2000 to 5.1 GtC-eq. per year in 2100 (average across all models; standard deviation range of 3.2–7.1 GtC-eq.year).** Despite this emission increase, the share of non-CO2 gases is expected to be reduced from 29% to 21%. Both CH4 and N2O are expected to grow slower than CO2, as their emissions originate mainly from agricultural activities (growing less rapidly than the main driver of CO2 emissions, energy use). Emissions of the group of F-gases are expected to grow considerably faster than CO2.

- **A multi-gas strategy can achieve the same climate goal at considerably lower costs than a CO2-only strategy.** The cost reduction may amount to about 30–40% for GDP losses and 35– 60% for the marginal abatement costs. The largest cost reductions are expected to occur early on in the mitigation policy.

- **The use of different metrics to aggregate and compare different greenhouse gases (either for the stabilization target or for substitution) plays a crucial role in the final results of a multi-gas strategy.** More analysis and assessment (for instance, by IPCC) could help to further develop insights into the consequences of selecting certain metrics. This is very important for both research and policy-making. The crucial impact of substitution metrics for multi-gas strategies can be directly seen in the EMF-21 results. Under a multi-gas strategy using the 100-year GWPs, the contribution of the non-CO2 gases in total reductions is very large early in the scenario period (50–60% in the first two decades). Later in this period, the contribution of most gases becomes more proportional to their share in baseline emissions. Not using GWPs, but determining substitution on the basis of cost-effectiveness instead of realizing a long-term target within models, implies that reductions in CH4 are delayed to later in the century. Regarding the stabilization target (the second metric), EMF-21 analysis has focused on stabilizing radiative forcing. However, some publications have indicated that stabilization of global temperature can be achieved more cost-effectively through profiles that result in radiative forcing levels that peak and then decline. Further research could focus on such overshoot scenarios.

- **Identified reduction potentials for non-CO2 gases become exhausted if substantial emission reductions are required, for instance, reductions to 40% for N2O compared to baseline across all models and to 50% for CH4 (compared to almost 70% for CO2).** Further research into identifying means to reduce agricultural CH4 and N2O emissions and expected technological change is therefore an important research topic.

7. STABILIZING GREENHOUSE GAS CONCENTRATIONS AT LOW LEVELS: AN ASSESSMENT OF REDUCTION STRATEGIES AND COSTS

Abstract. On the basis of the IPCC B2, A1b and B1 baseline scenarios, mitigation scenarios were developed that stabilize the greenhouse gas concentrations in the long-term at 650, 550 and 450 and – subject to specific assumptions – 400 ppm CO_2-eq. The analysis takes into account a large number of reduction options, such as reduction of non-CO_2 greenhouse gases, carbon plantations and measures in the energy system. The study shows stabilization as low as 450 ppm CO_2-eq. to be technically feasible, even given relatively high baseline scenarios. To achieve these lower concentration levels, global emissions need to peak within the first two decades. The present net present value of abatement costs for the B2 baseline scenario (a medium scenario) increases from 0.2% of cumulative GDP to 1.1% as the shift is made from 650 to 450 ppm. On the other hand, the probability of meeting a two-degree target increases from 0-10% to 20-70%. The mitigation scenarios lead to lower emissions of regional air pollutants (co-benefit) but also to increased land use. The uncertainty in the calculated costs is at least in the order of 50%, with the most important uncertainties including land-use emissions, the potential for bio-energy and the contribution of energy efficiency. Furthermore, creating the right socio-economic and political conditions for mitigation is more important than any of the technical constraints.

This chapter was published earlier as van Vuuren, D.P., den Elzen, M.G.J., Lucas, P.L., Eickhout, B., Strengers, B., van Ruijven, B., Wonink, S. and van Houdt, R. (2007). Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs. *Climatic Change*. 81: 2, March 2007, Pages 119-159.

7.1 Introduction

Climate change appears to be among the most prominent sustainability problems of this century. IPCC's Third Assessment Report concludes that the earth's climate system has demonstrably changed since the pre-industrial era and that – without climate policy responses – changes in the global climate are likely to become much greater, with expected increases in global temperature in the 2000-2100 period ranging from 1.4 to 5.8 °C (IPCC, 2001). Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) states as its ultimate objective: "Stabilization of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system". However, what constitutes a non-dangerous level is an open question, as this depends on all kinds of uncertainties in the cause–effect chain of climate change and on political decisions about the risks to be avoided. Some of the recent literature suggests that climate risks could already be substantial for an increase of 1–3°C compared to pre-industrial levels (see O'Neill and Oppenheimer, 2002; ECF and PIK, 2004; Leemans and Eickhout, 2004; Mastandrea and Schneider, 2004; Corfee Morlot et al., 2005; MNP, 2005a). As one of the political actors, the EU has adopted the climate policy goal of limiting the temperature increase to a maximum of 2°C compared to pre-industrial levels (EU, 1996; EU, 2005). However, uncertainties still allow for other interpretations of what constitutes dangerous climate change in the context of Article 2. Actors can, in their interpretation, weigh such factors as the risks of climate change as function of temperature increase, but also factors such as the potential and costs of adaptation, and the costs and effectiveness of mitigation action.

Apart from the temperature target, the required level of emission reduction also depends on the uncertain relationship between atmospheric GHG concentrations and temperature increase, in other words “climate sensitivity”. Several probability-distribution functions (PDF) for climate sensitivity have been published in recent years, each indicating a broad range of probable values for climate sensitivity (Wigley and Raper, 2001; Murphy, 2004). Several authors have indicated that these PDFs can be translated into a risk approach toward climate change (Azar and Rodhe, 1997; Hare and Meinshausen, 2004; Richels et al., 2004; Yohe et al., 2004; den Elzen and Meinshausen, 2005; Meinshausen, 2006). These studies show that a high degree of certainty in terms of achieving a 2°C temperature target is likely to require stabilization at low GHG concentration (for instance, a probability greater than 50% will require stabilization below 450 ppm CO_2-eq[i]). The stabilization of GHG concentrations at such a low level will require drastic emission reductions compared to the likely course of emissions in the absence of climate policies. Even for more modest concentration targets such as 650 ppm CO_2-eq., emissions in 2100 will generally need to be reduced by about 50% compared to probable levels in the absence of a climate policy (IPCC, 2001).

A large number of scenario studies have been published that aim to identify mitigation strategies for achieving different levels of GHG emission reductions (see among others Hourcade and Shukla, 2001; Morita and Robinson, 2001). However, most of these studies have focused on reducing only the energy-related CO_2 emissions, and have disregarded abatement options that reduce non-CO_2 gases and the use of carbon plantations. Furthermore, the number of studies looking at stabilization levels below 550 ppm CO_2-eq. is very limited. There are a few studies that explore the feasibility to stabilize CO_2 only at 350-450 ppm CO_2; the lowest multi-gas stabilization studies in the literature focus on 550 ppm CO_2-eq. (see Section 7.2). This implies that very little information exists on mitigation strategies that could stabilize GHG concentrations at the low levels required to achieve a 2-3°C temperature target with a high degree of certainty. As a matter of fact, even the number of studies looking at stabilizing at 550 ppm CO_2-eq. is far lower than for higher stabilization targets (Morita et al., 2000; see Swart et al., 2002). Finally, most earlier studies have not considered the more recent mitigation options currently being discussed in the context of ambitious emission re-

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[i] “CO_2 equivalence” expresses the radiative forcing of other anthropogenic radiative forcing agents in terms of the equivalent CO_2 concentration that would result at the same level of forcing. Here, the definition of CO_2-eq. concentrations includes the Kyoto gases, tropospheric ozone and sulfur aerosols.

duction, such as carbon capture and storage (CCS); the importance of this option is highlighted in Edmonds et al. (2004), IEA (2004a) and IPCC (2005). Given current insights into climate risks and the state of the mitigation literature, then, there is a very clear and explicit need for comprehensive scenarios that explore different long-term strategies to stabilize GHG emissions at low levels (Morita and Robinson, 2001; Metz and Van Vuuren, 2006).

This chapter explores different multi-gas stabilization scenarios for concentration levels for which no scenarios are currently available (below 550 ppm CO_2-eq). In order to study the impact of different stabilization levels, we have chosen to explore scenarios for a range of concentrations levels (i.e. 650, 550 and 450 ppm CO_2-eq. and, under specific assumptions, 400 ppm CO_2-eq)[ii]. As such, the study also goes beyond our own research that did not cover stabilization scenarios below 550 ppm CO_2-eq. (van Vuuren et al., 2006b)[iii]. The chapter makes an important contribution to the existing literature by exploring pathways to those GHG stabilization levels required for achieving global mean temperature change targets of 2-3°C with a high degree of certainty. We focus specifically on the following questions:

- What portfolios of measures could constitute promising strategies for stabilizing GHG concentrations at 650, 550 and 450 ppm CO_2-eq. and below?
- What are the cost levels involved in such strategies and what are the implications for the energy sector, investment strategies and fuel trade?
- How do uncertainties in the potentials and costs of various options play a role in terms of the costs and selection of a portfolio of measures?

The focus here will be on mitigation strategies, abatement costs and climate consequences from a global perspective. In a related article, we focused on the regional costs and abatement strategies[iv] (den Elzen et al., 2007). For costs, we focus on direct abatement costs from climate policy and do not capture macro-economic costs; for benefits, we focus on the impact on global mean temperature and co-benefits for air pollutants. Furthermore, for instance, we do not consider the avoided damages caused by climate change). In our analysis, we deliberately use an integrated approach, dealing with a wide range of issues that are relevant in the context of stabilization scenarios; these include land-use consequences and changes in the energy system. Although several of these issues were studied earlier for single stabilization scenarios, here we wanted to see how they are related to the GHG stabilization level.

The analysis was conducted using the IMAGE 2.3 model framework, including the energy model, TIMER 2.0, coupled to the climate policy model, FAIR–SiMCaP (for model

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[ii] The term “specific assumptions” here emphasizes the fact that we need to include additional reduction measures to reach this target as explained in Section 7.6.3).

[iii] Earlier we published emission profiles that would lead to stabilization at low GHG concentration levels, but that study did not look into the question how these emission profiles could be reached (den Elzen and Meinshausen, 2005).

[iv] Regional costs also depend on possible agreements on regional reduction targets and therefore constitute a separate topic that cannot be dealt with in the context of this article. It should, however, be noted that the analysis has been done using models that include regional detail.

description, see Section 7.3 and Chapter 2 of this thesis). A similar framework (using FAIR instead of FAIR–SiMCaP) was used earlier to study mitigation strategies, for example, in the context of EU climate policy targets (Criqui et al., 2003; van Vuuren et al., 2003c). This model framework was designed to provide a broad description of the issues involved in the chain of events causing climate change. It covers a broad range of emission sources (and therefore abatement options), dealing not only with the energy sector but also with land use, forestry and industry. It is therefore suitable for studying the type of mitigation strategies required to stabilize radiative forcing from GHG and the possible environmental and economic consequences of such strategies. We used this framework to explore stabilization strategies based on three different baseline scenarios, i.e. updated implementations of the IPCC SRES B2, B1 and A1b scenarios. We performed an extensive sensitivity analysis for the different options to map out some of the main uncertainties.

The chapter starts with a brief overview of earlier work on stabilization scenarios and is followed by an explanation of the methods used to develop the new scenarios. Then there is a discussion on the initial results from the stabilization scenarios and the associated benefits and co-benefits. We then present the results of our uncertainty analysis and also address the question of whether it is possible to reduce emissions to levels even lower than 450 ppm CO_2-eq. Subsequently, we compare our results to earlier studies and examine the implications of the uncertainties that have been identified. The chapter ends with a presentation of our overall findings.

7.2 Earlier work on stabilization scenarios

A large number of the scenario studies published have explored global mitigation strategies for stabilizing GHG concentrations. A recent inventory estimated the number of published GHG emission scenarios at a few hundred, although a large majority of these are baseline scenarios (scenarios that do not take the effect of climate policy into account) (NIES, 2005).[v] In the literature on mitigation scenarios, there are a number of recurring themes. These include:

- the issue of stabilization targets and overshoot;
- the identification of overall cost levels of stabilization;
- the issue of timing (early action or delayed response), partly in relation to technology development, and
- the role of individual technologies and mitigation measures.

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[v] It is possible to distinguish between *scenarios* and emission *pathways*. Emission pathways focus solely on emissions, whereas *scenarios* represent a more complete description of possible future states of the world. The literature distinguishes between baseline, and mitigation or stabilization scenarios. The first category includes scenarios without explicit new climate policies. These scenarios do, however, need to assume policies in other fields than climate policy, and may still unintentionally have a significant impact on GHG emissions (e.g. other environmental policies and trade policies). Mitigation scenarios (or climate policy scenarios) purposely assume climate policies to explore the impact of these policies. Stabilization scenarios are a group of scenarios that include mitigation measures intended to stabilize atmospheric GHG concentrations.

Here, we will briefly discuss the available literature and indicate how these themes have been dealt with. The IPCC Third Assessment Report (TAR) (Hourcade and Shukla, 2001; Morita and Robinson, 2001) and Fourth Assessment Report (AR4) (Fisher et al., 2007) provide an overview of the stabilization scenarios in a larger context.

On the issue of *stabilization targets*, many studies in the past have focused on stabilizing CO_2 concentration levels. Consistent with this, new multi-gas studies focus mostly on the comparable measure for the stabilization of radiative forcing (expressed in W/m^2 or CO_2-eq.) (van Vuuren et al., 2006d). Alternatively, some studies look at temperature increase targets (as they are more directly related to impacts). One implication of using a temperature target, however, is the higher level of uncertainty relating to mitigation action (Matthews and van Ypersele, 2003; Richels et al., 2004). Another issue is that staying below a certain temperature level with a specific likelihood can either be achieved by: (a) stabilizing at a certain radiative forcing level or by (b) peaking at somewhat higher levels, immediately followed by a reduction of the forcing level ("overshoot scenarios"). The second strategy prevents some of the temperature increase that will occur in the longer term (Wigley, 2003; den Elzen and Meinshausen, 2005; Meinshausen, 2006).

In general, these overshoot scenarios show lower costs than the corresponding stabilization scenarios for a given radiative forcing target. For the lower stabilization levels, overshoot scenarios are, in fact, the only feasible scenarios since current concentrations have either already passed these levels, or will do so in the very near future. In broad terms, the current scenario literature covers stabilization levels from 750 to 450 ppm CO_2 for "CO_2-only" studies. There are only a few studies that have looked into stabilizing concentrations at low concentration levels. Exceptions include the work of Nakicenovic and Riahi (2003), Azar et al. (2006) and Hijoka et al.(2005). These studies show that low stabilization levels (below 450 ppm CO_2) can, in principle, be achieved at mitigation costs in the order of 1-2% of GDP. However, both studies started from relatively low-emission baseline scenarios.

In multi-gas studies, the range of stabilization targets considered in analysis is actually much more limited, with studies typically only looking at 650 ppm CO_2-eq. (van Vuuren et al., 2006d; Weyant et al., 2006). The lowest scenarios currently found in the literature aim at 550 ppm CO_2-eq. (Criqui et al., 2003; van Vuuren et al., 2006b), a concentration level that leads to only a probability of limiting temperature increase to less than 2°C. For a range of probability-distribution functions (PDF), Hare and Meinshausen (2004) estimated the probability to be about 0-30%. The probability of staying within 2.5°C is 10-50%. A 50% probability (on average) of staying within 2°C is obtained for 450 ppm CO_2-eq. The only multi-gas studies in the literature that are currently exploring the consequences of aiming to achieve such low stabilization levels are emission pathway studies that do not specify the type of mitigation measures leading to the required emission reductions (den Elzen and Meinshausen, 2005; Meinshausen, 2006; Meinshausen et al., in press).

Different measures are used for the costs of mitigation. Energy system models (that do not describe the whole economy, but only the energy sector) generally report costs as increased energy system costs or abatement costs. These are annual costs that can be expressed as percentages of GDP. General equilibrium models describe the total macro-economy including the energy system, and can thus estimate the feedbacks on increased investments in the energy system. As a more integrated costs measure, these models generally report costs in terms of reductions of GDP or private consumption relative to the baseline scenario. For the 30-40 stabilization scenarios analyzed in TAR, the assessment found very small costs for stabilizing at 750 ppm and GDP losses in the order of 1-4% for 450 ppm (Hourcade and Shukla, 2001). Costs were found to be a function of the GHG stabilization level and the baseline emission scenario. This implies that socio-economic conditions, including policies outside the field of climate policy, are just as important for stabilization costs as climate policies.

The issue of the *timing* of the abatement effort was initiated by Hamitt et al. (1992) and later by Wigley et al. (1996). Wigley et al. (1996) argued that their scenarios, that postponed abatement action in comparison to earlier pathways developed by IPCC, were more cost-effective because of the benefits of technology development, more CO_2 absorption by the biosphere and ocean and discounting of future costs. Their arguments were confirmed in the analysis of the EMF-14 (Energy Modeling Forum) study (as reported by (Hourcade and Shukla, 2001). Other authors, however, responded that this conclusion depended on the assumptions on discounting, technological change, inertia and uncertainty (Ha-Duong et al., 1997; Azar, 1998; Azar and Dowlatabadi, 1999; van Vuuren and de Vries, 2001). For low-range concentration targets, Den Elzen and Meinshausen (2005) reported that delaying the peak in global emissions beyond 2020 would lead to very high reduction rates later in the century and therefore to probable high costs. Assumption of induced technology change (instead of exogenous technological progress simply as function of time) and explicit capital turnover rates could lead to a preference for early action, or at least a spread of the reduction effort over the century as a whole (see also van Vuuren et al., 2004). The debate about optimal timing is still ongoing. Yohe et al. (2004) recently showed that hedging strategies (i.e. cost-optimal reduction pathways incorporating the risk of more, or less, stringent action later in the century if new evidence comes in) to deal with uncertainties may lead to relatively early reduction pathways, leaving as many options open as possible (Berk et al., 2002).

Recently, considerable attention has been paid to extending the number of reduction options considered in scenario analysis. One possibility is the inclusion of *non-*CO_2 *GHGs*. The Energy Modeling Forum (EMF-21) performed a model comparison study, showing that extending the reduction options from CO_2 only to include other GHGs can reduce costs by about a third (van Vuuren et al., 2006d; Weyant et al., 2006). Recent publications also put forward several "*new technologies*" that could be pivotal in mitigation strategies. First of all, CCS could play an important role in reducing GHG emissions in the power sector. This technology could become cost-effective at emission permit prices of around 100-200 US$/tC (IPCC, 2005) and therefore considerably reduce mitigation costs (Edmonds et al., 2004; IEA, 2004a). Recent work on hydrogen as an energy carrier has shown that although hydrogen may also reduce mitigation costs, this conclusion will depend very much on the assumption of technology development (e.g. Edmonds et al., 2004). Bio-energy in combination with CCS could be an attractive technology if very ambitious stabilization targets were adopted (Azar et al., 2006). Finally, the debate is still ongoing about whether accounting for technology change (induced learning vs. exogenous assumptions) in itself results in different conclusions about optimal climate policies. Some studies claim that induced technological change will lead to very significant cost reductions, justifying a preference for early action (Azar and Dowlatabadi, 1999; van Vuuren and de Vries, 2001; Barker et al., 2005). Others report fewer benefits and/or no impact on timing (Manne and Richels, 2004).

What are the implications of the current state of knowledge for this study? The most important aim here is to determine whether low concentration levels are achievable. In terms of the objective of climate policy, we focus on the stabilization of concentration (and thus not temperature) to increase the comparability with other studies. Den Elzen et al. (2005) indicated how the results of the emission pathways compared to alternative peaking scenarios. With reference to the debate on new mitigation options, the model framework used in this study covers a large range of mitigation options and several technologies are described in terms of induced technological change. Given the major uncertainties involved in each of the mitigation options, we will analyze how some of these uncertainties impact the overall results.

7.3 Methodology

7.3.1 Overall methodology

For the construction of the stabilization scenarios, we used an interlinked model framework consisting of the IMAGE 2.3 Integrated Assessment model (IMAGE-team, 2001), which included the TIMER 2.0 energy model (Chapter 2) coupled to the climate policy model FAIR-SiMCaP (den Elzen and Lucas, 2005; den Elzen and Meinshausen, 2005). [vi] These models have been linked for the purpose of this analysis in a way similar to that described earlier by Van Vuuren et al. (2003c), as shown in Figure 7.1. Chapter 2 (TIMER and IMAGE) and Appendix 7.A (FAIR) provides additional information on the different models used.

The IMAGE 2.3 model is an integrated assessment model consisting of a set of linked and integrated models that together describe important elements of the long-term

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[vi] IMAGE 2.3 is an updated version of IMAGE 2.2, the difference being the option of exploring impacts of bio-energy and carbon plantations. TIMER 2.0 is an updated version of TIMER 1.0. The main differences are additions with respect to hydrogen, bio-energy and modeling of the electric power sector. The FAIR model used in this study is actually a version coupled to SiMCaP. Here, FAIR is a policy-support tool focusing on the costs of climate change and the influence of burden-sharing agreements. The SiMCaP model is able to develop emission pathways that lead to certain climate targets. The FAIR-SiMCaP model is further abbreviated to FAIR.

dynamics of global environmental change, such as air pollution, climate change and land-use change. IMAGE 2.3 uses a simple climate model and a pattern-scaling method to project climate change at grid level. At grid level, agriculture is described by a rule-based system driven by regional production levels. Finally, natural ecosystems are described by an adapted version of the BIOME model. The global energy model, TIMER 2.0, a component of the IMAGE model, describes primary and secondary demand for, and production of, energy and the related emissions of GHG and regional air pollutants. The FAIR model is a combination of the multi-gas abatement-cost model and module relating emission pathways to long-term targets (SiMCaP). The FAIR cost model distributes the difference between baseline and global emission pathways using a least-cost approach involving regional Marginal Abatement Cost (MAC) curves for the different emission sources (den Elzen and Lucas, 2005) (den Elzen and Meinshausen, 2005).[vii] Calculations in all three main models are carried out for 17 regions[viii] of the world.

The overall analysis consists of three major steps (Figure 7.1):

1. Both the IMAGE and the TIMER model are used to construct a *baseline emission scenario*. Furthermore, the TIMER model yields the *potentials and abatement costs* of reducing emissions from energy-related sources, while the IMAGE model provides the potentials and abatement costs associated with carbon plantations (7.3.2/7.3.3).
2. The FAIR/SIMCAP model is used to develop *global emission pathways* that lead to a stabilization of the atmospheric GHG concentration. The concentration calculations are done using the MAGICC 4.1 model (Wigley and Raper, 2001) that is included in FAIR/SIMCAP. The FAIR model distributes the global emission reduction from the baseline across the different regions, gases and sources in a cost-optimal way using the marginal abatement costs. It is assumed that these gases are substituted on the basis of GWPs. Furthermore, the model calculates the international permit price[ix], the regional emission reductions, and the global and regional costs of emission reductions (7.3.4).
3. The IMAGE/TIMER model implements the changes in emission levels resulting from the abatement action (emission reductions) and the permit price, as determined in the previous step, to develop the final *mitigation scenario* (emissions, land use, energy system). Furthermore, the environmental impacts are assessed using the climate model of IMAGE.

In our analysis, we assume that reductions could be cost-optimally distributed across all 17 regions from 2013 onwards. This implies the presence of some form of international mechanism that justifies this least-cost assumption, such as emission trading.

[vii] Marginal Abatement Cost (MAC) curves reflect the additional costs of reducing the last unit of CO_2-eq. emissions.

[viii] Canada, USA, OECD-Europe, Eastern Europe, the Former Soviet Union, Oceania and Japan, Central America, South America, Northern Africa, Western Africa, Eastern Africa, Southern Africa, Middle East and Turkey, South Asia (incl. India), South-East Asia and East Asia (incl. China) (IMAGE-team, 2001).

[ix] This “permit price” is equal to the marginal costs of reducing greenhouse gas emissions to the required level of reduction. In the energy model the permit price is equal to carbon tax.

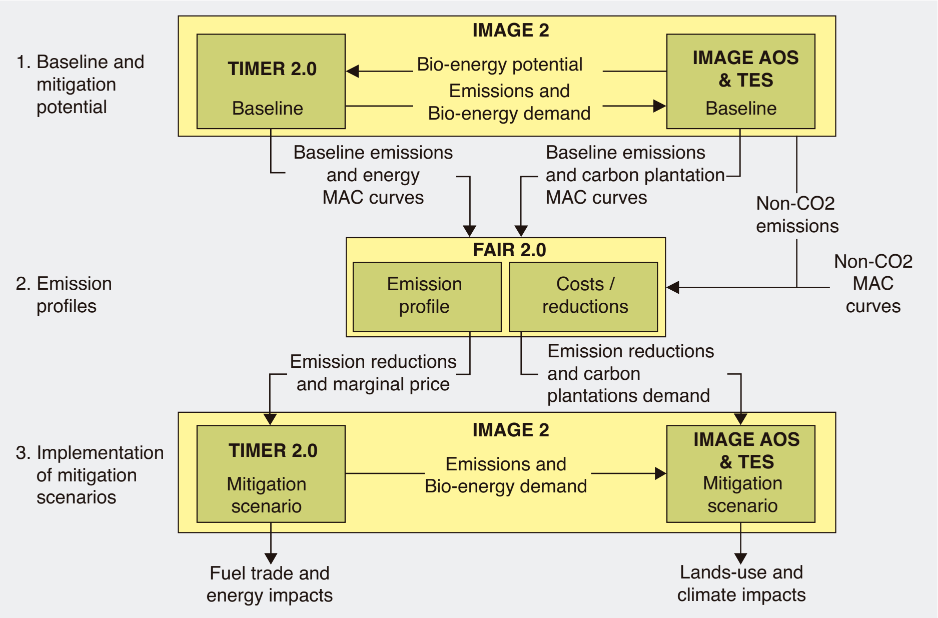

Figure 7.1 Linkage and information flows of the applied modeling framework. The 3 numbers in the figure are explained in the text. AOS = Atmosphere/Ocean System; TES = Terrestrial environment system.

7.3.2 Baseline emissions

The baseline scenarios used in this study are based on IPCC-SRES scenarios (Nakicenovic and Swart, 2000). This set of baseline scenarios explores different possible pathways for GHG emissions and can roughly be categorized along two dimensions: the degree of globalization vs. regionalization, and the degree of orientation towards economic objectives as opposed to an orientation towards social and environmental objectives. In 2001, the IMAGE team published detailed elaborations of these scenarios (IMAGE-team, 2001). Chapters 4 and 5 provide more information on the assumptions and storylines underlying the SRES scenarios. Although the scenarios are still broadly consistent with the literature, new insights have emerged for some parameters. For instance, current projections for population and economic growth for low-income regions are generally lower than assumed in SRES (Chapter 3). Against this background, a set of updated IMAGE scenarios was developed recently (see Figure 7.2). Here, we use the B2 scenario as the main baseline scenario, with the A1b and B1 scenarios being used to show the impacts of different baseline assumptions.

The new implementation of B2 focuses explicitly on exploring the possible trajectory of greenhouse gas emissions on the basis of medium assumptions for the most important drivers (population, economy, technology development and lifestyle). In terms of its quantification, the B2 scenario follows roughly the reference scenario of the World Energy Outlook 2004 for the first 30 years (IEA, 2004b). After 2030, economic growth

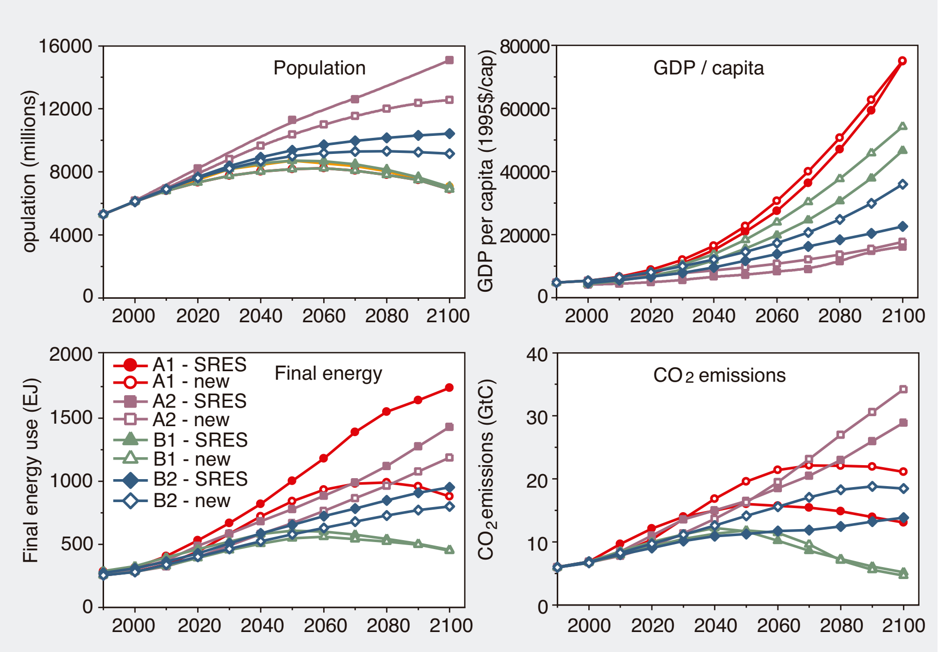

Figure 7.2 Driving forces and fossil fuel CO_2 emissions in the IMAGE 2.3 SRES scenarios in comparison to the IPCC SRES Marker scenarios (Nakicenovic and Swart, 2000).

converges to the B2 trajectory of the previous IMAGE scenarios (IMAGE-team, 2001). The long-term UN medium population projection is used for population (UN, 2004).

The A1b scenario, by contrast, represents a world with fast economic growth driven by further globalization and rapid technology development. As the scenario also assumes material-intensive lifestyle, energy consumption grows rapidly. The B1 scenario describes a world characterized by strong globalization in combination with environmental protection and a reduction of global inequality. It assumes the use of very efficient technologies, resulting in relatively low energy use. The assumptions for population and economic growth in the A1 and B1 scenarios have been taken from, the Global Orchestration and Technogarden scenarios of the Millennium Ecosystem Assessment, respectively (Carpenter and Pingali, 2006). In all three scenarios, trends in agricultural production (production levels and yields) are also based on the Millennium Ecosystem Scenarios, which were elaborated for these parameters by the IMPACT model (Rosegrant et al., 2002). All other assumptions conform to earlier implementation of the SRES scenarios.

As shown in Figure 7.2, the resulting emissions are still broadly consistent with the IPCC Marker scenarios. The A1 scenario shows higher emissions than the corresponding marker, given slightly different assumptions on technology change and fuel choices – but is easily within the range of other elaborations of this storyline. The B2 scenario also has higher emissions than the corresponding marker, partly reflecting the shift in storyline from an environmental-focus scenario to a medium emission scenario as described above.

7.3.3 Assumptions in the different subsystems and marginal abatement costs

We adopted a hybrid approach to determine the abatement efforts among the different categories of abatement options. First, the possible abatement in different parts of the system (energy, carbon plantations and non-CO_2) is translated into aggregated baseline- and time-dependent MAC curves. These curves are then used in the FAIR model to distribute the mitigation effort among these different categories and to determine the international permit price. Finally, the corresponding reduction measures at the more detailed level are determined by implementing the permit price in the different “expert” models for energy (TIMER) and carbon plantations (IMAGE). For instance, in the case of energy, the TIMER model results in a consistent description of the energy system under the global emission constraint set by FAIR.

The TIMER, IMAGE and FAIR models have been linked so that output of one model is the input of the second model (see Figure 7.1). In addition, also the model-specific assumptions in the different models have been harmonized. In most cases, this was done on the basis of the storyline of the different scenarios being implemented. For example, technology development is set low for all parameters in the different models in the A2 scenario. The same holds for other driving forces. In terms of land use, both carbon plantations and bio-energy calculations start with the same land-use scenario (implementation factors prevent them using the same land) and the same land price equations. A 5% per year social discount rate is used to calculate the Net Present Value for the mitigation scenarios (this discount rate is chosen for comparison with other studies (Hourcade and Shukla, 2001); the level is relatively high, but as costs in this study are mostly used in comparison to income levels or relative to other levels, it does not really impact the results of the study. In the energy system, investment decisions are compared using a 10% per year discount rate, which provides a better reflection of the medium-term investment criteria used in making such investments. Table 7.1 summarizes some of the assumptions made. All costs are expressed in 1995 US$.

Energy

The TIMER MAC curves (used by the FAIR model) are constructed by imposing an emission permit price (carbon tax) and recording the induced reduction of CO_2 emissions[x]. There are several responses in TIMER to posing an emission permit price. In energy supply, options with high carbon emissions (such as conventional use of coal and oil) become more expensive compared to options with low or zero emissions (such as natu-

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[x] The carbon tax is intended to induce a cost-effective set of measures and is, in the model, equivalent to an emission permit price. In the rest of the article, we will use the term (emission) permit price. It should be noted that in reality, the same set of measures as induced by the permit price can also be implemented through other types of policies.

ral gas, fossil fuels with CCS, bio-energy, nuclear power, solar and wind power). The latter options therefore gain market shares. In energy demand, investments in efficiency become more attractive.

To construct the MAC curves, the induced reduction of CO_2 emissions is recorded for sight years from 2010 to 2100 (in ten-year steps). In the energy model TIMER, the response to a carbon tax does depend on the pathway of introduction (e.g. early introduction leads to induced technology change); see also Chapter 8. To capture (as a first-order approximation) the time pathway, two very different permit price profiles were used to explore responses: one that assumes a linear increase from 2010 to the permit price value in the sight year ("linear price MAC") and one that reaches the maximum value 30 years earlier ("block price MAC"). The second profile results in more CO_2 reductions because the energy system has more time to respond (corresponding to "early-action"). Depending on the pathway of the actual permit price in the stabilization scenario, FAIR combines the linear price MAC curves and the block price MAC curves, so that some of the dynamics can be captured.[xi]

In the baseline, stricter investment criteria are used for investments in energy efficiency than for investments in energy supply. Investments in energy efficiency are made only if the apparent average pay-back time is less than three years (for industry) or two years (other sectors) (see de Beer, 1998)[xii]. In low-income countries, we assume that lower efficiency in industry and other sectors are caused by even lower apparent average pay-back-time criteria (de Vries et al., 2001). The criteria used in energy supply (based on a 10% discount rate and the economic life time depending on the type of technology applied) corresponds more-or-less to a pay-back time of 6-7 years. The difference between demand and supply investment criteria is based on historical evidence (barriers to demand-side investments that include lack of information, more diffuse investors, higher risks and lack of capital). Under climate policies, investments into energy efficiency could therefore form a very cost-effective measure if these barriers can be overcome. In our calculations, we assume that this is the case as a result of: 1) an increase in attention for ways to reduce carbon emissions (leading to more information) and 2) the availability of capital flows, including flows to developing countries, which could result from carbon trading (or other flexible mechanisms). Based on this, we assume a convergence of the pay-back-time criterion to six years as a function of the existing emission permit price – with full convergence at the highest price considered, i.e. 1000 US$/tCeq.

[xi] The actual tax profile chosen in FAIR is compared to the underlying the two TIMER "MACs". On this basis, FAIR constructs a linear combination for the next time step of the two types of response curves. A rapidly increasing tax in FAIR implies that the profile resembles more the profile underlying the linear tax, while a more constant tax level in FAIR implies that the profile shows more resemblance to the block tax. In the former situation more emphasis is given to the MAC of the linear tax profile, while in the latter the block tax MAC is given more weight.

[xii] A pay-back-time is a simple investment criterion that indicates the time-period required to earn back the original investment. Research indicates that many actors are not aware of the energy efficiency improvement measures or face all kinds of implementation barriers. As a result, the average apparent pay-back-time of a sector is considerably lower than the investment criteria that are stated to be used by these actors (de Beer, 1998).

Carbon plantations

The MAC curves for carbon plantations have been derived using the IMAGE model (for methodology, see Graveland et al., 2002; Strengers et al., 2007). In IMAGE, the potential carbon uptake of plantation tree species is estimated for land that is abandoned by agriculture (using a 0.5 x 0.5 grid), and compared to carbon uptake by natural vegetation. Only those grid cells are considered in which sequestration by plantations is greater than sequestration by natural vegetation. In the calculations, we assumed that carbon plantations are harvested at regular time intervals, and that the wood is used to meet existing (commercial) wood demand. Regional carbon sequestration supply curves are constructed on the basis of grid cells that are potentially attractive for carbon plantations. These are converted into MAC curves by adding two kinds of costs: land costs and establishment costs. We found the cumulative abandoned agricultural area under the SRES scenarios to range from 725 and 940 Mha in 2100, potentially sequestering 116 to 146 GtC over the century (the term agricultural land in this chapter covers both cropland and pasture land). The costs of the reductions vary over a wide range.

Non-CO_2 gases

For non-CO_2 gases the starting point of our analysis consists of the MAC curves provided by EMF-21 (van Vuuren et al., 2006d; Weyant et al., 2006). This set is based on detailed abatement options, and includes curves for CH_4 and N_2O emissions from energy- and industry-related emissions, and from agricultural sources, as well as abatement options for the halocarbons. This set includes MAC curves over a limited cost range of 0 to 200 US$/tC-eq., and does not include technological improvements over time. Lucas et al. (2007) have extended this set on the basis of a literature survey and expert judgement on long-term abatement potential and costs. They assume that the long-term potential is significantly higher than current potential as a result of technology development and the removal of implementation barriers. The overall potential amounts to about 3 GtC-eq. annually (with the lion's share available below 200 US$/tC-eq.).

7.3.4 Emission pathways

This study uses the global multi-gas emission pathways that meet the GHG concentration stabilization targets 450, 550 and 650 ppm CO_2-eq. (den Elzen et al., 2006). As explained by Den Elzen et al., these emission pathways are different from hypothetical emission pathways constructed in some other studies, given the fact that at each point of time they are constrained by reduction potential of the MAC curves discussed above. As these curves aim to reflect technically feasible reductions, also the pathways can be considered as such. In that context, three additional criteria were used in developing the pathways:

- First, a maximum reduction rate was assumed, reflecting the technical (and political) inertia that limits emission reductions. Fast reduction rates would require early replacement of existing fossil-fuel-based capital stock, and this may involve high costs. The selected values (maximum 2-3% per year) are based on the reduction rates

Table 7.1 Default assumptions for various reduction options and the alternative assumptions used in the sensitivity analysis

Mitigation option	Pessimistic assumption	Base case	Optimistic assumption
Carbon plantations	Carbon uptake reduced by 25% + implementation factor reduced to 30%	Implementation factor is 40% (i.e. 40% of maximum potential is used).	Carbon uptake increased by 25% + implementation factor increased to 50%
Non-CO_2	20% increase in costs; 20% decrease in potential	Expert judgment as described in Lucas et al. (2007). Total reduction potential of non-CO_2 gases slightly above 50%.	20% decrease in costs; 20% increase in potential
Hydrogen	No hydrogen penetration	Default assumptions lead to hydrogen penetration by the end of the century in the baseline scenario.	Optimistic assumptions for fuels cells and H_2 production costs (10% reduction of investment costs) lead to penetration around 2050 (baseline scenario).
Efficiency improvement	Climate policies do not lead to removal of implementation barriers for efficiency.	Climate policies lead to some removal of implementation barriers for efficiency.	Climate policies lead to full removal of implementation barriers for efficiency.
Bio-energy	Less available land for bio-energy (50% less)		Bio-energy can also be used in combination with CCS technology.
Technology development	No climate policy-induced learning	Climate policy-induced learning	
Carbon capture and storage	No carbon capture and storage	Medium estimates for CCS storage potential (see Table A1)	
Nuclear	Nuclear not available as mitigation option	Nuclear available as mitigation option	
Emission trading	Emission trading restricted due to transaction costs of 15$/tC.	Full emission trading	
Land use	Agricultural yields do not improve as fast (following MA's Order from Strength Scenario).	Medium yield increases (following MA's Adaptive Mosaic Scenario).	Agricultural yields improve fast (following MA's Global Orchestration scenario).
Baseline	IMAGE 2.3 A1b	IMAGE 2.3 B2	IMAGE 2.3 B1
All	All above, excluding land use and baseline	All above, excluding land use and baseline	All above, excluding land use and baseline

Note: Not for all the options were more optimistic assumptions tested. The variation of baseline in this sensitivity analysis changes also storyline-related assumptions for other parameters.

of the post-SRES mitigation scenarios (e.g., Swart et al., 2002) and the lower range of published mitigation scenarios (Nakicenovic and Riahi, 2003; Azar et al., 2006).
- Secondly, the reduction rates compared to baseline were spread as far as possible over time –avoiding rapid early reduction rates.
- Thirdly, the reduction rates were only allowed to change slowly over time.

In the case of the 650 and 550 ppm CO_2-eq. goals, the resulting pathway leads to stabilization between 2100 and 2200 below the target level and without overshoot. For the 450 ppm CO_2-eq. concentration target, however, a certain overshoot (or peaking) is assumed. In other words, concentrations may first increase to 510 ppm before stabilizing at 450 ppm CO_2-eq. before 2200. This overshoot is justified by reference to present concentration levels, which are already substantial (430 ppm CO_2-eq, not accounting for sulfur aerosols and slightly below 400 ppm if sulfur is included). Overshoot is also justified by the attempt to avoid drastic sudden reductions in the emission pathways presented.

The FAIR model distributes the global emission across the different regions, gases and sources in a cost-optimal way, using the marginal abatement costs. Different gases are assumed to be substituted on the basis of Global Warming Potentials, an approach consistent with climate policies under the Kyoto Protocol and the US domestic climate policy (White-House, 2002). Chapter 6 of this thesis discusses the consequences of using a GWP-based approach.

7.4 Stabilizing GHG concentration at 650, 550, 450 ppm: central scenarios

7.4.1 Emission pathways and reductions

Under the central baseline, B2, worldwide primary energy use nearly doubles between 2000 and 2050 and increases by another 35% between 2050 and 2100. Most of this growth occurs in non-Annex I regions (about 80%). Oil continues to be the most important energy carrier in the first half of the century, with demand being mainly driven by the transport sector. Natural gas dominates new capacity in electric power in the first decades, but starts to be replaced by coal from 2030 onwards due to increasing gas prices. As a result, coal becomes the dominant energy carrier in the second half of the 21st century. Energy-sector CO_2 emissions continue to rise for most of the century, peaking at 18 GtC in 2080. Total GHG emissions[xiii] also increase, i.e. from about 10 GtC-eq. today to 23 GtC-eq. in 2100 (Figure 7.3). Figure 7.3 also shows that compared to the existing scenario literature; this baseline is a medium-high emission baseline. As a result of decreasing deforestation rates, CO_2 emissions from land use decrease. At the same time, CH_4 emissions, mostly from agriculture, increase. The GHG concentration

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[xiii] The term total GHG emissions in this report refers to all GHG covered by the Kyoto Protocol: i.e.CO_2, CH_4, N_2O, HFCs, PFCs and SF_6.

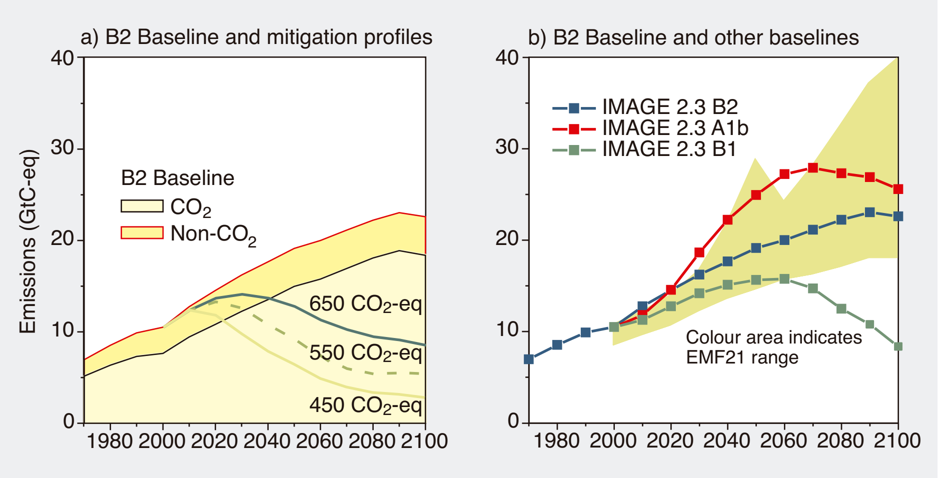

Figure 7.3 Global CO_2-eq. emissions (all sources$_2$) for the B2 baseline emission and pathways to stabilization at a concentration of 650, 550 and 450 ppm CO_2-eq. (panel a; left) and the B2 baseline emissions compared to alternative baselines (panel b; right). Sources:(van Vuuren et al., 2006d; Weyant et al., 2006), for EMF-21 scenarios.

reaches a level of 925 ppm CO_2-eq., leading to an increase in the global mean temperature of 3°C in 2100 (for a climate sensitivity of 2.5 °C, i.e. the equilibrium temperature increase for a doubling of GHG concentrations).

Figure 7.3a shows that in order to reach the selected emission pathway that leads to stabilization of GHG radiative forcing at 650, 550 and 450 ppm CO_2-eq., GHG emissions need to be reduced in 2100 by 65%, 80% and 90%, respectively, compared to the B2 baseline. The short-term differences are even more significant. In the case of the 650 ppm CO_2-eq. pathway, emissions can still increase slightly and stabilize at a level that is 40% above current emissions in the next 3 to 4 decades, followed by a slow decrease. In the case of the 550 ppm CO_2-eq. pathway, however, global emissions need to peak around 2020, directly followed by steep reductions in order to avoid overshooting the 550 ppm CO_2-eq. concentration level. For stabilization at 450 ppm CO_2-eq., short-term reductions become even more stringent, with global emissions peaking around 2015/2020 at a level of 20% above 2000 levels.

7.4.2 Abatement action in the stabilization scenarios

7.4.2.1 Abatement across different gases

Figure 7.4 shows the (cost-optimal) reduction in the mitigation scenarios in terms of different gases (upper panel). Table 7.2, in addition, indicates the emission levels. In all stabilization scenarios, a substantial share of the reduction is achieved in the short term by reducing non-CO_2 gases while only 10% of the reductions come from reducing energy-related CO_2 emissions (see also Lucas et al., 2005). The disproportionate contribution of non-CO_2 abatement is caused mainly by relatively low-cost abatement options that have been identified for non-CO_2 gases (e.g. reducing CH_4 emissions from

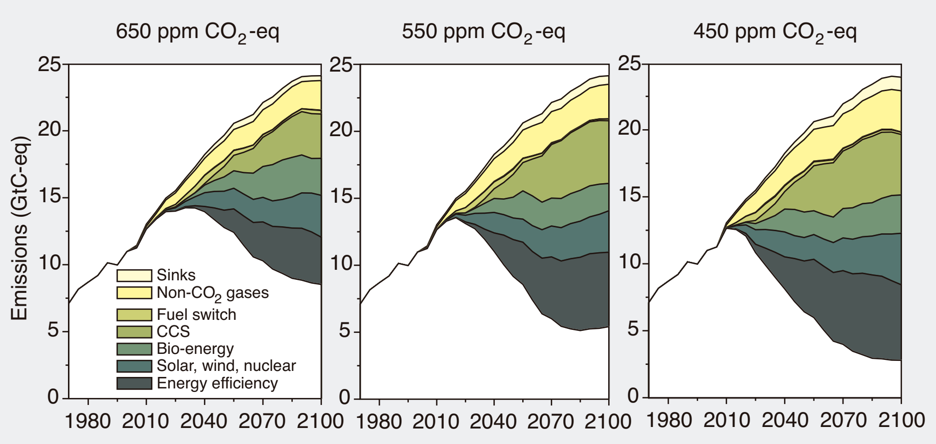

Figure 7.4 Emission reductions for total GHG emissions contributed by gas (upper panel; a) and for energy CO_2 emissions contribute by reduction measure category (lower panel; b) applied to stabilization scenarios at 650, 550 and 450 ppm CO_2-eq.

energy production and N_2O emissions from adipic and acidic acid industries). It should be noted that this is related to the fact that we use GWPs to determine the cost-effective mix of reductions among the different GHGs (see method section and Chapter 6 of this thesis). Alternative approaches, e.g. long-term costs optimization under a radiative forcing target, may result in a different mix (van Vuuren et al., 2006d). After 2015, more and more reductions will need to come from CO_2 in the energy system, increasing to 85% by 2100. This shift simply reflects that non-CO_2 represents about 20% of total GHG emissions and the limited reduction potential for some of the non-CO_2 gases. In addition, some non-CO_2 GHGs cannot be reduced fully due to limited reduction potential (this is the case for some sources of land-use-related CH_4 but is particularly true for some of the N_2O emission sources, see below). The proportion of non-CO_2 abatement does decline somewhat further in the 450 ppm CO_2-eq. scenario than in the 650 ppm CO_2-eq. scenario (with the proportion being limited by the absolute non-CO_2 reduction potential).

More detailed analysis across the different sources shows that for CH_4 relatively large reductions are achieved in for the sources landfills and the production of coal, oil and gas. In total, under the 450 ppm CO_2-eq. stabilization scenario, emissions are reduced by 70% compared to the baseline. In the less stringent 650 ppm stabilization case, CH_4 emissions are halved (returning roughly to today's levels). In the case of N_2O, substantial reductions are achieved for acidic and adipic acid production (up to 70% reduction). However, in comparison to land-use related N_2O emissions, this only represents a small source. For the land-use-related N_2O sources, emission reduction rates are smaller. As a result, total N_2O emission reductions in the strictest scenario amount to about 35% compared to baseline. In the most stringent case, emissions of halocarbons are reduced to almost zero for the group as a whole. In the other two scenarios, considerable reduction rates are still achieved.

Table 7.2 Emissions in 2000 and in 2100 for the B2 baseline and the stabilization scenarios

	2000	2100			
		Baseline	Stabilization scenarios (ppm CO2-eq.)		
			650	550	450
			GtC-eq.		
CO_2 energy/industry					
Electricity sector	2.38	7.96	1.04	0.23	0.09
Industry	0.62	1.54	0.38	0.18	0.03
Buildings	0.50	0.80	0.32	0.23	0.06
Transport	0.79	2.48	0.69	0.32	0.03
Other	0.79	2.11	0.82	0.40	0.15
Total	**6.96**	**18.40**	**5.20**	**2.50**	**0.94**
CO_2 land use	0.90	0.10	0.75	0.67	0.77
CH_4	1.88	3.02	1.33	1.11	0.91
N_2O	0.68	1.03	0.81	0.78	0.69
F-gases	0.14	0.87	0.35	0.27	0.04
Total	**10.56**	**23.42**	**8.44**	**5.33**	**3.35**

The use of carbon plantations contributes about 0.9 GtC annually to the overall mitigation objective in 2100 in the 450 ppm CO_2-eq. scenario, but less in the other two scenarios (0.5 and 0.25 GtC annually). All three scenarios, East Asia, South America and the Former Soviet Union, together account for more than 50% of the carbon plantation mitigation effort (regional detail not shown in figures – but can be found in Strengers et al. (2007)). The trees used vary according to the location and include *Populus nigra* (East Asia and Europe), *Picea abies* (Canada, USA and former USSR) and *E. grandis* (South America, Central Africa and Indonesia). In all three scenarios, high sequestration rates (more than 0.1 GtC annually) are achieved only after 2030-2035 due to the fact that we only allow sinks on abandoned agricultural land, a possibility not available early on. Some of the mitigation by carbon plantations can be achieved at relatively low costs, forming a substantial part of the potential used in the 650 ppm CO_2-eq. stabilization scenario. As a result, the use of carbon plantations depends more on external assumptions (demand for land for food production, yield increases) than on the stabilization target.

7.4.2.2 Abatement action in the energy system

Figure 7.5 shows that the climate policies required to reach the stabilization pathways lead to substantial changes in the energy system compared to the baseline scenario (shown for 450 ppm CO_2-eq.). These changes are more profound when going from 650 to 450 ppm CO_2-eq. In the most stringent scenario, global primary energy use is reduced by around 20%. Most of this reduction occurs in the 2015-2040 period as a result of a rapidly increasing carbon tax. Clearly, the reductions are not similar for the different energy carriers. The largest reductions occur for coal, with the remaining coal consumption being primarily used in electric power stations using CCS. There is also a substantial reduction for oil. Reductions for natural gas are less substantial, while other

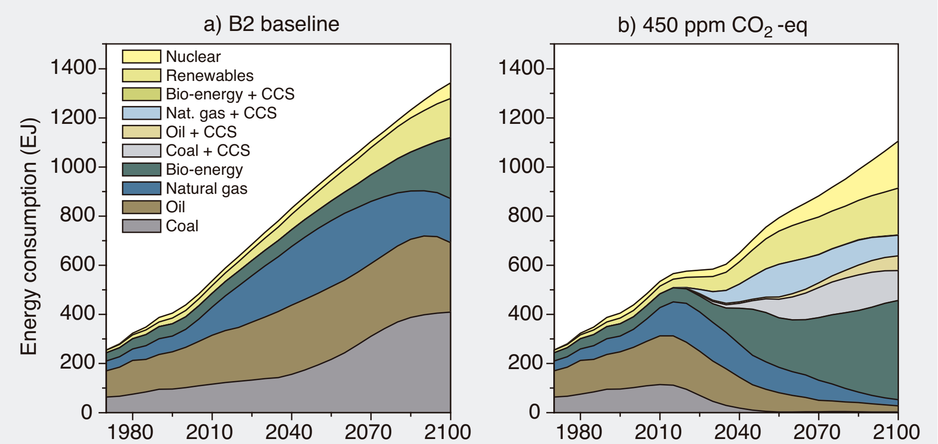

Figure 7.5 Primary energy use in the B2 baseline (left; panel a) and the 450 ppm CO_2-eq. stabilization scenario (right; panel b). Note: Nuclear, solar, wind and hydro power have been reported at a virtual efficiency of 40%; "bio-energy" includes traditional bio-energy; renewables include hydro, solar and wind power.

energy carriers – in particular, solar, wind and nuclear-based electricity and modern biomass – gain market shares.[xiv]

The largest reduction in the energy sector results from changes in the energy supply (Figure 7.4; lower panel). Some changes stand out. First of all, under our default assumptions, CCS – mainly in the power sector – accounts for a major proportion of the emission reductions (up to a third of the reductions in energy-related CO_2 emissions). As a result, large amounts of CO_2 are stored. In the 650 ppm case, 160 GtC, or about 2 GtC annually on average, needs to be stored, mainly in empty gas and oil fields. In the 550 and 450 cases, these numbers are 250 GtC and 300 GtC, or about 3 GtC annually. Here, we use medium estimates of storage capacity (around 1000 GtC) but estimates in the low range are in the order of 100 GtC (Hendriks et al., 2002a). In the more densely populated regions, we find that under our medium assumptions reservoirs from depleted fossil fuel resources will be filled near the end of the century so that these regions will also use aquifers as a storage option[xv]. The decreasing reservoir capacity will lead to slightly higher costs. It should be noted that CCS technology still has to be proven in large-scale application – and safe aquifer capacity (with sufficiently low leakage risks) is uncertain.

[xiv] Modern biomass includes gaseous or liquid fuels produced from plants or trees. It differs from traditional biomass, which refers to gathered wood, straw, dung, charcoal, etc.

[xv] In our analysis we have used the reservoir estimates of Hendriks et al. 2002, including their estimates for aquifers. Hendriks et al. (2002) restricted the potentially available storage capacity in aquifers strictly based on safety requirements for storage. Still, one might argue that the reservoir estimates for aquifers are more uncertain than those for (empty) fossil fuel reservoirs.

Bio-energy use also accounts for a large proportion of the emission reductions. In the baseline scenario of this study about 200 EJ of bio-energy are used. In the most stringent stabilization scenario, bio-energy use increases to 350 EJ. In terms of crops, the bio-energy is produced from a mixture of sources (sugar cane, maize, woody bio-energy and residues, depending on the region). The use of bio-energy in most cases requires land where, in the baseline, there would be natural vegetation sequestering carbon (see Section 7.5.2). The decrease in carbon sequestration by bio-energy production compared to natural vegetation re-growth amounts to about 1–5 kg C per GJ of bio-energy produced, depending on the region and biome (this number represents the annual average across the whole scenario period, by taking the cumulative bio-energy production and the cumulative difference in carbon uptake between the land used for bio-energy production and the original vegetation). This compares to standard emission factors of 25 kg C per GJ for coal, 20 kg C per GJ for oil and 15 kg C per GJ for natural gas. The contribution indicated in Figure 7.4 is the net contribution.

Solar, wind and nuclear power also account for a considerable proportion of the required reductions (it should be noted that we assume that solar, wind, nuclear and hydro power do not lead to GHG emissions; an assumption that is not always correct). In our baseline scenario, the application of renewables (i.e. hydro, wind and solar power) is considerably larger than that of nuclear power (based on current policies and costs). In the mitigation scenarios, both categories increase their market share. For hydro power, we assumed no response to climate policy, given the fact that in the baseline most regions are already approaching their maximum potential levels and that investments into hydropower are often related to other objectives than energy alone. As a result of their intermittent character, the contribution of solar and wind power is somewhat limited by a declining ability to contribute to a sufficiently reliable electric power system at high penetration rates. As a result, the increase in nuclear power shown in the model compared to the baseline is larger than that of renewables. The finding that under climate policy, nuclear power could become a competitive option to produce electric power is consistent with several other studies (MIT, 2003; Sims et al., 2003). However, more flexible power systems, different assumptions on the consequences of intermittency for renewables, the development of storage systems, technological breakthroughs or taking account of public acceptance of nuclear power could easily lead to a different mix of nuclear power, solar and wind power and CCS technologies (and still lead to a similar reduction rate).

Energy efficiency represents a relatively important part of the portfolio early on in the century – but a much smaller share compared to baseline later on. The main reason for the decreasing impact is that the (assumed) cost reductions with zero carbon energy supply options reduce the effectiveness of energy efficiency measures. In addition, the fact that energy efficiency will be closer to the technology frontier in many parts of world will slow down further improvement. Globally, energy use is reduced in 2100 by about 10% in the 650 ppm case and about 20% in the 450 ppm case (see Figure 7.4). The contribution of efficiency differs strongly by region and over time. In Western Europe, for instance, the annual rate of real efficiency improvement in the model in the baseline is about 1.1% per year in the first half of the century, and 0.8% per year over the century as a whole. These numbers refer to the underlying efficiency indicators in the model (see Chapter 2), not the energy intensity (energy over GDP) that improves even somewhat faster due to structural change. The increased energy prices under climate policies in combination with the reduction of investment barriers could raise the numbers to 1.5% and 1.0% per year, respectively, in the 450 ppm CO_2-eq. scenario. In India, climate policy could have a much larger impact. Here, baseline efficiency improvement is assessed at 2.2% per year in the first 40 years and 1.8% per year over the century. Climate policies could push up these numbers to 2.9% per year and 2.1% per year respectively.

An alternative way to look at these data is to use the Kaya indicators of energy intensity (GJ/$) and the carbon factor (kg C/GJ) (Kaya, 1989). Under the baseline scenario, energy intensity improves significantly by about 70% worldwide between 2000 and 2100. The carbon factor remains virtually constant (in line with historic trends). It is only in the last few decades that some decarbonization occurs as high oil prices induce a transition to bio-energy. This implies that in the baseline scenario energy intensity improvement is the main contributor to decreasing the ratio between CO_2 emissions and GDP growth. In the mitigation scenarios, the rates increase for both energy intensity and carbon factor improvement. While the contribution of the two factors to emission reductions compared to baseline levels is about the same in 2020, changes in the carbon factor compared to baseline (in other words: changes in energy supply) in 2050 and 2100 contribute much more to lower emission levels than energy intensity. This can be seen in Figure 7.6 by the fact that in 2020 the mitigation scenario points are moved parallel to the diagonal compared to the baseline scenario points, while in 2050 and 2100 they move strongly in the direction of carbon factor increases. Under the 450 ppm scenario, the carbon factor decreases by about 85% compared to baseline by the end of the century.

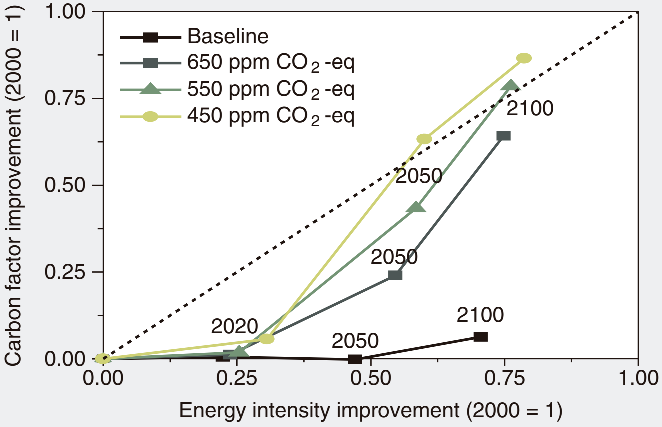

Figure 7.6 Relative changes in global energy intensity (energy/GDP) and the carbon factor (CO_2/energy) in the B2 baseline and the three mitigation cases compared to 2000 values. Note: The diagonal line indicates equal reduction in the energy intensity and carbon factor compared to 2000. Values are indicated for all the scenarios: 2020, 2050 and 2100.

7.4.3 Costs

7.4.3.1 Abatement costs

As cost measures, we will focus on permit prices and abatement costs. The latter are calculated on the basis of the surface under marginal abatement cost curves and represent the direct additional costs due to climate policy, but do not capture macro-economic costs or feedbacks (nor the avoided damages of climate change). Figure 7.7 shows that the scenarios involving stabilization at 650 and 550 ppm CO_2-eq. ppm are characterized by a rather smooth increase in the permit price, followed by a drop by the end of the century. This drop is caused by a fall in emissions in the baseline and further cost reductions in mitigation technologies (in particular, hydrogen fuel cells start entering the market by this time, allowing for reductions in the transport sector at much lower costs). For the 450 ppm stabilization scenario, the price rises steeply during the first part of the century – reaching over 600 US$/tC-eq. by 2050 – and finally stabilizes at 800 US$/tC-eq. by the end of the century. The high price is particularly necessary to reduce emissions from the more non-responsive sources such as CO_2 emissions from transport or some of the non-CO_2 emissions from agricultural sources, while other sources, such as electric power, already reduce their emissions to virtually zero at a permit prices of "only" 200-300 US$/tC-eq.

Costs can also be expressed as abatement costs as a percentage of GDP. This indicator is shown over time (Figure 7.7; right panel), and accumulated across the century (net present value; discounted at 5%) (Figure 7.8). In the 650 ppm CO_2-eq. stabilization scenario, costs first increase to about 0.5% of GDP, after which they decline slightly to about 0.3% of GDP. This reduction is caused by an increase in global GDP and a stabilization of climate costs due to a somewhat lower permit price and a stabilizing emission gap between baseline and the mitigation scenario. The same trend is observed for the

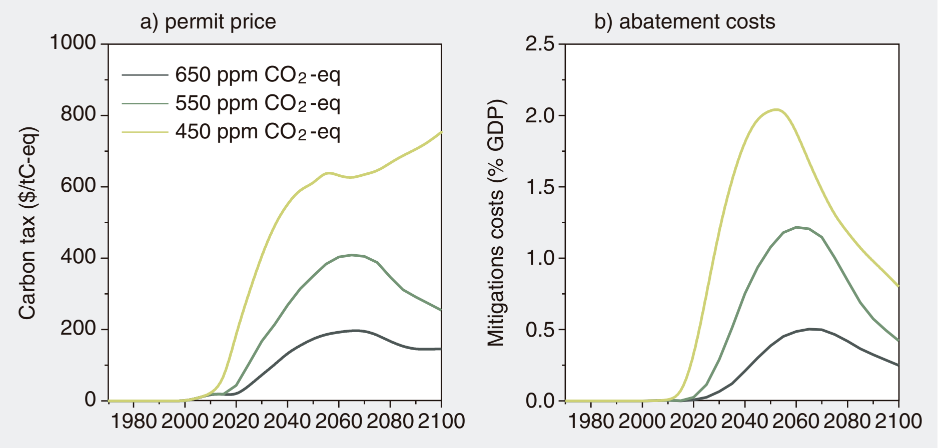

Figure 7.7 Marginal carbon-equivalent price for stabilizing greenhouse gas concentration at 650, 550 and 450 ppm CO_2-eq. from the B2 baseline (left; panel a) and abatement costs as a percentage of GDP for these scenarios (right; panel b).

other stabilization scenarios, although at higher costs. The abatement costs of the 550 ppm CO_2-eq. stabilization scenario increase to 1.2% of GDP, while the abatement costs of the 450 ppm CO_2-eq. stabilization scenario increase to 2.0% of global GDP. The direct abatement costs of about 0–2.5% of GDP can be compared to the total expenditures of the energy sector (which, worldwide, are about 7.5% of GDP today and expected to remain nearly constant under our baseline) or to the expenditures on environmental policy (in the EU around 2.0–2.8%, mostly for waste and wastewater management).

The net present value of the abatement costs follow a similar trend (across the different stabilization levels), as described above for the costs over time (Figure 7.8). For default baseline (B2), the costs vary from 0.2% of GDP for stabilization at 650 ppm to 1.1% of GDP in the 450 case.

7.4.3.2 Changes in fuel trade patterns

Figure 7.9 shows the imports and exports of different fuels in 2050. The clearest differences are found in the oil and coal trades, which are greatly reduced as a result of lower consumption levels. So, on the one hand, oil-exporting regions will see their exports reduced by a factor of about 2–3. On the other hand, the oil imports of importing countries are significantly reduced. Interestingly, natural gas trade is hardly affected because natural gas will be used in combination with CCS. An interesting aspect is the role played by the bio-energy trade. This trade increases substantially, a factor that major exporting regions (including, for instance, South America and the Former Soviet Union) could benefit from. Currently, oil-importing regions (such as the USA, Western Europe and Asia) could become major bio-energy importing regions. Obviously, the changes in fuel trade depicted here also lead to substantial changes in the financial transfers related to fuel trade (significantly impacting regional costs and benefits of climate policy).

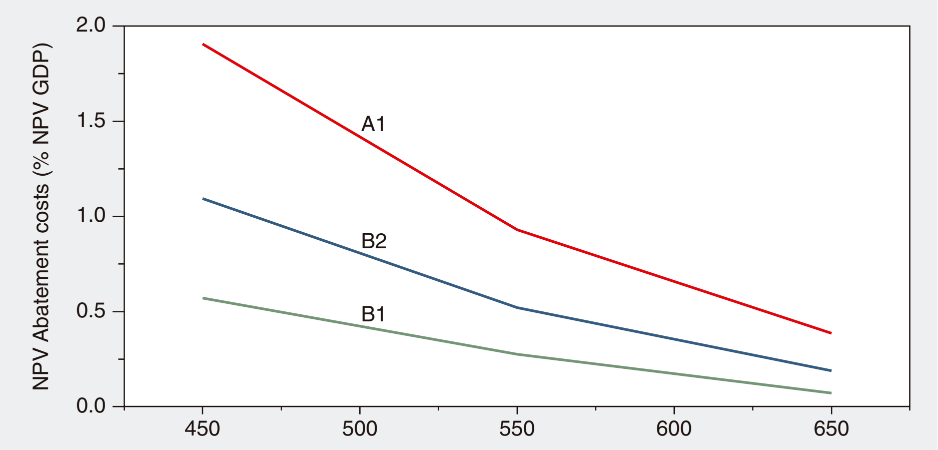

Figure 7.8 Net Present Value (NPV) of abatement costs for different stabilization levels as percentage of the NPV of GDP, starting from different baseline scenarios (discount rate 5%).

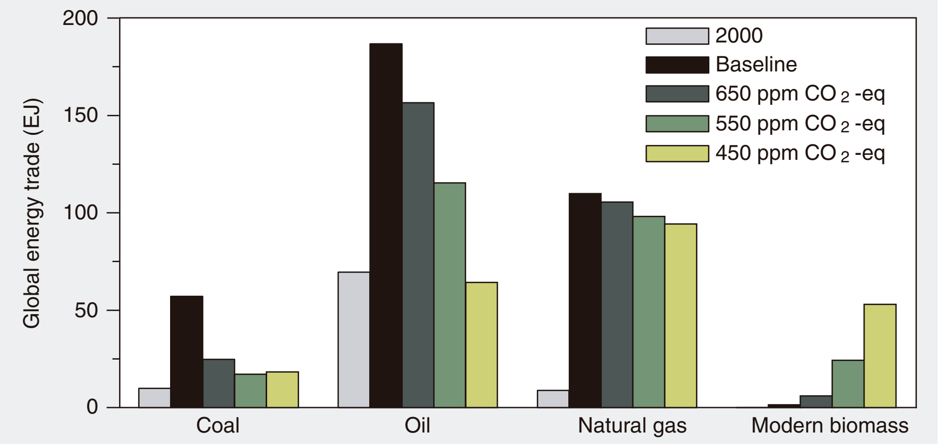

Figure 7.9 World volume of fuel trade between the 17 world regions (EJ) in 2000 and 2050. Baseline (B2) and stabilization scenarios (650, 550 and 450 ppm CO_2-eq)

7.5 Benefits and co-benefits

7.5.1 Climate benefits of stabilization

The three multi-gas stabilization scenarios analyzed here lead to clearly different temperature increases, both during this century and in the long term. Table 7.3 shows some of the parameters, describing the different scenarios in more detail and using a single value for climate sensitivity (2.5°C). The table shows that, in 2100, the 650 and 550 ppm CO_2-eq. stabilization scenarios are still approaching the stabilization levels, while the 450 ppm CO_2-eq. scenario has, in fact, overshot its target (as designed) and is approaching its target from a higher concentration level (the 2100 CO_2-eq. concentration is 479 ppm). For CO_2 only, our three scenarios generate CO_2 concentrations of 524, 463 and 424 ppm for 2100 and this is indeed on the lower side of existing CO_2-only stabilization scenarios in the literature.

It should be noted, however, that the temperature results of the different stabilization scenarios do depend to a considerable extent on the uncertain relationship between the GHG concentration and temperature increase. This implies that impacts on tem-

Table 7.3 Overview of several key parameters for the stabilization scenarios explored

	Concentration in 2100 (in ppm)		*Reduction of cumulative emissions in 2000-2100 period*	*Temperature change (in °C)*	
	CO_2-eq.	*CO_2*	*%*	*2100*	*Equilibrium*
B2	*947*	*708*	*0*	*3.0*	*-*
B2 650 ppm CO_2-eq.	625	524	36	2.3	2.9
B2 550 ppm CO_2-eq.	538	463	50	2.0	2.5
B2 450 ppm CO_2-eq.	479	424	61	1.7	2.0

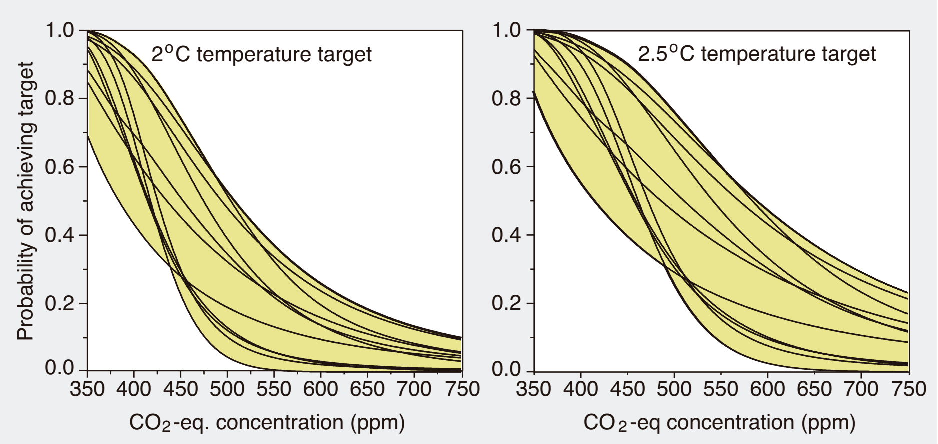

Figure 7.10 Probability of equilibrium temperature change staying within the 2°C or 2.5°C limit compared to pre-industrial for different CO_2-eq. concentration levels compared to pre-industrial (following calculations of (Meinshausen, 2006). Note: The lines indicate the probability function as shown in the individual studies quoted by (Meinshausen, 2006); the grey area indicates the total range from the highest and lowest studies.

perature can better be expressed in probabilistic terms. Figure 7.10 shows, on the basis of the work of Meinshausen (2006), the probabilities of overshooting a 2°C and a 2.5°C target in the light of the different stabilization levels explored in this chapter (the corridor shown is a result of Meinshausen's consideration of several PDFs published in the literature). In the case of a 2°C target, stabilizing at 650 ppm gives a probability of meeting this target between 0 and18%, depending on the PDF used. By contrast, stabilizing at 450 ppm results in a probability range of 22-73%. Similar numbers apply to a 2.5°C target. Here, 650 ppm provides a probability range of 0-37%, and 450 ppm, a range of 40-90%.

Although we have not specifically targeted any rate of temperature change, a rate can be a useful proxy for the risk of adverse impacts from climate change (in particular, ecosystems) (see Figure 7.11). In the baseline scenario, the rate of temperature change is around 0.25°C per decade. In the mitigation scenarios, the rate of temperature increase drops significantly, particularly in the second half of the century. In the 650 ppm stabilization scenario, the rate drops below 0.2°C per decade around 2050 and below 0.1°C in 2080. In the 550 and 650 stabilization scenarios, the rate of change drops even further while, for 450 ppm CO_2-eq., the rate actually falls below zero in 2100.

In the early decades (up to 2030), the mitigation scenarios hardly perform any better than the baseline. The reason is that, in the mitigation scenarios, changes in the energy system to reduce CO_2 emissions also lead to a reduction in sulfur cooling (as already emphasized by Wigley, (1991)[xvi]. In our earlier calculations, in fact, this could even lead to an temporarily higher rate of temperature increase for some of our mitigation scenarios compared to baseline (van Vuuren et al., 2006b). The somewhat smaller impact

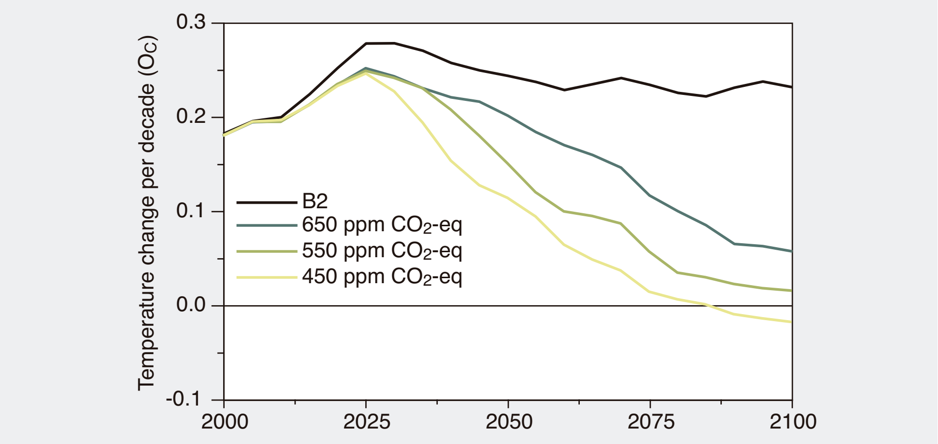

Figure 7.11 Rate of temperature change for 2000-2100 assuming a 2.5°C climate sensitivity.

here is mostly due to the increased potential for reducing non-CO_2 GHGs in combination with the higher overall rates of GHG emission reduction. By using GWPs as the basis of substitution between the different greenhouse gases, our method evaluates CH_4 emission reduction as relatively cheap compared to reducing CO_2 (see also (van Vuuren et al., 2006d). As reducing CH_4 is much less coupled to reducing sulfur and the impact of reducing CH_4 on radiative forcing is much more direct, the high degree of CH_4 reduction in our scenarios mitigates the impact of reduced sulfur cooling. This is somewhat comparable to the "alternative" mitigation scenario suggested by Hansen et al. (2000).

7.5.2 Co-benefits and additional costs

7.5.2.1 Impacts on regional air pollutants

Many air pollutants and GHGs have common sources. Their emissions interact in the atmosphere and, separately or jointly, cause a variety of environmental effects on local, regional and global scales. Emission control strategies that simultaneously address air pollutants and GHGs may therefore lead to a more efficient use of resources on all scales (so-called co-benefits). Current studies indicate that, when climate policies are in place, potential co-benefits could be substantial in the short-term (in particular the Kyoto period), with financial savings in the order of 20–50% of the abatement costs of the climate policy (see Chapter 9 of this thesis). In this study, we have focused our analysis on the consequences of climate policies for SO_2 and NO_x emissions by using the same emission coefficients for SO_2 and NO_x as those assumed under the baseline (reflecting similar policies for emissions of these substances). We also aimed at simply quantifying the impact of changes in the energy system on emissions.

[xvi] The impact of sulfur emissions on temperature increase is calculated in IMAGE on the basis of a pattern-scaling methodology that was developed by (Schlesinger et al., 2000).

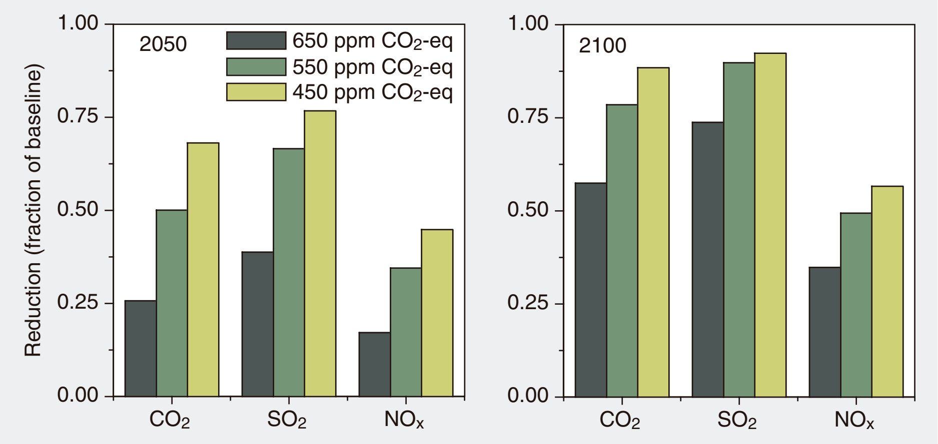

Figure 7.12 Reduction of CO_2, SO_2 and NO_x emission compared to baseline (0% is no reduction; 100% is full reduction) in the 3 B2 stabilization scenarios (2050 on left; 2100 on right).

Figure 7.12 shows that the changes induced by climate policy in the energy system to reduce CO_2 emissions also reduce SO_2 emissions, in particular at lower reduction levels. This can be explained by the fact that coal, in particular, is used in conventional power plants, contributing to an even larger proportion of SO_2 emissions than of CO_2 emissions. Phasing out conventional fossil-fired power plants and reducing oil inputs into transport, and replacing them by either fossil plants with CCS or renewables, does significantly reduce SO_2 emissions. In the case of NO_x, there is a similar relationship between CO_2 emission reductions and NO_x emission reductions – although here NO_x emissions reductions are smaller than those of CO_2. The figures show that there are clear co-benefits for regional air pollution resulting from climate policy. In low-income countries, a focus on the potential synergies of climate change policies and air pollution policies could be even more important than in high-income countries. Synergy effects of climate policies on regional and urban air pollution may, in fact, be a reason for non-OECD countries to contribute to early emission reductions.

7.5.2.2 Impacts on Land Use

Several of the mitigation options considered have an impact on land use. Table 7.4 describes land use under the three main mitigation scenarios. As explained in the methods section, for bio-energy crops the modeling system may use 60% of the abandoned agricultural land and 25% of natural grassland or similar biomes. Carbon plantations may use 40% of abandoned agricultural land. The potential thus does not include the land currently used for food production nor does it include forests. It should be noted that land impacts of other energy options (e.g. wind power, solar power, hydro power, fossil fuel production) have not been accounted for, but these are small compared to those of bio-energy and carbon plantations.

In our scenarios significant amounts of agricultural land (for food production) are abandoned through the simulation period. In the first half of the century, this occurs in OECD regions and the Former Soviet Union – mostly as result of a stabilizing food demand (due to a stabilizing population) and continuing yield increases (see (IMAGE-team, 2001; Rosegrant et al., 2002; Strengers et al., 2004). In some developing regions (e.g. East Asia) similar dynamics may result in the availability of abandoned agricultural land in the second half of the century (Strengers et al., 2004). This result obviously depends on the yield improvements that are assumed in the scenarios.

In the mitigation scenarios, the most significant change compared to the baseline is the increased demand for land for bio-energy: from 3.9 million km^2 in the baseline scenario to 9.3 million km^2 in the 450 ppm CO_2-eq. stabilization scenario. This means that the bio-energy crop area is equal to about 50% of the total food and feed crop area in 2100. Most of this land is located in the former Soviet Union, South America, and the USA and, in the second part of the century, East Asia (see also Hoogwijk et al., 2004). In 2100, carbon plantations occupy about 2.6 million km^2 (about 5% of all forest at that time). Here, most of the land is in the former Soviet Union, South America and again East Asia (Strengers et al., 2007). It should be noted that the agricultural land area for food and feed crops increases slightly. Although we have not included agricultural land in our bio-energy and carbon plantation potential, in the actual scenario implementation some conflicts may still occur (the model chooses at any point in time the most attractive area for each option that requires land).

Moreover, reducing the CO_2 concentration also reduces the carbon fertilization effect. The total “domesticated” area increases by nearly 20% while, in the baseline, land use in 2100 is virtually equal to land use in 2000. Land use does not differ much for the different stabilization scenarios as most of the bio-energy and carbon plantation potential is also used as part of the portfolio for stabilization at less ambitious levels.

The question of whether the land-use consequences shown here lead to a similar loss of biodiversity is a more difficult one. The area used for bio-energy production and carbon plantations is mostly abandoned agricultural land, including both crop and pasture land, with a considerable area coming from natural grass land. In the former case, secondary forest would, at best, have grown in these locations. Although others have pointed out that, in many cases, land is not likely to recover automatically, in which case it will be transformed into degraded land. Moreover, it is to some degree possible to combine biodiversity targets and carbon plantations. The impact on biodi-

Table 7.4 Land use under the baseline (IMAGE 2.3 SRES B2 scenario) and mitigation scenarios in 2100 (million km^2)

	Baseline	650 ppm CO2-eq.	550 ppm CO2-eq.	450 ppm CO2-eq.
Agricultural land	43.5	44.7	45.3	45.6
Land for bio-energy	3.9	9.3	9.3	10.2
Land for carbon plantations	0.0	1.6	2.2	2.6
Total	47.4	55.5	56.7	58.3

versity, therefore, is likely to be much smaller than the reduction suggested by looking at the land-use impacts alone.

7.6 Uncertainties in stabilizing emissions

In the discussion of the existing literature in Section 7.2, it was concluded that there are several categories of uncertainties that can substantially influence the results of stabilization scenarios. Here, we will discuss two of these: the baseline scenario and specific assumptions for individual technologies.

7.6.1 Reducing emissions from different baselines

Four scenario families were developed in the SRES report. Of these, the B2 scenario represented the most average development. The A1b and B1 families lead to higher and lower emissions respectively. Hourcade and Shukla (2001) showed the baseline to be just as important for mitigation costs as stabilization levels. We have therefore explored the influence of costs here on the basis of the implementation of these scenarios in the IMAGE 2.3 model. It should be noted that we have not included the A2 scenario. The reason is that the storyline of this scenario, i.e. little international cooperation and little focus on environmental issues, provides a very unfavorable situation for climate policy to be developed.

The A1b scenario leads to far higher per capita energy use than B2, although it has a lower population level and a lower share of coal in total energy use. Total GHG emissions are substantially higher than the B2 level, at around 26 GtC-eq. in 2050 and 25 GtC-eq. in 2100. The B1 scenario, by contrast, results in much lower energy use as a result of greater efficiency and lower population levels. Here, total GHG emissions peak at around 2050 at 15 GtC-eq. and decline thereafter to 8 GtC-eq. in 2100. As a result, the emission reduction objectives for the different stabilization levels are higher for the A1b scenario and lower for the B1 scenario (see also Figure 7.3).

The costs of stabilization from these baselines for the low-range stabilization targets explored in this study are shown in Figure 7.8. As expected on the basis of higher baseline emissions, abatement costs for the A1b scenario are higher than those for the B2 scenario. In fact, the NPVs of abatement costs for each of the A1b stabilization cases are about double the costs of the corresponding B2 cases. By contrast, the costs of stabilization for B1 are substantially lower. In addition, across the range considered here, costs rise more slowly for B1 than for A1b and B2 as a result of the smaller absolute gap between baseline emissions and the emissions under the stabilization case, the high technology development rate and the resulting lower prices.

7.6.2 Sensitivity to key assumptions for abatement options

Our analysis takes a wide range of abatement options into account. In all cases, the reduction potential and costs are subject to considerable uncertainties. The long time scale used (100 years) implies that assumptions need to be made about technology development, implementation barriers and fundamental changes in the system as a whole; these may either assist or hinder certain reduction measures. As the uncertainties with regard to the individual options accumulate in our combined assessment, we have therefore performed a sensitivity analysis for the 550 ppm CO_2-eq. stabilizing scenario, as indicated in Table 7.1. The results are shown in Figure 7.13.

In the case of emissions from the *energy sector*, one set of critical uncertainties include factors such as the rate of technology change, lifestyle, economic growth and population dynamics. The impacts of these “storyline-related” uncertainties have been explored earlier as part of the influence of the baseline scenario (A1b and B1) and taken together could impact costs by at least a factor of 2. However, several other important uncertainties exist. As pointed out by Edmonds et al. (2004), the development of hydrogen technology itself is not strongly influenced by climate policy. However, once hydrogen is part of the system, stronger reductions are feasible than without hydrogen, given the fact that hydrogen can – at relatively low additional cost – be produced without GHG emissions (Edmonds et al., 2004; Van Ruijven et al., in press). In the analy-

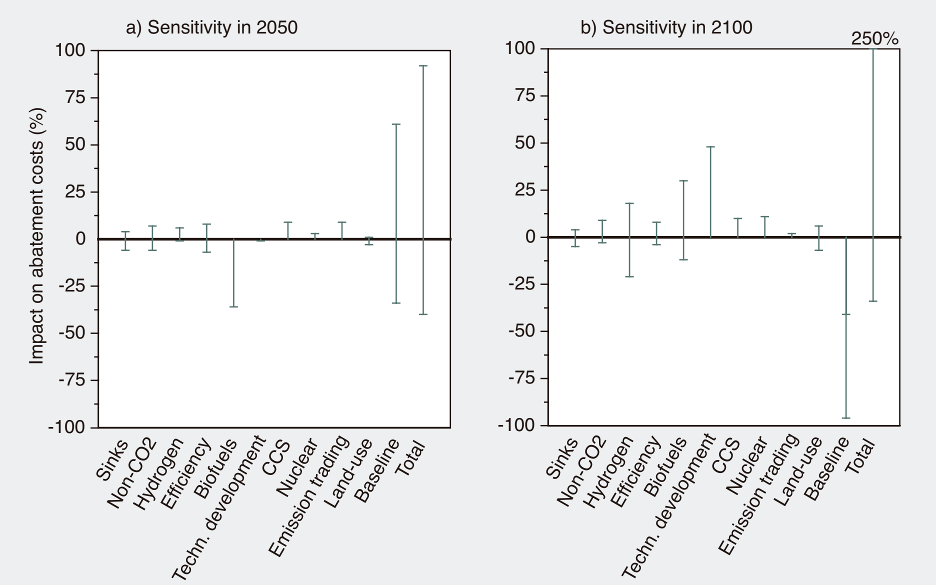

Figure 7.13 Impacts of different uncertainties on global abatement costs (compare to Figure 7.8) for stabilization at 550 ppm CO_2-eq., 2050 (left) and 2100 (right). The column total is restricted to the assumptions that only impact the stabilization scenario, and therefore does not include the impacts of baseline and land-use.

sis, therefore, we explored the impact of a scenario with no hydrogen (a pessimistic assumption) and a scenario with large-scale penetration of hydrogen. The sensitivity to these assumptions was found to be small in 2050 (as the system hardly contains hydrogen) but substantial in 2100 (20% difference in abatement costs either way).

Another important uncertainty concerns the potential of, and technology used for, bio-energy. As shown by Hoogwijk (2004), the uncertainty relating to bio-energy supply results in figures for potential use of between 100 and 800 EJ. In our central assumptions, the bio-energy use is about 400 EJ. We have lowered supply in our sensitivity runs for the pessimistic case. Azar et al. (2006) have shown that including the option of Bio-Energy and Carbon Storage (BECS) can reduce costs at low concentration levels by at least 50%. We will therefore use BECS for the high end of our range. Figure 7.13 shows that this is, in fact, a very important uncertainty, influencing costs by about 40% downward (in the case of BECS) or 30% upwards (in the case of restricted bio-energy supply). The influence of BECS is relatively low in the long term as the analysis is done for the 550 ppm stabilization scenario – for which the reduction requirement in the long term is still relatively low compared to the number of reduction options.

Another uncertainty relates to the contribution of energy efficiency. In the default run, we assumed that the permit price and international emissions trading would lead to a convergence of investment criteria in energy efficiency worldwide towards levels that currently also apply to energy supply. In our sensitivity analysis, these assumptions ranged from full convergence towards supply-side criteria to no convergence. The influence of this factor is shown to be relatively modest – and to influence costs in 2100 by about 10% either way.

The results show that the cost-optimal implementation of the stabilization scenarios includes the large-scale use of CCS and nuclear power. For both options, not only do technological uncertainties play an important role, but also social acceptability; for instance, at the moment several countries have indicated that they will not build new nuclear power plants. In this context and as a form of sensitivity analysis, we excluded both options (one by one). In each case, costs for 2100 are about 10% higher. In 2050, the influence on costs is smaller. The reason for the relatively small impact is that by excluding only one option, the electric power sector still has enough reduction potential left to effectively respond to climate policy.

Another uncertain factor is induced technology change (in terms of investment costs) in response to climate policy. This factor is described by learning curves in the default run for solar, wind and nuclear power, bio-energy conversion, hydrogen production technologies, production of oil, natural gas and coal, and costs of energy efficiency. In Chapter 8, we will show that most of the “learning” already occurs under the baseline scenario; the additional learning that results from the investments induced by climate policy is (in most cases) smaller than the baseline improvements (see also (van Vuuren et al., 2004)). In the sensitivity run, we set this second factor, induced technology change, at zero, implying that technology change in the mitigation scenario is equal to baseline development. While this factor is not important in 2050, it still represents a major uncertainty in the long term (around 50% increase in cost), as shown in Figure 7.13.

The effect of several crucial parameters that work directly on the supply and cost of *carbon sequestration through plantations* was examined in Strengers et al. (2007). These parameters are the CO_2 fertilization factor, the harvest regime, land costs, land use, the establishment costs, the discount rate and the increased growth rates of managed trees over natural trees (additional growth factor). Of these, the last factor proved to have the most impact on outcomes. If the additional growth factor is reduced by 20%, potential sequestration by carbon plantations is found to fall by about 37% and average cost of sinks to increase sharply. On the other hand, an increase of 20% results in 33% more sequestration potential and a cost decrease of 35%. Another important factor is the degree to which areas suitable for carbon plantation can actually be used for that purpose. A shortage of planting material, lack of knowledge and experience, other priorities for the land (e.g. bio-energy), etc. may reduce the abandoned agricultural area that can actually be planted. Waterloo et al. (2001) estimated that, in the case of CDM under the Kyoto Protocol, only 8% of the potential area would actually be available. This number could increase in time and with increasing permit prices. As a result, in our standard runs, we defined an exogenous implementation factor equal to 40% of the total potential. In the sensitivity runs, this factor varied between 20% and 50%, respectively. However, the impact of these assumptions on overall global costs is relatively minor given the small contribution of carbon plantations to the total portfolio of reduction measures (about 5% of cost increase or decrease, both in 2050 and 2100).

The *non-CO_2 emission reduction potential* is based on the EMF-21 database and extrapolated for the period up to 2100 on the basis of assumptions on technological developments, and maximum reduction potentials and accompanying costs. The assumptions about the maximum reduction potentials have the most impact on the final outcomes. To assess this impact from a pessimistic perspective, we reduced the reduction potential by 20% - and increased costs by 20%. In the optimistic case, we assumed the opposite. We found that sensitivity of overall costs to the non-CO_2 assumptions are about 5-10%, comparable to the sensitivity to the carbon plantation assumptions.

Land use represents another major uncertainty. It impacts our results in several ways: 1) by influencing directly CO_2 emissions from land use change, 2) by determining land available for carbon plantations and 3) by determining land available for bio-energy. With respect to CO_2-emission-related changes in land use, it should be noted that even current base-year emission levels are highly uncertain. Houghton (2003) estimated carbon emissions at 2.2 GtC/yr, with an uncertainty range varying from 1.4 to 3.0 GtC per year. Future projections for the carbon budget vary even more given uncertainties on the effect of CO_2 fertilization, the response of soil respiration due to changes in climate and the uncertainties in future land-use patterns (Leemans et al., 2002; Gitz and Ciais, 2004; Strengers et al., 2004). If we focus solely on the latter factor, future land-use change depends on both socio-economic developments and technological improvements in the agricultural system (Rosegrant et al., 2002; Bruinsma, 2003). In the literature, there are different views about the possibilities of technological improvement (Carpenter and Pingali, 2006).

To take these uncertainties into account, we assessed the implications of uncertainties in technological improvement by varying the achieved agricultural yields – and recalculating CO_2 emissions from land-use change and the Marginal Abatement Curves for carbon plantations and energy (bio-energy). We took the yield increase of the least positive scenario in the Millennium Ecosystem Assessment (the Order from Strength scenario) as a basis for the pessimistic run, and the yield increase of the most optimistic scenario (the Global Orchestration scenario) as the optimistic run. This variation provides an understanding of the importance of uncertainties in technological improvement for land-use emissions and potentials for bio-energy and carbon plantations. The impact of these assumptions on global costs is in the order of 5-10% (in both directions).

We have not varied the other factors mentioned above for land-use related emissions such as CO_2 fertilization and other parameters that influence the carbon cycle. The carbon cycle feedbacks are assumed at their IPCC TAR default values. It should be noted, however, that the latest insights seem to suggest that carbon fertilization might be substantially weaker than assumed earlier. If this is the case, all greenhouse gas concentrations – in particular those for the higher concentration levels – will shift upward. Or, by the same token, more abatement action (and higher costs) will be needed to achieve the same stabilization level.

As discussed earlier in Section 7.6.1, Figure 7.13 confirms the baseline development to be one of the most crucial uncertainties determining overall costs. The overall sensitivity here is in the order of 50–100% (on the basis of the alternative B1 and A1b scenarios). It should be noted that in 2100, both the A1b and B1 scenario have lower cost compared to GDP than the central B2 scenario. Therefore, the annual costs in 2100 are (as a result of our sensitivity analysis set-up) only influenced downward. It should be noted, however, that other baselines could have an upward influence on 2100 abatement costs – and also that despite lower costs in 2100, the A1b scenario still results in higher 2000-2100 cumulative costs as shown in Figure 7.8. The major role played by the baseline assumptions is to be expected since it changes the overall reduction objective, as well as technology assumptions, preferences for reduction options and GDP levels (used here as the nominator of the cost indicator).

In the last sensitivity runs, we combined all high-cost and low-cost assumptions (except for baseline and land use). Variation was far higher than suggested by the individual options, especially on the high-cost side. The reason is that without CCS and nuclear power as zero-carbon options in the electric power sector and with low bio-energy supply, this system is much less amenable to substantial emission reductions. While undergoing a one-by-one sensitivity analysis, the system has enough flexibility to substitute, but when all uncertainties work in a negative way, this flexibility disappears.

So in summary, the most important parameters in terms of sensitivity of stabilization costs include baseline, bio-energy, assumptions on hydrogen penetration, and the rate of technology development. Other important uncertainties are future land use (agricultural yields), bio-energy (the use of BECS), assumptions about efficiency improvement and, to some degree, the availability of CCS and nuclear power. The combined effect of all parameters can be far larger than the effect of individual options, so that abatement costs estimates range from 1 to 4% of GDP by 2050.

7.6.3 Possibility of stabilizing at even lower levels

In our analysis, we explored a set of scenarios that would lead to stabilization at levels as low as 450 ppm CO_2-eq. In the previous section, we showed that there are important uncertainties in our analysis, some of which might lead to lower costs (and/or more reduction potential). With the more optimistic assumptions, it would also be possible to stabilize at lower levels than those explored in our central scenarios. Such scenarios will first overshoot the target concentration (given all delays in the system) and only start to approach this target by the end of the century. Of the uncertainties explored earlier, in particular more optimistic assumptions for land use, efficiency and bio-energy (both the available potential and the combination of bio-energy and CCS, BECS) could significantly increase reduction potential and thus allow lower stabilization levels to be reached. Here, we specifically explored whether changing our assumptions for bio-energy alone –from the default assumption to the optimistic assumptions that allow for the combination of BECS– would be enough to reach the emission levels of a 400 ppm CO_2-eq.

The results, as indicated in Figure 7.14, show that this change alone is sufficient to reach the emission pathway. An important element here is that adding BECS allows for a net carbon uptake during the growth of bio-energy which is then stored under-

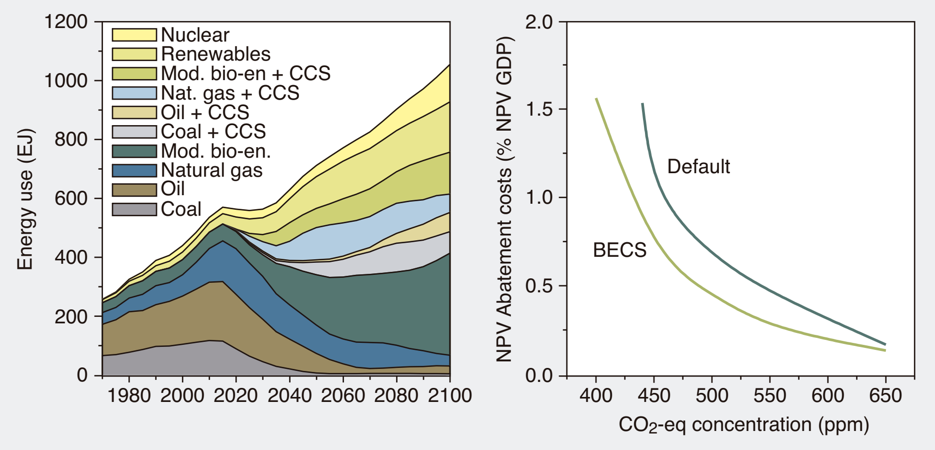

Figure 7.14 Alternative scenario for stabilizing GHG concentration at 400 ppm CO_2-eq. (left panel) and the associated costs (right panel).

ground. These net “negative emissions” are, in particular, important for low emission scenarios (Azar et al., 2006). The costs of BECS are a combination of the bio-energy costs and CCS costs, which certainly makes this technology attractive at the permit price levels explored earlier for the 450 ppm CO_2-eq. scenario. Thus, as a result of the more optimistic assumptions, our overall costs are comparable to our default case, but this obviously requires conditions that allow for the achievement of this more optimistic view of technology development. This is illustrated by Figure 7.14b, where abatement costs are plotted for several stabilization levels, both including and excluding BECS as abatement option.

7.7 Discussion

7.7.1 Important limitations of the current study

In this study, we used a linked set of integrated assessment models (TIMER, FAIR and IMAGE) to explore scenarios that lead to low GHG concentration levels using a multi-gas approach. There are a few important limitations to the study that are essential to interpreting the results:

- The cost concept used in this study refers to direct abatement cost only on the basis of marginal abatement curves derived from underlying expert models – and does not capture the macro-economic impacts of climate policy. Macro-economic cost measures (such as consumption or GDP losses, but also sectoral impacts) might in some cases be larger as they also include effects of transaction costs, combined effects of climate policy and existing taxes etc. On the other hand, they can also be smaller, since there be will sectors and industries that profit from climate policy and since there might be benefits from recycling the revenues of carbon taxes (see (Weyant, 2000)).
- The IMAGE 2.3 model does not explicitly model land-use competition. For this reason, we have restricted the potential land use for climate policy (bio-energy, carbon plantations) to those areas that do not impact food production (i.e. abandoned agricultural land and natural grasslands). It might be interesting to explore how climate policy may impact food production in models that endogenously model competition for land.
- Not all reduction options are included. For instance, in the electric power system, emissions can also be reduced by geothermal power or concentrating solar power plants. However, as such technologies will compete mainly with other zero-carbon emission options; we do not think that including the new options will lead to significantly different results.
- The emission pathways are created by employing the FAIR–SiMCaP model, which uses a different climate model (MAGICC) than IMAGE 2.3. Considerable attention, however, was given to making sure that the results of the two models were consistent. The remaining differences (for example, up to about 10 ppm for CO_2 concentration) are certainly within the uncertainty ranges.

- In view of this being a long-term study, many assumptions are beset with uncertainty. This, for instance, is the case for assumptions on technological progress, and reduction potential. Some of these uncertainties have been taken care of by an extensive sensitivity analysis (Section 7.6.2).
- Finally, the most important limitation is that we do not deal with all kinds of societal barriers that exist in formulating ambitious climate policies. Such barriers may include the specific interests of different actors, inertia in international negotiations, other societal priorities etc. Instead, we assumed that from 2013 onwards all regions participate in climate policy (without necessarily paying for it). . This allowed us to explore, first, how ambitious climate stabilization strategies may look. In future research, it will be important to explore further what barriers exist – and how these may impact the results shown.

7.7.2 Comparing the results to other studies

As indicated in the introduction, there are hardly any other studies that describe mitigation strategies for all GHGs at relatively low concentration levels. Comparison therefore has to be made mostly on the basis of the CO_2 concentration that is achieved in our scenarios (instead of total GHG forcing).

In terms of mapping mitigation costs as a function of stabilization levels, the main comparisons that can be made are with the studies summarized in the IPCC Third Assessment Report (TAR) (these studies focus on CO_2 only). Figure 7.15 shows the stabilization costs in terms of the discounted net present value as a function of CO_2 concentration levels on the basis of this study, the TAR ranges and two more recent studies.

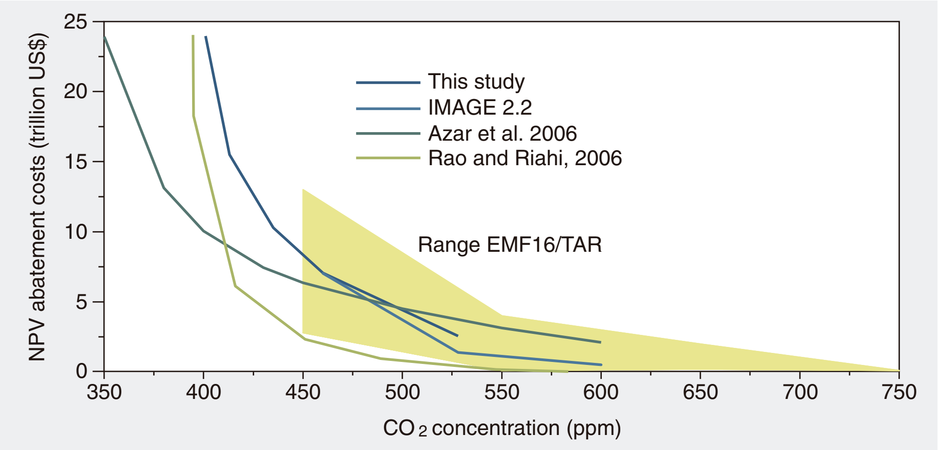

Figure 7.15 Cost levels in this chapter compared to alternative studies. All studies report the Net Present Value of mitigation costs (discount rate of 5%). The sources of the data shown are: EMF-16 results [(Hourcade and Shukla, 2001).Note that the EMF-16 results have been summarized here in terms of the highest and lowest values for different concentration levels across a range of models]; IMAGE 2.2 (van Vuuren et al., 2006b); Azar et al. (2006) and (Rao and Riahi, 2006).

Average cost values reported in IPCC TAR are around 0.8, 1.3 and 6.4 trillion US$ for stabilizing at 650, 550 and 450 ppm $CO_{2,}$ respectively (the lowest and highest values are typically 75% lower and 2-3 times higher, respectively). The corresponding values found in this study are 0.5, 1.7 and 8 trillion (interpolating our results to the rounded-off concentration levels on the basis of the CO_2 concentration in 2100). Our cost numbers, however, also include the mitigation costs for reducing non-CO_2 gases (about 20-30%). Given our baseline emissions (following the updated B2 scenario), and correcting for these non-CO_2 costs, we can conclude that values found (including the trend) are generally consistent with those reported for CO_2 stabilization studies. Azar et al. (2006) and Rao and Riahi (2006) also discuss similar cost levels as a function of concentration targets (again only for CO_2) for considerably lower levels (here, we report the results of their study for model runs that include fossil fuel CCS). Across the whole range of concentration levels, the function of costs as a function of lower concentration level are comparable – although for individual concentration levels, costs may differ over a factor of 5. Reasons that can lead to different cost levels (between all studies cited here) include differences in baseline, the number of options included, and the technology assumptions for these options and the type of models.

For multi-gas stabilization strategies, a comparison can be made with the results of EMF-21 (van Vuuren et al., 2006d; Weyant et al., 2006). With a few exceptions, the results of the models participating in EMF-21 are only available for stabilization at 650 ppm CO_2-eq. In general terms, the findings described in this study seem to be consistent with those found in the EMF-21 study, where the contribution of non-CO_2 gases and overall cost levels is concerned; however, they extend them to lower levels. Given the wider range of abatement options considered, the marginal costs are lower than those presented by Van Vuuren et al. (2006b). Included in the options are a larger potential to reduce non-CO_2 gases, a larger potential for carbon plantations and more possibilities to apply CCS).

7.7.3 Dealing with uncertainties

Uncertainty plays a dominant role in determining relevant targets for climate policy. Climate impacts are uncertain and – probably most important – climate sensitivity is very uncertain, creating a range of possible temperature outcomes for different stabilization levels, as indicated in Figure 7.10. This chapter has also shown that the potential and costs of several mitigation options are subject to uncertainties.

Designing climate strategies that can manage uncertainty will therefore be important. In this light, it is crucial to note that not all uncertainties are similar. An important difference is the lag time between impact, the time when the impact becomes noticeable and the reversibility of the impact. It can still take decades before the uncertainty related to climate impacts and climate sensitivity is significantly reduced. Moreover, once the uncertainties are resolved (in whole or in part), the climate system may already be irreversibly on a path of “dangerous anthropogenic interference” because of all the delays. Most of the uncertainties relating to mitigation options, however, are much more directly noticeable. For instance, if costs develop less favorably for major mitigation options, mid-course corrections can be made in either the portfolio of mitigation options used, the stabilization target or the financial budget (policies will not, after all, be cast in stone for the next 50 or 100 years). Similarly, if certain options prove less effective, they can be removed from the total package. There are some exceptions to this, however. One is that if a mitigation option leads to lock-in effects, a change of course might be less easy to accomplish. Secondly, in theory, CCS and nuclear power could lead to a situation of irreversible damage if the storage of CO_2 or nuclear waste is not as safe as expected. In this light one may ask what elements can be used to establish strategies that can cope with uncertainties?

First of all, such a strategy will include elements of hedging against climate risk. As described by Yohe at al. (2004), hedging implies aiming in the short term for emission pathways that do not exclude the possibility of reaching low stabilization levels. This is obviously important if the climate system proves to be near the upper ranges of current estimates. Secondly, monitoring of the most crucial uncertain elements will be important. Obviously, this in particular relates to parameters associated with temperature increase and climate impact, but also to the costs and potential of mitigation options. Thirdly, it will be necessary, as far as possible, to select a portfolio of mitigation options instead of only a few options. As shown in this chapter, a portfolio is in fact already the result of the modeling that has taken place, but risk reduction is an additional argument not included in the modeling itself. A fourth element is flexibility in targets. Here, there is obviously a trade-off between providing enough long-term certainty to actors involved in climate mitigation to make long-term investments attractive, while being flexible enough to deal with resolving uncertainty.

7.8 Conclusions

The main issue addressed in this chapter was to indicate what portfolio of measures could constitute promising strategies for stabilizing GHG concentrations at low levels. The lowest multi-gas scenarios up to recent discussions in the literature examine stabilization at 550 ppm CO_2-eq. and higher. These scenarios only have a small chance of limiting global mean temperature change to 2°C or 2.5 °C. The main purpose of this chapter therefore has been to try to identify whether stabilization at lower concentration levels is feasible. Against this background, we developed a set of mitigation scenarios for stabilizing atmospheric GHG concentrations at 650, 550 and 450 ppm CO_2-eq., and – subject to specific assumptions – 400 ppm. The scenarios focus on a larger set of mitigation options than most other studies, and extend the lower range of multi-gas scenarios currently discussed in the literature. The analysis has led to the following conclusions.

- **Technically, stabilizing greenhouse concentrations at 650, 550, 450 ppm and, under specific assumptions, 400 ppm CO_2-eq. is feasible from median baseline scenarios on the basis of known technologies.**

In order to prevent “dangerous anthropogenic interference with the climate system”, the stabilization of GHGs at low levels (e.g. 450 ppm CO_2 eq. or below) might be needed. Currently, there are only a limited number of studies that identify mitigation strategies that could lead to such low stabilization levels – and none of these are based on a multi-gas approach. Here, we show that there are sufficient technical options to reduce emissions to the level required, and that these options can be combined into effective stabilization strategies. In fact, under favorable conditions, stabilization at 400 ppm is also within the realm of technical options.

For 650 ppm and 550 ppm CO_2-eq. stabilization, it is possible to develop strategies that stabilize at these concentrations without overshooting the required target. For 450 ppm CO_2-eq., overshooting this level before returning to the target during the 22nd century seems unavoidable. For both 550 ppm CO_2-eq. and 450 ppm CO_2-eq. (and even lower levels), emissions will have to peak within the next two decades followed by strong emission reductions. Our calculations show this to be the most difficult period for climate change policy, even assuming the full participation of all countries under a climate regime. The costs of not peaking global emissions within the next two decades could include higher temperature change and/or more rapid emission reduction rates in the longer term (which can be costly if requiring premature replacement of capital).

- **Creating the right socio-economic and institutional conditions for stabilization will represent the single most important step in any strategy towards GHG concentration stabilization.**
  The types of reduction described in this chapter will require major changes in the energy system, stringent abatement action in other sectors and related large-scale investment in alternative technologies. Moreover, we have assumed that the world will find a mechanism to tap reduction potential in all parts of the world. In this context, creating the right socio-economic and institutional conditions that enable these transitions will be more important than any of the technologies discussed. This includes, for example:
  - creating a sense of urgency about emission reduction in all parts of the world in order to develop an effective global climate regime;
  - creating conditions for technology development, and more important, technology dispersal and transfer;
  - overcoming current barriers to effective/cost-effective measures for reducing GHG emissions (e.g. information to improve investment in energy efficiency).

  The impact of socio-economic and institutional conditions can also be illustrated by our analysis of the impact of alternative baseline scenarios. While stabilization at 450 ppm CO_2-eq. represents a major challenge starting from the B2 baseline, the challenge is much smaller when starting from a B1 baseline.

- **The Net Present Value of abatement costs increases from 0.2% to 1.2% of the Net Present Value of GDP (5% discount rate) when moving from 650 to 450 ppm. On**

the other hand, the probability of meeting a two-degree target increases from 0-18% to 22-73%.
Here, we have mapped out some of the costs and benefits of stabilizing GHGs at low levels. Costs clearly increase for lower levels of stabilization, but so do benefits. The net present value of stabilizing at 450 ppm CO_2-eq. at our standard assumptions are about 1.2% of GDP (accumulated over the century), but they reach a peak of around 2% in the period, 2040-2070. At the same time, stabilization also provides clear benefits at low concentration levels. In order to achieve a certainty (on average) of at least 50% in reaching a 2^oC target, the CO_2-eq. concentration needs to stabilize at 450 ppm CO_2-eq. or below.

In addition to direct abatement costs, stabilization also involves indirect costs and benefits. There are, for example, the consequences for fuel trade. Stabilization policies are likely to reduce the volume and change the pattern of global trade in fossil fuels, in particular, oil and coal. This will reduce the exports of some countries, but at the same reduce imports of others. Regions that could export bio-energy may compensate some of reduced oil export by bio-energy exports. CCS does limit the impact of climate policy on fuel trade, especially for gas and coal.

- **Strategies consist of a portfolio of measures. There is no magic bullet.**
  The reductions in our stabilization scenarios are achieved through a set of measures rather than a single measure. The reasons for this include: 1) limitations in the potential of individual options, 2) regional and sub-regional differentiation, 3) increasing costs for penetration rates as a result of depletion, and 4) differentiation between different sectors. In addition to these model results, another important advantage of a strategy based on a portfolio of measures is that the reduced risk if the development of a single technology is slower than expected (even a technology may be found altogether unacceptable, which could happen to nuclear power after a major accident). There is also an important disadvantage: the dispersal of R&D capacity, learning-by-doing and economies of scale. However, we feel that this disadvantage is outweighed by the benefits mentioned above.

- **Given our default assumptions, carbon capture and storage (CCS) represents a very attractive technology to reducing greenhouse gas emissions.**
  CCS could be the single most important technology for reducing CO_2 emissions from the energy sector given its relatively low current costs estimates (IPCC, 2005) compared to technologies that are chosen in the absence of climate policy. Its contribution could be around 30-40% of total CO_2 emissions reduced in the energy sector or 25% of total emission reductions. At the same time, the role played by CCS can, if necessary, be replaced by nuclear power and/or additional use of solar and wind power (at somewhat higher costs). It should be noted that these options are subject to several uncertainties. CCS still has to be proven in large-scale applications, and for CCS, nuclear power and wind power societal acceptance can play an important role in determining their real potential.

Other important contributions to overall emission reductions (in the absolute sense) under our default scenario include energy efficiency, the reduction of CH_4 emissions, bio-energy and nuclear, solar and wind power.

- **Stringent stabilization strategies do result in co-benefits but also in additional costs.**
  The systemic changes in the energy system induced by a stringent climate policy can result in important co-benefits. Emissions of regional air pollutants, in particular SO_2 and NO_x, will be reduced substantially, leading either to the improvement of regional and urban air pollution or to reduced abatement costs for these pollutants. Another co-benefit is the likely positive impact of climate policy on energy security issues (less dependency on oil imports). However, in addition to co-benefits, there will also be additional costs. The most important is that stringent climate policies are likely to lead to increased demand for land. This, in turn, could lead to impacts on biodiversity and possibly on food security.

- **Uncertainties are important.**
  Uncertainty constitutes an important factor in the development of stabilization strategies. Here, we also focused on uncertainties relating to the effectiveness and cost of mitigation options. These uncertainties are partly caused by uncertainty with respect to technology development, but also regarding public attitudes (e.g. acceptance of nuclear power, CCS or large-scale bio-energy). Together, these uncertainties can easily double or halve the mitigation costs for a certain mitigation target, or even put certain targets out of reach. Crucial uncertainties, for instance, include those related to land use, baseline emissions, bio-energy use, and potential and technology development. Climate policies should therefore include strategies that can cope with these uncertainties.

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Appendix 7.1 Additional information

The FAIR 2.1 model (Framework to Assess International Regimes for differentiation of future commitments) was designed to quantitatively explore the outcomes of different climate regimes in terms of possible environmental and economic impacts (including emission trading). It is a decision-support tool with at its core the option of designing rule-based systems that simulate different proposals for differentiating of future commitments (also referred to as “burden differentiation” or “burden sharing”). The model uses expert information from more complex models such as baseline emissions and marginal abatement costs curves (in particular, TIMER and IMAGE) to calculate the consequences of these proposals. The basic assumption of the model is that regions will meet their emission reduction commitments on the basis of least cost – i.e. across different mitigation options (multi-gas) and across different regions (set by certain trading rules). Recently, FAIR 2.1 has been integrated with the SiMCaP 1.0 model to allow simultaneous calculations of climate impacts based on the MAGICC model (Wigley and Raper, 2001) included in SiMCaP. Extensive documentation of the FAIR 2.1 model can be found in Elzen and Lucas (2005) and FAIR–SiMCaP 1.1 model in Den Elzen and Meinshausen (2005).

Information on reduction potentials have been transferred to FAIR, as indicated in Figure 7.1. Table A.1 (topmost rows) summarizes the reduction potentials for 2500 and 2100 according to three main categories (under default assumptions). Three cost levels (200, 500 and 1000 US$/tC) are indicated for two years (2050, 2100). A single number is provided for carbon plantations and non-CO$_2$ gases; while for CO$_2$ emissions from energy, emission reductions depend on the pathway, which is why the table provides ranges. The bottom rows provide for comparison the total emissions under the scenario (bottommost rows).

Table A.1 Overview of reduction potential under the main baseline (B2) (top) and baseline emissions (bottom)

		2050 Reduction potential			2100 Reduction potential		
		Permit price			Permit price		
		200 US$/tC	500 US$/tC	1000 US/tC	200 US$/tC	500 US$/tC	1000 US$/tC
Reduction potential (GtC-eq.)	CO$_2$ fossil fuels(*)	5.6/7.9	9.6/11.2	11.7/12.6	13.5/14.2	15.8/16.2	16.7/16.8
	Carbon plantations	0.3	0.4	0.4	0.4	0.8	0.9
	Non-CO$_2$	1.8	2.4	2.6	2.6	3.1	3.3
	Total	**7.7**	**12.4**	**14.7**	**17.1**	**20.1**	**21.0**
		2050 emissions			2100 emissions		
Emissions baseline (GtC-eq.)	CO$_2$ fossil fuels	19.8			20.8		
	CO$_2$ land use	-0.2			-0.1		
	Non-CO$_2$	5.3			4.9		
	Total	**24.9**			**25.6**		

(*) For CO$_2$ from fossil fuels, the maximum reduction potential depends on the trajectory of the carbon tax. Indicated are (left and right of the / sign) the minimum and maximum reduction potential based on a linearly increasing and block tax profile.

8. RESPONSES TO TECHNOLOGY AND TAXES IN A SIMULATED WORLD

Abstract A set of model experiments was performed to analyze the role of technology development on energy system responses to a uniform global carbon tax. Stabilization at a carbon dioxide concentration of 550 ppmv from the IMAGE 2.2 B2 baseline was shown to be technically feasible at limited cost based on a combination of improved energy efficiency, fuel switching and in the longer introduction of carbon-free options. Technology development under baseline conditions, induced technology development by climate policies and technology inertia (based on their lifetimes) are identified as important factors in explaining the different responses under different conditions. For example, technology development, modeled as learning by doing, increases the global carbon reduction in 2030 from nearly 40 to 60% as a result of a 300 US$/tC tax. The relative importance of the three factors mentioned plays a major role in the optimal timing of abatement efforts. For long-term responses not only has technology development been shown to be important, but also other dynamic processes in the energy system, such as depletion, which can sometimes work in the opposite direction.

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8.1 Introduction

According to the IPCC assessment report, climate change observed over the 20th century was mostly caused by human activities (IPCC, 2007). As further global warming is likely to result in increasing risks of negative impacts on both natural systems and human societies around the world, significant reductions of greenhouse gas emissions may be needed. IPCC reports also indicate that technologies for significantly reducing current emissions with respect to baseline development in the next 20 years are already available (IPCC, 2001). However, reducing emissions on a large enough scale to prevent significant climate change using current technologies is seen in a number of studies to be costly. For this reason, development of better technologies will, certainly in the long term, need to play an important role in providing a pathway to further reduce emissions at reasonable costs.

Several tools are used to study pathways to less greenhouse gas-intensive futures and the role which might be taken by different (types of) technologies within these pathways: see, for instance, IPCC's Third Assessment Report (Metz et al., 2001) for an overview., The focus on the role of technology development has significantly increased in the last few years. Several concepts of technology development and its driving forces have been explored, including (descriptions of) autonomous improvement, R&D-driven improvement and improvement driven by use ("learning-by-doing"). The last category, in particular, has received considerable attention from modelers, both thanks to its empirical basis and the means provided to endogenize technological progress in models (see e.g. Grübler et al., 1999; Wene, 2000). Understanding the processes that determine technology development, and related to this, the potential of different technological options, is very important for developing mitigation strategies, both in terms of their costs and their timing.

In this chapter, we will focus on the role of technology development within different mitigation scenarios and its possible consequences for mitigation costs, for example. More specifically, we will search for relevant dynamics within the system that could be important for the role that technological development may play, both in the long and medium terms. Such dynamics include, for instance, the relationship with capital turnover rates (and inertia in the system), technology development already included in the baseline scenario, development induced by climate policies (both based on learning curves) and the influence of resource depletion. The relative contribution of these different processes is crucial in the debate on the timing of mitigation action.

The analysis was done with the TIMER 1.0 model, part of the integrated assessment model IMAGE 2.2 (see Chapter 2). The model was developed to study the long-term dynamics of the energy system, in particular, transitions to systems with low carbon emissions (de Vries et al., 2001; IMAGE-team, 2001). TIMER is a system-dynamic energy system model at a medium level of aggregation. The model uses learning curves for almost all its technologies. The position of TIMER within the integrated assessment framework of IMAGE also allows us to study not only such factors as environmental impacts and co-benefits – but also land-use consequences of mitigation choices. Earlier, the model was used to explore pathways to reach a stabilization of the atmospheric concentration of CO_2 at 450 ppmv from the B1 scenario (van Vuuren and de Vries, 2001). In this chapter, we continue this type of analysis by looking at different mitigation scenarios that will bring the carbon concentration to 500-600 ppmv by the end of the century, starting from the B2 baseline scenario[i].

We will first address several methodological issues, including some of the relevant processes of technological change in relation to climate policies, and the most relevant features of TIMER. Secondly, we will briefly describe how the B2 baseline scenario is implemented in TIMER, providing the context for our further analysis. Thirdly, we will look at the results of the various mitigation experiments explored. These are divided into three experiments. The first investigates how stabilization of greenhouse gas concentrations can be achieved starting from the B2 scenario. The second experiment looks into some of the relevant dynamics of long-term mitigation scenarios (until 2100). The last experiment looks in detail at the different processes relevant for medium-term energy-system response to mitigation action. The last section deals with the main conclusions.

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[i] Both the B1 and B2 baseline scenarios are part of total set of 6 IPCC scenarios introduced in the Special Report on Emission Scenarios (Nakicenovic and Swart, 2000). B2 is a medium emission scenario in the total set. The scenario will be discussed in more detail later.

8.2 Theoretical background and methodology

The IMAGE 2.2 integrated assessment model and its energy system model, TIMER, used in the analysis, will be overviewed later in this section. First, we discuss some of the dynamic processes of particular importance for the influence of technology development (assuming the use of learning curves) on the response of the energy system to mitigation action. The modeling experiments are outlined at the end of the section.

8.2.1 Dynamic processes that influence technological development

The main focus here is the role of technology development on the costs of emission reductions in the medium and long term. The term technology development refers to changes in the portfolio of technologies used to supply energy to end-users. In stricter sense it refers to changes to the set of available technologies that change (improve) their performance either in terms of utility or costs. A method to explore the influence of technology development in an energy model is to analyze the response of the model to externally applied carbon tax. Several authors have used such a method, in which taxes are progressively increased, to develop so-called marginal-abatement cost curves (Ellerman and Decaux, 1998; Criqui et al., 1999)[ii]. This concept functions as a main element in our analysis – defining system response R, as indicated in equation (8.1). Here, E_{tax} represents the emissions after a tax has been applied and $E_{baseline}$ the emissions in the case of a baseline.

$$R = E_{tax} / E_{baseline} \tag{8.1}$$

The focus in this chapter is on changes in the system response R as a result of technological change at the global level. The use of an energy-system model allows us to study these responses in the context of the (full) dynamics in the world energy system, including depletion and trade but also several technology-relevant processes. In fact, we recognize six dominant dynamic processes in models that are directly related to technological development – and directly influence the response of the model to external impulses. These are:

- switches between different technologies as a result of changes in relative costs;
- technology development under baseline conditions;
- induced technology development in response to a carbon tax;
- technology inertia as result of limited capital turnover rates;
- investments in research and development;
- impacts of technology-specific resource depletion.

[ii] The curves can be interpreted as marginal-abatement cost curves where the carbon tax is seen as an indicator of mitigation costs. A more general term for these curves is “system-response” curves.

We will discuss these processes in the context of the modeling experiments explored, indicating their importance for the total system response. Here, these processes are only briefly introduced:

- *Switches between different technologies as a result of changes in relative costs.* The most direct impact of a carbon tax is that it changes the relative costs of fuels/technologies and thus also their penetration. This leads to additional use of zero/low carbon fuels/technologies.
- *The influence of the technology progress already included in the baseline scenario.* In general, costs of new renewable (zero-carbon) technologies such as solar/wind and biomass will, under the baseline, decrease more rapidly than the costs of more mature, fossil-based technologies (in a model, this process can be formulated in terms of learning-by-doing if niche markets exist or alternatively by exogenous assumptions). As a result, the gap that climate policies need to bridge over time in enforcing the penetration of the more expensive zero carbon options (compared to the cheaper fossil options) decreases. A consequence of this, all other factors being equal, is that later introduction of a tax will lead to a stronger response (in terms of equation 8.1) than if the same tax had been introduced earlier.
- *The influence of technology progress induced by climate policies.* The learning-by-doing mechanism (see also section 8.2.3) implies that further employment of renewable technologies in response to a carbon tax will cause further cost reductions of these technologies. These technologies would then become more attractive, and thus, all other factors being equal, the response to a carbon tax would slowly increase over time.
- *The influence of technology inertia.* There is much inertia in the energy system. As capital is normally only replaced at the end of its lifetime, a response to a carbon tax can only slowly penetrate into the system. The response of some energy demand sectors can be somewhat swifter than in other sectors as technical lifetimes of the technologies used are shorter than in energy production. Futhermore, to some degree, behavioral changes and so-called good housekeeping measures may allow for almost immediate responses. Thus, as a result of inertia alone, the response to a carbon tax will slowly increase over time.
- *Investment in research and development.* Another important process that could stimulate technology development is investing in research and development (R&D). There is some discussion whether this process can be seen as a separate process for technology development ("learning-by-searching"), or whether it should be seen in conjunction with learning-by-doing (Grübler et al., 1999). If seen as a separate process, investments into R&D can bring down costs of more expensive low-carbon options without applying these technologies first, increasing the response to a carbon tax in time.
- *The influence of resource depletion.* Indirectly, the use of a carbon tax also changes the resource depletion dynamics of different forms of energy (e.g. depletion of fossil fuel resources, higher production costs of renewable energy as less suitable sites are used etc.). Important in this context is that different fuels/technologies have their own depletion characteristics.

These different processes are strongly related to the earlier discussion on the timing of mitigation action. The second process (learning at the baseline) leads to the conclusion that it is better to wait for technologies to develop before implementing strict climate policies. This argument was forcefully presented in Wigley et al. (1996) in their discussion on timing of mitigation action. In contrast, the third process enforces the argument that climate policies should be seen as a lever with which to bring about climate-friendly technical innovation and diffusion, favoring an early-action type of approach (Azar and Dowlatabadi, 1999; Wene, 2000; van Vuuren and de Vries, 2001). The fourth process translates into an argument that climate policy should not result in premature replacement of capital. This argument was used by Wigley et al (1996) as a reason for later abatement being cheaper. However, others have argued that after including fully all system inertia, this argument actually gives preference to early action to make the transition as smooth as possible (Grubb, 1997; Ha-Duong et al., 1997). The fifth process might, in turn, favor a strategy in which first strong investments into R&D are made, followed later by large-scale employment of available technologies (once they have become competitive). Finally, the influence of the sixth process is ambiguous. A crucial issue arising from a final decision on timing is how important these processes are in relation to each other.

In an earlier publication, we looked into how the total set of processes could be worked out in a scenario with very positive assumptions about technology development and low energy use (the SRES B1 scenario) (van Vuuren and de Vries, 2001). We found early action to be a more favorable strategy than delayed response for a discount rate of 4% and lower, as postponing measures foregoes the benefits of learning-by-doing. Using higher discount rates would favor a delayed response approach. Here, we intend to analyze the underlying technology dynamics in greater detail, and relate the outcomes to the discussion on timing of climate policy as described above.

8.2.2 Modeling framework

We used the TIMER 1.0 energy system model and the integrated assessment framework IMAGE 2.2[iii].

IMAGE 2.2

IMAGE 2.2 was developed to assess the impact of global environmental problems, in particular, climate change (IMAGE-team, 2001). IMAGE consists of a set of linked and integrated models collectively describing the chain of global environmental change from population and economic change to impacts on ecosystems and agricultural systems. The models operate on two geographical scales. Most of the drivers and socio-economic processes (population, economy, agricultural demand, energy use, emissions) are calculated for 17 world regions. In addition, a large number of the environmental parameters are calculated at the grid level of 0.5 x 0.5 degrees. The IMAGE 2.2

[iii] An abbreviation of Integrated Model to Assess the Global Environment

scenarios cover the 1970-2100 period. In 2001, the model was used to re-implement the IPCC SRES scenarios (base year updated to 1995) (IMAGE-team, 2001).

TIMER 1.0

TIMER 1.0 is an energy-system model describing the supply and demand of 12 different energy carriers for 17 world regions. A description of the model is given in Chapter 2 of this thesis, while a full description of TIMER 1.0 can be found in De Vries et al. (2001). The main objective of the TIMER model is to analyze the long-term trends in energy demand and efficiency and the possible transition towards renewable sources. The model focuses particularly on several dynamic relationships within the energy system, such as inertia, learning-by-doing, depletion and trade among the different regions. This makes the model very suitable for studying some of the long-term dynamics related to technology development discussed in section 8.2.1.

The energy demand submodel of TIMER determines demand for fuels and electricity in five sectors (industry, transport, residential, services and other) based on structural change, autonomous and price-induced change in energy intensity (“energy conservation”) and price-based fuel substitution. The demand for electricity is fulfilled by fossil-fuel based thermal power, hydro power and two other non-thermal alternatives, i.e. nuclear power and solar/wind. The option “solar/wind” describes a renewable electricity option with characteristics of both solar and wind power. Both nuclear power and solar/wind penetrate the market based on relative costs. The thermal power option consists of four alternative options: coal-based, oil-based, natural-gas based and biomass-based, all of which are fully intercompetitive. The exploration and exploitation of fossil fuels (either for electricity or direct fuel use) are described in terms of depletion and technological development. Biofuels can be used in place of fossil fuels, and are, in turn, also assumed to be subject to technological development and resource depletion dynamics. Below we will describe the processes in TIMER that relate directly to the dynamic processes discussed in section 8.2.1. More detailed on these processes are given in Chapter 2.

Technology development

An important aspect of the TIMER model is the endogenous formulation of technological development on the basis of “learning-by-doing”. This phenomenon has been investigated in detail, and for a variety of products and processes. The concept also received great interest as a meaningful representation of technological change in global energy models (Azar and Dowlatabadi, 1999; Grübler et al., 1999; Wene, 2000). A general formulation is that a cost measure tends to decline as a power function of an accumulated learning measure:

$$y = \alpha^* \, Q^{-\pi} \tag{8.2}$$

where π is the learning rate, Q, the cumulative output and α, a constant. Often, the learning rate, π, is expressed by the progress ratio ρ, which indicates how fast the costs measure, y, decreases with the doubling of experience, Q. It is easy to see that $\rho=2^{-\pi}$.

Many illustrations of this law have been found and published. The progress ratio in almost all cases investigated was found to be between 0.65 and 0.95, with a median value of 0.82 (Argotte and Epple, 1990). In Chapter 2, the dynamics of the "learning-by-doing" formulation are illustrated for some hypothetical examples.

In the TIMER model, "learning-by-doing" influences the costs of coal, oil and gas production, the investments of renewable and nuclear energy, and the decline of the energy conservation cost curves. The value of the progress ratio (ρ) varies from 0.7 to 1.0, based on historic ρ values for the different technologies. The choice of these values will depend on the technologies and scenario-setting. First of all, the progress ratios of solar/wind and biomass have been set lower than those for fossil-based technologies founded on observed historic trends (Wene, 2000). There is evidence that in the early stages of development, ρ values for learning-by-doing curves are lower (thus faster learning) than for technologies that have already been in use for long periods (see also Chapter 2). In TIMER all ρ values are time-dependent, with ρ values rising to 0.9 or higher before 2100 for all technologies. The development of the learning rates is also related to the storyline of the scenario. Table 8.1 gives the ρ values used in the B2 scenario of TIMER.

An interesting question is whether learning curves should be applied at the level of regions or for the world as a whole. On the one hand, technologies developed in one region will, in most cases, also be available in other regions. On the other hand, a significant portion of cost reductions are actually representative of the experience gained by applying the technology. In TIMER, the learning curves are applied at the level of separate regions; however, to model the influence of technology transfer, we assume that all other regions will benefit partly from the additional knowledge gain of the forerunner (de Vries et al., 2001).

Depletion

The role of depletion varies according to the technology/energy carrier. Depletion is described in terms of long-term supply curves (related to cumulative production) for the fossil-fuel technologies and nuclear energy (see Chapter 2 for a discussion of these curves for different technologies). The curves used in TIMER 1.0 are derived from Rogner (1997) and the World Energy Assessment (Goldemberg, 2000). Contrarily, for

Table 8.1 Progress ratios used in the B2 scenario as implemented in TIMER

Technology	*Progress ratio 1995*	*Progress ratio 2100*
Coal production	0.90-0.94	0.95-0.96
Oil production	0.85	0.92
Natural gas prod.	0.86-0.93	0.90
Efficiency	0.85-0.9	0.92
Nuclear	1.00	0.96
Solar/wind	0.80	0.90
Biomass	0.88	0.92

Note: The trajectory for values between 1995 and 2100 is linear.

renewable sources, depletion is described as a function of production. This formulation assumes that less attractive sites or technologies will have to be used at higher production levels. Specific investment costs and the maximum production levels for renewable energy have been derived from various sources, as indicated in the model documentation (de Vries et al., 2001). These derived values include, in particular, the resource estimates of the World Energy Assessment and calculations made using the IMAGE 2.2 land-use model (Goldemberg, 2000; Hoogwijk, 2004). A specific form of "depletion" is found in the electricity sector – where it is assumed that only a limited share of solar and wind power can be adopted free of charge– after which additional investments need to be made into the system to assure sufficient reliability (e.g. storage or grid extensions). These additional costs are assumed to come into play where the share of solar/wind in total electricity production is above 20%[iv].

Substitution between different technologies

Substitution among energy carriers and technologies is described in the model with the multinomial logit model (Edmonds and Reilly, 1985):

$$IMS_i = \exp(-\lambda^* c_i) / \sum_j \exp(-\lambda^* c_j) \tag{8.3}$$

IMS_i is the indicated share in total investments of production method, i, λ, the so-called logit parameter determining the sensitivity of markets to relative prices and c_i, the cost or the price of production method, i. The last factor may include other factors such as those related to premium, additional investment costs and cost increases as result of a carbon tax. The multinomial logit model implies that the share of a certain technology (or fuel type) depends on its costs relative to its competitors. The cheapest option gains the largest market share. However, it does not get the full market share, since the formulation assumes heterogeneity within the market, creating specific niches for technologies with higher average costs (but lower costs than its alternatives within this specific niche). The multinomial logit mechanism is used within TIMER to describe substitution among end-use energy carriers, different forms of electricity generation (coal, oil, natural gas, solar/wind and nuclear) and substitution between fossil fuels and biofuels. It should be noted that the mechanism is actually used to determine shares in new investment only, which implies that actual market shares respond much slower. Again, Chapter 2 illustrates the dynamics of this formulation for hypothetical examples.

8.2.3 Modeling experiments

In order to learn more about the possible role of different technology pathways, we performed three different model experiments, starting from IMAGE implementation of the SRES B2 scenario, i.e.:

[iv] As can be seen in Chapter 2, the modeling of the power sector has been heavily updated in TIMER 2.0. Instead of one factor capturing additional costs, processes that may lead to increased costs are now modeled independently (declining capacity credit, mismatch between supply and demand and spinning reserve).

a) A scenario aimed at stabilization of atmospheric carbon dioxide concentration at 550 ppmv (around 2150);
b) A series of three model runs in which a 100 US$/tC carbon tax is introduced: i) going immediately from zero to 100 US$/tC between 2000 and 2010; ii) increasing at 25US$/tC per decade in the first 40 years after 2000 – and staying constant at 100 US$/tC after 2040, and iii) increasing at 10 US$/tC per decade for the whole 2000-2100 period (see Figure 8.4).
c) A series of model runs in which different levels of carbon taxes are applied in 2000, 2010, 2020 and 2030, with the response recorded 10-30 years later.

In the first experiment, we looked at the types of technologies chosen by the model to achieve the required level of mitigation. Attention is also paid to the emission reductions of other greenhouse gases and impacts on energy-exporting regions. The emission profile leading to the 550 level is based on the so-called WRE profiles (Wigley et al., 1996). In the second set of experiments, a carbon tax was introduced in three different modeling runs, in all cases reaching a level of 100 US$/tC (see Figure 8.4); however, the rates of introduction varied among the different experiments. The aim of this experiment was to find out whether technology dynamics within the system would result in different responses to these taxes in the long term. Specifically, one might expect the run reaching the final 100 US$/tC tax level early in the simulation to benefit more from the induced technology development than any of the other runs. The last set of experiments took place in a much shorter time frame. It also searched specifically for the different contributions to the overall system in its response to a carbon tax of induced technological learning, where learning forms part of the baseline and inertia.

It is important to note that the model applied in this study does not take into account physical carbon sequestration (removing carbon from the energy system for underground/underwater storage) or options to reduce land-use related emissions.

8.3 Baseline scenario

The IPCC SRES B2 scenario has been developed within a total set of six baseline scenarios, none of which includes explicit climate policies (Nakicenovic and Swart, 2000). The IPCC SRES scenarios are based on the development of narrative “storylines” and the quantification of these storylines using six different integrated models from different countries. For each scenario, the elaboration by one specific model has been chosen as being characteristic for that particular storyline, the so-called “marker scenario”. Elaboration of the same storyline by other models needs to fulfill certain criteria in order to qualify as a fully harmonized scenario. The B2 storyline describes a regionalized world with a focus on environmental and social values, but in reality for most of implementation of this scenario a “dynamics-as-usual” interpretation is chosen (Riahi and Roehrl, 2000). The IMAGE 2.2 implementation, in contrast, has put slightly more emphasis on the original storyline thus resulting in somewhat lower emissions than the marker (IMAGE-team, 2001). The IMAGE 2.2 B2 scenario can still be regarded as

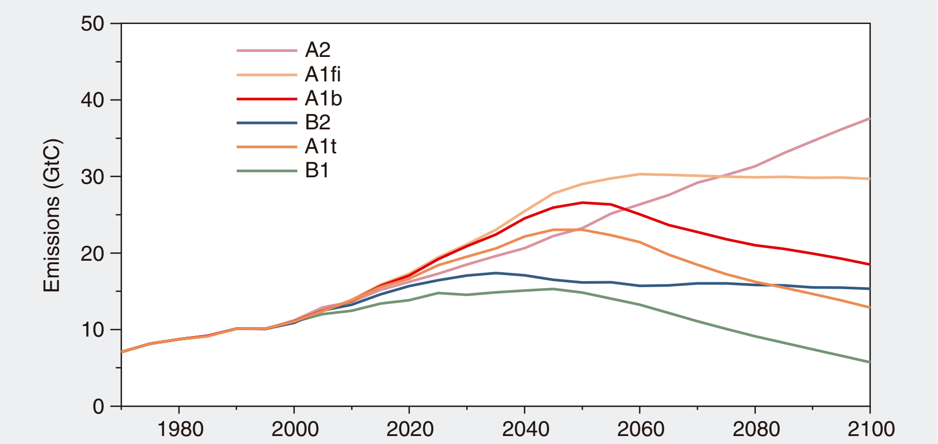

Figure 8.1 Global greenhouse gas emissions in the IMAGE 2.2 implementation of the SRES scenarios (all Kyoto gases and all sources) (IMAGE-team, 2001).

a medium emission scenario, with global greenhouse gas emissions increasing from 10 GtC-eq. in 2000 to around 15 GtC-eq. in 2100 (see Figure 8.1) (In comparison with the total literature, this can be regarded as a medium emission scenario - see Chapter 6). In terms of sectors, energy use remains the cause of the larger share of emissions. Driven by increasing emissions, the atmospheric carbon dioxide concentration in the B2 scenario increases from 370 ppmv to 605 ppmv in 2100 (or 425 ppmv CO_2-eq to 820 ppmv CO_2-eq), which is more than double pre-industrial levels. The global temperature increase is found in the range of almost three degrees above 1970 levels (using a climate sensitivity of 2.5°C).

8.4 Mitigation experiments

The results of the experiments described in section 8.2.3 are outlined below.

a) Stabilization at 550 ppmv

Reaching a profile that stabilizes the atmospheric carbon dioxide concentration at 550 ppmv from the IMAGE B2 scenario requires a reduction of cumulative emissions in the 2000-2100 period of about 25%. Such a reduction could be regarded as a relatively modest one[v]. If we introduce a uniform carbon tax (across regions and sectors) in TIMER, we need a tax slowly rising to 190 US$/tC to achieve such a reduction (no carbon tax is applied to land-use-related carbon emissions). The profile of the required carbon tax is shown in Figure 8.2.

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[v] The reduction is in size of the same magnitude as the reduction that is required for achieving stabilization at 450 ppmv of carbon dioxide in the atmosphere starting from the B1 baseline scenario that we described earlier (van Vuuren and de Vries, 2001). Further in this section we compare the results to those of the B1 450 ppmv analysis.

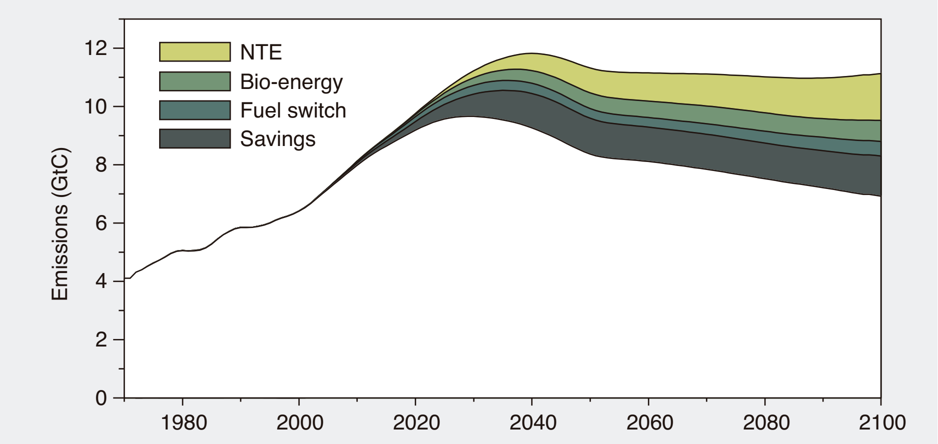

Figure 8.2 Allocation of carbon dioxide emission reduction from B2 to a 550 ppmv stabilization scenario.

In total, the required carbon tax reduces global primary energy use by about 10-15%. This decrease is unequally divided among the different energy carriers. Cumulative use of coal declines by almost 50%. The cumulative consumption of natural gas and oil declines by about 10% (the decline in natural gas is slightly higher than for oil, as natural gas experiences considerable competition from non-fossil energy carriers in the electricity market). Other, low/zero carbon, energy carriers gain a market share such as modern biomass (14% increase in cumulative consumption), and nuclear power and electricity from renewables (gain totals 36%).

In Figure 8.2, we attributed the reduction in carbon emissions from B2 to B2-550 to the different changes within the system[vi]. In the first two decades, the lion's share of the reductions come from energy efficiency improvement and the fuel switch from coal to other fossil fuels. By 2030, the other options start to become important: for example, use of biofuels instead of fossil fuels and non-thermal electricity modes (solar/wind and nuclear power) instead of fossil-based electricity[vii]. The largest reductions are likely to occur in the electrical power sector. This result can easily be understood if one looks at generation costs of the two fully competitive non-fossil power options compared to those of thermal power (Figure 8.3). In the baseline, from 2000 until around 2030 there is still a very clear gap between the generation costs of these options in favor of fossil-fuel based options; solar/wind still hovers around a factor that is 2-3 times more

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[vi] The actual size of each option depends somewhat on the order in which options are allocated. We first determined the total contribution from efficiency improvement, next from penetration of solar/wind and nuclear power and biofuels, then from biofuel penetration and finally for a fuel-switch among the different fossil fuels.

[vii] We have allowed additional use of nuclear power as a mitigation option in these calculations. In fact, as the cost of this option is lower in the baseline than the solar/wind power option, it represents the most attractive alternative in terms of a first response. The "learning" capacity of this option is, however, assumed to be lower than for solar/wind power. It should be noted that generation costs for fossil-based electricity is, in fact, calculated in the model through a weighted average of coal, oil and natural gas generation costs.

expensive, while the difference with nuclear power is somewhat smaller. In time, the costs of solar/wind power and nuclear power by learning-by-doing slowly decline, and around 2050 generation costs become nearly equal. As solar/wind power gain a considerable market share at that time, cost reductions start to be offset by lack of production sites – the best sites are already occupied. Besides this, the further penetration requires higher storage and/or distribution costs. As a result, fossil-fuel-based electricity remains the cheapest of the supply options in the baseline throughout the century. If a carbon tax is introduced into this system, it will easily shift the costs of the thermal options upwards (above the alternative costs for nuclear and solar/wind). This induces in the model a strong penetration of these options into the power generation system, allowing for sharp reductions of carbon dioxide emissions.

The strongest impact of the carbon tax is on coal use. Hence, the largest changes in terms of energy use will occur in regions with relatively high coal consumption and production rates. This includes China, India, South Africa and the USA. Impacts on oil use and trade are much smaller – in view of the relatively modest taxes required to reach 550 from the B2 scenario (also note that trade levels in B2 are somewhat lower than in other SRES scenarios). Middle East oil exports, for instance, decrease in terms of the ratio of export revenues to GDP from 11.6 to 11.1% in the 2000-2050 time period (Table 8.2). Impacts in regions with slightly higher production costs, such as the FSU, could be larger in relative terms. A number of other import regions could benefit from reduced oil imports around 2050, in particular, China and India.

Interestingly, changes in the trade of other fuels can paint a different picture for total energy exports as a percentage of GDP. The Former Soviet Union, for instance, suffers in the long-run (2030-2060) from reduced oil exports. The exploitation of this region's oil resources, very competitive by that time under the baseline, is subject to a carbon

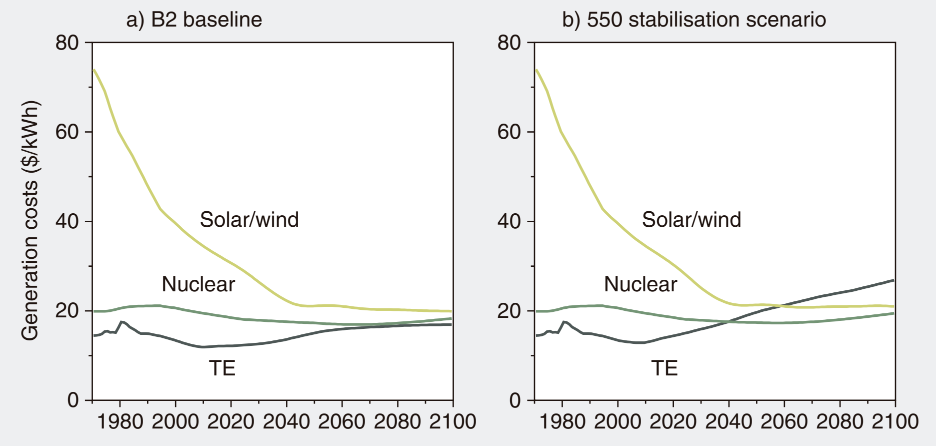

Figure 8.3 Generation costs of non-thermal options (solar/wind and nuclear) versus electricity from thermal-power plants (mostly fossil-fueled, but including biofuel, TE; electricity generation in the B2 baseline (left) and the 550 stabilization scenario (right).

Table 8.2 Volume of fuel trade as % of GDP in selected regions (2000-2050) (net imports negative; net exports positive)

	Oil export (% GDP)			*All energy export (% GDP)*		
	B2	B2-550	Diff.	B2	B2-550	Diff.
USA	-0.75	-0.71	*0.04*	-1.36	-1.41	*-0.04*
South America	1.09	1.02	*-0.07*	2.44	2.70	*0.26*
Western Europe	-0.57	-0.52	*0.05*	-1.14	-1.12	*0.02*
FSU	3.37	3.01	*-0.36*	10.44	10.97	*0.53*
Middle East	11.64	11.13	*-0.51*	13.58	13.11	*-0.47*
South Asia	-2.07	-1.93	*0.14*	-3.54	-3.53	*0.00*
East Asia	-0.70	0.67	*0.03*	-1.11	-1.22	*-0.11*
Japan	-0.66	-0.63	*0.03*	-1.28	-1.25	*0.03*

tax that by then will have reached a level of 50-100 US$/tC. In contrast, (2010-2030) this region benefits significantly in the medium term from increased natural gas exports to Western Europe and Japan. South America also sees some losses in oil exports – but these are offset as the region gains its experience in producing biofuels and becoming an important exporter of these fuels. Finally, for China, the reduction in oil exports is off set by an equally sharp increase in natural gas – and later biofuel imports (van Vuuren et al., 2003d).

The reduction of energy and industry-related carbon dioxide emissions amounts to about 25% in 2050 and 40% in 2100 (the latter being equal to 4.3 GtC/year). As a result of the induced changes in the energy system to the carbon tax (more energy crops to produce biofuels, thus less land for new forests), land-use emissions increase slightly by about 0.4 GtC. (a form of carbon leakage that could be reduced by additional policies oriented to land-use related emissions). The carbon tax does not directly tax non-carbon dioxide greenhouse gases either. However, as the carbon tax induces changes in the energy system, the emissions of other energy-related gases are reduced. For instance, energy-related methane emissions are reduced by about 10% compared to baseline (a 60% increase in emissions instead of a 70% increase), with corresponding advantages in terms of greenhouse gas concentrations. Sulfur emissions are also reduced by about 10% compared to baseline. The latter gives rise to important co-benefits of climate policies in terms of reduction of both urban and regional air pollution (van Vuuren et al., 2003a).

The B2-550 stabilization scenario developed here results in a rise in global average temperature of 2.6 °C vis-à-vis a temperature increase of 2.9 °C in the B2 baseline scenario. The gains from the reduction in the radiative forcing of carbon dioxide take place,, in particular, in the first decades, somewhat offset by a decrease in the negative forcing of sulfur aerosols.

If we compare the results for stabilizing the carbon concentration at 550 ppmv from the B2 scenario to our earlier analysis, we see that the required efforts and consequences are very comparable. Stabilizing the carbon concentration at 450 ppmv from the B1 scenario required a 200-230 US$/tC carbon tax by the end of the century (depending on the timing), versus the 190 US$/tC used here. Responses in terms of the contribution of different technologies also seems to be comparable – although reducing coal use is slightly more important in this B2-550 analysis in view of the higher shares of coal use in total energy use. In contrast, impacts on oil trade are smaller – most probably due to the more fragmented oil market in the B2 scenario.

Responses to different 100 US$/tC taxes

In the second set of experiments, a carbon tax is introduced that reaches a level of 100 US$/tC – but is introduced using three different rates.(see Figure 8.4).

Figure 8.5 shows that carbon dioxide emissions are reduced the fastest in the scenario that has already reached the 100 US$ level in 2010 (1), followed by the second and third scenarios. As a result, by 2100 the first scenario has a considerably lower carbon dioxide concentration than the third. We can also compare the relative reductions for the same tax levels. These are not always similar; apparently, model dynamics do play a role here. However, the expected effect (see section 8.2) of a sharper 2100 emission reduction in the first scenario compared to the others, due to a longer period of induced learning, is not visible. There are four important reasons inherent in the model for this:

- *Learning slows down with knowledge gained.* The learning curve describes technical progress as a function of the logarithm of cumulative production. This means that a similar improvement in production costs can be realized for each doubling of cumulative production, as explained in Section 8.2. Production itself cannot keep "doubling" its production rates throughout the century, thus cost reductions slow down in time. The scenario that reaches the 100 US$/tC as early as 2010 benefits from fast learning early in the scenario – but also experiences the consequences of slower learning afterwards.

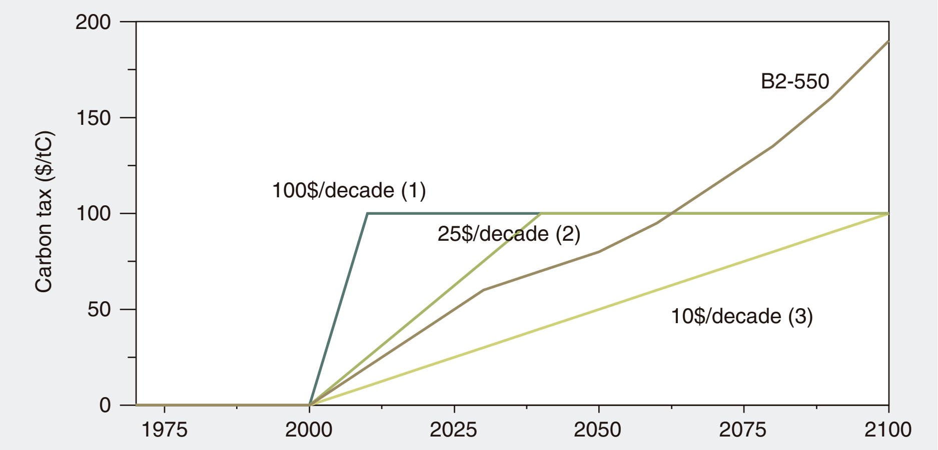

Figure 8.4 Overview of the taxes applied.

- *High production rates for renewables are costly.* We assume that depletion of renewable technology options are directly related to production rates (see section 8.2): high production rates imply that less favorable options (e.g. less favorable sites for wind power) have to be chosen. The early tax scenario results in higher production rates of these options – and thus experience higher depletion.
- *High shares of renewables induce costs.* Most of the renewable electricity options have a lower reliability than fossil-fuel options (i.e. due to the intermittent character of solar and wind power, renewable based capacity might not be able to generate power at the right moment). Therefore, total electricity production can only absorb a limited percentage of renewable electricity options (we assumed 20%) before requiring additional investments into the system to improve its reliability (e.g. storage or grid extensions that enlarge the system). This dynamic element has similar consequences to depletion described above.
- *Some cheap oil and gas are still available.* Finally, the competitive fossil-based alternatives will have slightly lower production costs in the first scenario than in the second and third scenarios as less depletion of cheap resources will have taken place.

In conclusion, in addition to "learning-by-doing" there are also other technology-relevant dynamic processes, some of which may work in the opposite direction to the expected gains for early action scenarios of "learning-by-doing". Under the B2 model assumptions in TIMER, these processes completely off set the gains of early action in terms of costs by 2100. On the other hand, it should be noted that the early action benefited from lower costs for solar/wind during most of the simulation (see Figure 8.6). Moreover, the environmental impacts of these three scenarios are certainly not similar (see carbon dioxide concentration in Figure 8.5).

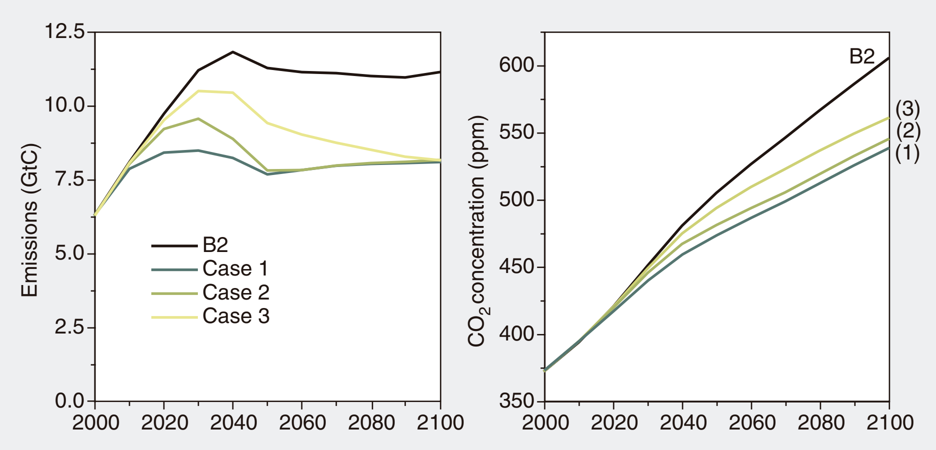

Figure 8.5 Global carbon dioxide emissions (left) and carbon dioxide concentration (right). Note: the numbers correspond to the different tax profiles of Figure 8.4.

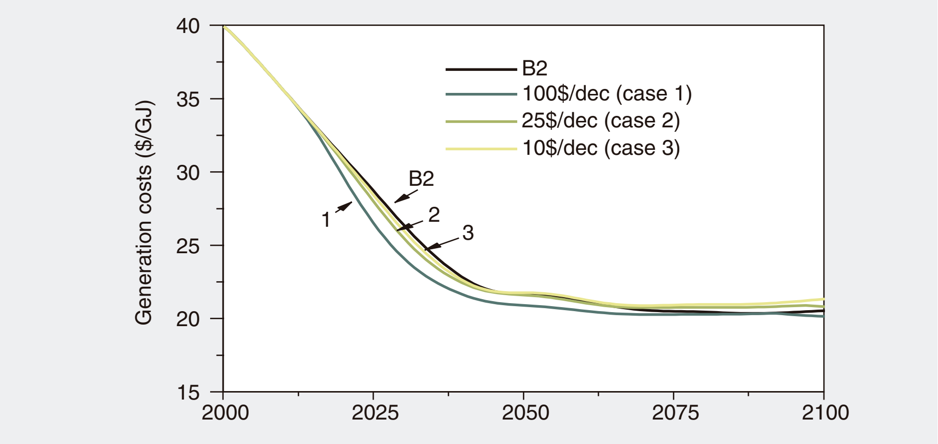

Figure 8.6 Costs of solar/wind power generation in TIMER.
Note: the numbers correspond to the different tax profiles of Figure 8.4.

c) Responses to carbon taxes with and without learning
In the last set of experiments, we took a shorter time horizon (2000-2030) and investigated whether we could identify the role of different relevant dynamics to determine the response to a carbon tax as defined in equation 8.1. We assumed that some of the dynamics discussed in the previous section were of less importance on this medium-term time scale, in particular those related to depletion. The three types of dynamics of particular importance for the medium-term response are technology development under baseline, induced technology development and system inertia.

We tried to get an idea of the influence of the three processes through a set of experiments in which we recorded the system response as a function of the year of introduction (t_{in}), the year in which we measure the system response (t_{rec}) and the level of the tax (T). For both t_{in} and t_{rec}, values were applied in five-year steps between 2000 and 2030. The level of the carbon tax varied between 0 and 600 US$/tC.

In the first experiment we focused on the recording year (t_{rec}). We introduced a carbon tax into the TIMER model in the year 2000 (t_{in}) of 10 US$/tC (T) and recorded its immediate impact in 2000, and its impact in 2010, 2020 and 2030 (t_{rec}) and after 10, 20 and 30 years, respectively. This experiment was repeated for the different tax levels between 10 and 600 US$/tC in steps of 10 US$/tC. This process is very similar to experiments in which modelers record the response of their model to carbon taxes in order to derive so-called Marginal Abatement Curves (MAC). However, in contrast to the normal MAC experiments, we looked at how the system response develops over time in the period after introduction of the carbon tax. Figure 8.7a shows the results of this experiment. The recordings have resulted in four system-response curves that indicate the reduction in global carbon emissions in four different years. All of the curves show the typical form of a MAC, in which the response increases along with the level of the tax but with decreasing additional gains. Figure 8.7a shows the response to the carbon

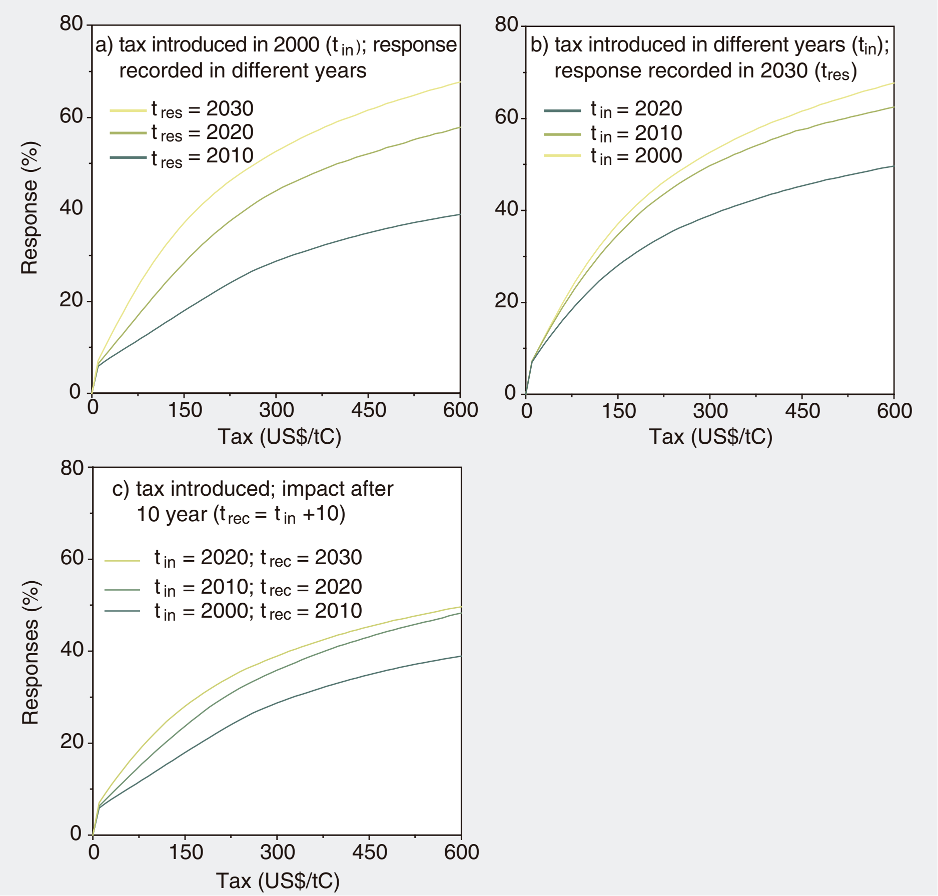

Figure 8.7 Response to a carbon tax: a. introduction year 2000 - different recording years; b. recording year 2030 - different introduction years and c. recording year 10 years after introduction year.

tax increasing with time. A 300 US$ tax introduced in 2000, for instance, has only a very limited response in 2000 itself but causes a 30% reduction of global carbon emissions after 10 years – and reduces global emissions by more than 50% after 30 years. “Baseline learning”, “induced learning” and “inertia” all contribute to this increasing response over time.

In a second experiment we brought in the time of introduction of the tax (t_{in}). What happens if the tax is not introduced in 2000, but in 2010 or 2020? We recorded the impact in 2030 (t_{rec}) of three different series of taxes introduced in 2000, 2010 and 2020, respectively (Figure 8.7b). The results are fairly similar to the previous experiment. A tax introduced in 2000 has the largest response, benefiting again from both baseline and induced learning processes, and having sufficient time to overcome the existing inertia. The 2030 response to a tax introduced in 2020 is significantly smaller. Interestingly, this curve lies some 10% above the curve in Figure 8.7a of the 2010 response of tax introduced in 2000 (both curves are included in Figure 8.7c). In terms of time elapsed after the tax was introduced, these cases are similar as both curves show the situation 10 years after the tax was introduced. Assuming that the role of inertia and induced learning will therefore be comparable, technology development under the baseline can be identified as an important process explaining these differences. Figure 8.7c shows all three curves, recorded 10 years after the introduction of the tax.

We continue this line of thinking, but now considering the introduction time t_{in} and the recording time t_{rec} as two independent axes in one graph. In this graph we show, for a given tax level T (in this case 300 US$/tC), all possible responses as a function of combinations of t_{in} and t_{rec}, in five-year steps. The surface that is created in this way obviously shows the strongest response in the lower right corner, as this depicts the situation of an early introduction of the tax (2000) and late recording (2030). The diagonal from the lower left corner ($t_{in =}$ 2000, t_{rec} = 2000) to the right upper corner (t_{in} = 2030; t_{rec} = 2030) represents all points in which response is recorded immediately after the introduction of the tax – and responses along this diagonal are therefore small. All points going to the left upper corner from this diagonal are zero by definition (recording time before the introduction of the tax). This representation allows for a comparison in different directions. Horizontal and vertical lines through the graph show the influence of changes in recording time and introduction time, respectively, while diagonals compare cases with a constant time between t_{in} and t_{rec}. The highlighted diagonal in the graph, for instance, shows all cases with a 20-year time period between introduction of the tax and recordings for the 2020-2030 period.

We will first look at the results of this graph in the normal model mode (Figure 8.8; left upper graph). A 300 US$/tC tax gives a maximum response of almost 60% reduction of global CO_2 emissions if introduced in 2000 and recorded in 2030 (lower right corner). An important observation is that the graph is not symmetrical in its response to the two different time axes. The cause of this is mainly the “learning under the baseline” that creates different starting situations for our experiments.

In the model, we can now switch off different dynamics step-by-step. First, the additional “learning-by-doing” induced by a carbon tax is completely switched off (learning is equal to baseline), resulting in Figure 8.8 (upper right graph). Instead of reaching a maximum reduction near 60%, the maximum reduction is now 40-50% (lower right corner). Thus, induced learning between 2000 and 2030 to a 300 US$/tC tax creates an additional 10% response under the B2 assumptions relative to the response that would be obtained if no induced learning was included in the model. Interestingly, the difference between the first and second graph becomes less for the cases where there is a shorter period between the year of introduction and the recording time. This result can be understood, as this also decreases the period in which induced learning can take place.

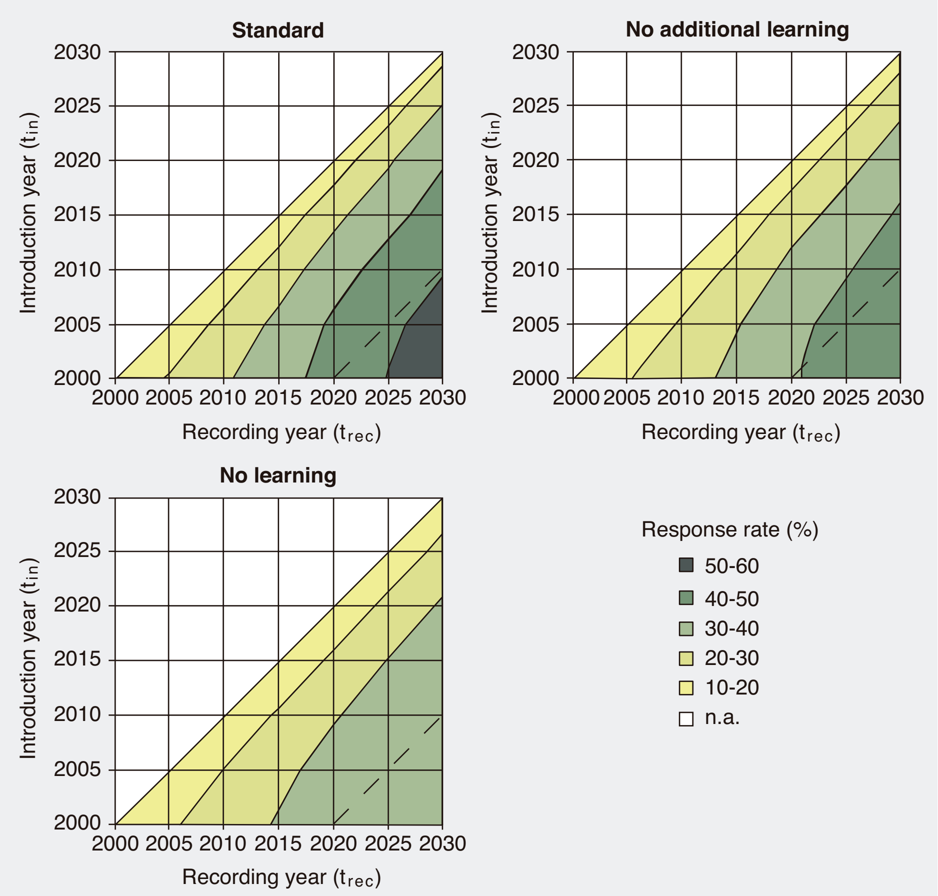

Figure 8.8 Global carbon response rate (in % reduction compared to baseline) to a US$300/tC tax as a function of introduction and recording year. The introduction year represents the year the tax is introduced, the recording year the year that the response to the tax is recorded. The dashed line indicates, as an example, all points in which the response is recorded 20 years after the introduction.

In the last experiment, we also switched off all learning that had already occurred in the baseline – leaving all technology frozen at its 2000 level[viii] (Figure 8.8; lower left). This means that inertia completely determine our results. Again, taking out the process of technological development reduced the response of the system to the carbon tax. The maximum response is now around 35% for the 2000 introduction, and 2030 recording years(lower right corner), thus, again, a loss of about 10% in terms of carbon emission reduction. Secondly it was observed that the graph had become more symmetrical. This is consistent with our explanation that the asymmetric response shown in the first two graphs of Figure 8.8 is at least partly related to learning under the

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[viii] Obviously, this also changes the baseline itself in terms of emissions. However, as we are interested in relative responses, this does not create major obstacles for comparing the different cases.

baseline. The remaining asymmetry is caused largely by depletion of fossil fuels in time (weakening the competitive position of fossil-fuel based technologies).

This set of experiments shows the importance of assumptions about technology development for the effectiveness of reducing carbon dioxide emissions – and for the abatement costs, if we take the level of the carbon tax as a proxy for total costs. In our experiments, we have more-or-less untangled the different roles of technology development in the baseline, induced technology development and inertia. Both induced technology development and technology development in the baseline contribute to 10% more reduction of carbon dioxide emissions in the case of a 300US$ tax introduced in 2000 and recorded in 2030. Inertia is very important as well, and on its own leads to a difference of between a 10% reduction of global emissions after five years and a 35% reduction after 30 years. It should be noted that these results reflect the full dynamics in the (simulated) world energy system, including depletion and trade.

8.5 Discussion and main conclusions

We have studied a set of different mitigation experiments, with a particular focus on the role of technologies in terms of mitigation responses to a carbon tax.

In interpreting the results of these experiments, we obviously need to take into account the model characteristics and assumptions. TIMER is an energy system model with a strong focus on relevant dynamic relationships among the various mitigation options but without macro-economic feedbacks. A second point of consideration refers to the baseline and the options that were used in our mitigation scenarios. The IMAGE B2 baseline, used as a baseline for our analysis, should be regarded as a medium- to low-emission scenario, so that most of the reductions studied here can be regarded as reductions with a medium level of ambition (e.g. a 40% reduction of carbon emissions required by 2100 to reach stabilization at 550 ppmv). On the other hand, the TIMER 1.0 version does not include all available mitigation options, which holds, in particular, for carbon sequestration, whether by means of capture and storage or sink enhancements.

Using an energy model in the context of an integrated assessment model allowed us to study some indirect changes of climate policies as well. First of all, the changes in the energy system in response to the carbon tax not only change carbon emissions but also other greenhouse gases and sulfur emissions. We have shown here that the environmental effectiveness – certainly in the short term – is limited as a result of a reduction in the aerosol cooling effect. Secondly, the integrated analysis used shows some of the trade-offs between reducing energy-related carbon dioxide emission by using biofuels and the impact of the analysis on land-use emissions. In our current results, biofuel use has a net mitigation effect, but some of the mitigation is offset by the additional demand for agricultural land, which increases land-use emissions.

The results lead to the following main conclusions.

- **Technological improvement is a crucial aspect of climate mitigation strategies**. This is shown in the case of the first two experiments, for instance, by cost reductions in solar/wind technology. This is most clearly observed in the results of the last set of experiments. Leaving out all forms of technology development reduces the response to a 300 US$/tC carbon tax in 2030 from a 60% reduction to only 30% (both compared to the baseline). Partly as a result of these technology developments, stabilization at 550 ppmv from the IMAGE B2 baseline appears feasible at relatively low costs through the introduction of a uniform carbon tax and a variety of measures induced by this tax. Interestingly, the costs and measures taken in going from B2 to 550 stabilization are more-or-less comparable to those found earlier in going to a 450 ppmv stabilization target from the B1 baseline (van Vuuren and de Vries, 2001). This shows how important baseline assumptions can be for the costs of reaching different stabilization levels; particularly the sustainable development orientation and the strong technology development assumed in the B1 baseline can allow for reaching lower stabilization levels at bearable costs when compared to other baseline scenarios.

- **In breaking down the results for the B2-550 stabilization scenario, an improved efficiency is shown to be the single most important factor in the first decades in terms of the mitigation response. However, from 2030 onwards, introduction of carbon-free supply options provides the bulk of the required reductions.** As a result, the changes in global energy intensity remain near the upper end of the historically observed range, whereas decarbonization rates reach levels above historical rates for the whole century. In terms of energy carriers, the sharpest reduction takes place for coal: 50% reduction in cumulative coal use. This implies that the greatest changes take place in regions with high shares of coal consumption or production. Alternatively, these regions might need to develop carbon storage capabilities (excluded in our experiments). In terms of fuel trade, carbon-tax induced changes in oil trade appear to be modest. Changes in trade of other energy carriers may be of the same order of magnitude and, depending on the region, work in the same direction as changes in oil trade – or completely offset them. The latter is, for instance, the case for the Former Soviet Union, where natural gas and biofuel exports offset the losses in oil exports.

- **Technology development needs to be studied in the context of other dynamic processes that are important to the world energy system.** In our simulated B2 world of the TIMER model, early-action scenarios result in accelerated technology development in the short and medium term. In the long term, however, there are a number of processes that may work in the opposite direction, such as the maximum share of renewable technologies that can be absorbed in the electric power system without additional costs, and the impacts on the depletion of both fossil fuels and renewables. These results depend on the assumptions made. In the current runs, scenarios with early carbon taxes lead to lower carbon dioxide concentrations in

2100. However, in 2100 they show similar emissions reduction as the scenarios with a slower introduction of the same carbon tax levels. It is important to study the role of these dynamic processes in more detail.

- ***Three technological processes that have a direct influence on the mitigation response to carbon taxes are the technology development in the baseline, induced technology development as a result of climate policy and inertia.*** **The relative importance of these different processes is directly related to the discussion on timing of mitigation action.** In our analyses, we have indicated how these processes all play a role. Learning that is part of the baseline will indeed make a 2030 response to a 2020 tax that is 5-10% higher than a 2010 response to a 2000 tax. However, the other two processes work in the opposite direction and are, at least, just as strong. Induced learning results in a 10% larger emission reduction in response to a 300 US$/tC tax in 2030; without learning, inertia will result in a 10% reduction of global emissions after five years and a 35% reduction after 30 years. Collectively,, the processes over this short time period of evaluation that support an early action response seem to dominate over the processes that favor a delayed response approach – at least, if no discount rate is applied. At what discount rate the balance shifts to a preference for a delayed response approach has not been analyzed here. In any case, the dynamics behind different technological processes have been found to be very important to understand the system response to carbon prices . Providing sufficient pressure to stimulate low technology development in the direction of carbon energy systems seems to be crucial. Sufficient resources for research and development, and climate policies, can help to facilitate the developments in this direction.

9. EXPLORING THE ANCILLARY BENEFITS OF THE KYOTO PROTOCOL FOR AIR POLLUTION IN EUROPE

Abstract. An integrated approach to climate change and regional air pollution can harvest considerable ancillary benefits in terms of environmental impacts and costs. This is because both problems are caused to a large extent by the same activity (fossil fuel consumption). Substantial ancillary benefits were found for regional air pollution (SO_2, NO_x, VOC and particulate matter) of implementing the Kyoto Protocol (greenhouse gas emissions) in Europe. The benefits apply both to mitigation costs and to emissions. For instance, while three different scenarios on Kyoto implementation showed reduction of European CO_2 emissions by 4-7%, they also showed reduction of European emissions of SO_2 by 5-14% compared with a no Kyoto policies case. The total cost savings for implementing current policies for regional air pollution stated in the Kyoto Protocol are in the order of 2.5-7 billion Euro. In all cases, this is in the order of half the costs of the climate policy (4-12 billion Euro). The magnitude of ancillary benefits depends on how flexible mechanisms and surplus emission allowances are used in meeting the Kyoto targets. Using flexible mechanisms reduces emissions of air pollutants for Europe as a whole even further than domestic implementation (e.g. 10-14% versus 5% for SO_2 emissions), but the reductions have shifted from Western Europe to Central and Eastern Europe and Russia. The use of surplus emission allowances (so-called “hot air”) to achieve the Kyoto targets decreases the ancillary benefits, in particular, for the latter group of countries.

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9.1 Introduction

Policies aimed at mitigation of environmental impacts in one area can have significant effects on other aspects of environmental quality. Control strategies that consider cost-effectiveness and environmental effectiveness of proposed solutions in an integrated fashion can therefore often prevent inefficient use of resources and implementation of sub-optimal solutions. The Protocol to the Convention on Long-range Transboundary Air Pollution (CLRTAP) to Abate Acidification, Eutrophication and Ground-level Ozone (the so-called Gothenburg Protocol), (UN/ECE, 1999), is an example of how several environmental problems can be examined in an integrated way. The emission ceilings adopted in this Protocol were designed to realize important efficiency gains by simultaneously controling acidification and eutrophication risks, along with ground-level ozone concentrations.

Important links have also been identified between regional air pollution and climate change, although these are currently still hardly considered in policy-making (e.g., (RIVM et al., 2001; Syri et al., 2001; Alcomo et al., 2002; Mayerhofer et al., 2002; Van Harmelen et al., 2002)). Links exist because greenhouse gases and regional air pollutants originate to a large extent from the same activity, i.e. fossil fuel consumption. Moreover, reduction options for each of the gases can affect the emissions of other pollutants, either beneficially or adversely. Finally, the pollutants interact within the environmental system. Some substances directly influence both climate change and regional air pollution, for instance, sulfur dioxide (SO_2) and nitrogen oxides (NO_x). There are also more indirect effects such as the impacts of climate change on weather patterns, which cause impacts on the atmospheric transport and deposition of pollutants and the buffering capacity of soils (Posch, 2002). Despite these linkages, both types of problems have, to date, usually been explored separately using different tools and models, concentrating on different technical solutions. While analysis of greenhouse gas mitigation focuses generally on changes in the energy system, analyzing mitigation of atmospheric pollutants concentrates mostly on end-of-pipe technologies.

Recently, several studies have been published on the linkages between climate change and regional air pollution in Europe. All those studies indicated that a considerable share of investments in climate policies can be recovered through lower costs of air pollution control (generally in the order of 20-30% or higher; see also discussion) (van Vuuren and Bakkes, 1999; RIVM et al., 2001; Brink, 2002; Van Harmelen et al., 2002). The reason is that the reduction of CO_2 emissions through structural changes in the energy sector also brings about a decrease in the emissions of air pollutants. Of these studies, only the RIVM et al.(2001) study looked specifically into the consequences of implementing the Kyoto Protocol – but for Western Europe only and without properly accounting for emission trading. In reality, there are several ways the protocol can be implemented, one crucial difference in these has to do with whether the target is achieved through domestic measures only or (partly) through the so-called Kyoto Mechanisms (i.e. Joint Implementation, Clean Development Mechanism and Emission Trading). Clearly, this also affects the potential ancillary benefits for air pollution (emissions, control costs and environmental impacts). To date, studies have not addressed this important issue.

The objective of this chapter is to explore the emission reductions of air pollutants and change in control costs and environmental impacts resulting from different ways in which the Kyoto Protocol is implemented in Europe, in particular, with regard to the use of Kyoto Mechanisms. The results presented are of a descriptive "what-if" character and do not pretend to be prescriptive for any future implementation of the Protocol and air pollution policies. The discussion will focus primarily on three country group-

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[i] The actual calculations for the climate policies are made using global models based on 17 world regions. The WE region includes EU15, Switzerland, Norway and Iceland. The CE region includes the new EU member states (except Cyprus and Malta), Bulgaria and Romania, and the Balkan countries. Finally, the EE region includes Belarus, Moldova, Russian Federation and Ukraine. For Russia, energy consumption and emissions are reported only for the European part (west of the Urals) as covered by the EMEP region.

ings/regions. These are: Western Europe (WE), Central Europe (CE) and Eastern Europe (Ukraine, Moldova, Belarus and Russia, west of the Ural and EE)[i]. Calculations for climate policy are done at the levels of these regions. The calculations on air pollution policies, in contrast, are done at the national level and aggregated to the regional level. The study is restricted to carbon dioxide (CO_2), leaving the remaining five greenhouse gases covered by the Kyoto Protocol un-addressed.

The analysis was performed using three linked models that collectively simulate different ways of achieving the Kyoto targets for climate change and targets for controlling regional air pollution. Section 9.2 describes the methodology, scenarios and the models used, while Section 9.3 discusses the baseline scenario. Section 9.4 presents the results of three mitigation scenarios. Finally, sections 9.5 and 9.6 discuss the results and draw conclusions. More details of this study can be found in Van Vuuren et al. (2003).

9.2 Methodology

Three climate policy scenarios have been developed to assess the potential impacts of the different ways to implement the Kyoto Protocol in Europe,. The scenarios are compared to a baseline scenario, which assumes no new climate policies. For this analysis, several models that have so far been used have been independently linked. The results of the study are intended to be explorative in ascertaining the ancillary benefits in larger European regions.

The changes in the energy system induced by climate policies will (in most cases) have a downward impact on emission of air pollutants (e.g. SO_2). This “ancillary benefit” (or co-benefit) can be captured in theory in three different ways.

- *Reduced air pollution control costs:* Emissions of air pollutants are held at the same level as the original baseline. In such a case, less air pollution control is needed and ancillary benefits are substantiated in terms of reduced costs of achieving these air pollutant emission levels.
- *Reduced emissions:* The technologies introduced to control air pollution levels are held at the level as the baseline scenario. In such a case, ancillary benefits exist in terms of emissions reductions.
- *Both:* The ancillary benefits are determined on the basis of existing policies. For European countries, the most relevant policies are the air pollution emission targets under the Gothenburg Protocol and the EU National Emission Ceilings Directive. In our baseline, we have assume these targets to be achieved, i.e. if required by additional investments into air pollution control. In this case, introduction of climate policies results in: a) cost savings as long as meeting the targets still required additional investments and b) additional environmental benefits if the targets have already been met through existing policies and the induced changes through climate policies alone. This situation differs from country to country.

The third case is explored in this study as it is the most policy-relevant for the European situation. Analytically, the disadvantage is that ancillary benefits are obtained along two different axes – mostly, in terms of reduced costs for air pollution control, but partly also in terms of reduced emission of air pollutants.

9.2.1 Scenarios explored

The Kyoto Protocol and the Marrakesh Accords provide for three mechanisms that parties may use in addition to domestic implementation to facilitate compliance with their commitments. These mechanisms are: *Joint Implementation* (JI), *Clean Development Mechanism* (CDM) and *Emission Trading* (ET)[ii]. Current emission projections suggest that implementation of the Kyoto Protocol within Europe will require significantly more abatement effort by the countries in Western European region than in the Central and Eastern European regions (EEA, 2002a). As a result, the Western European region may use the Kyoto Mechanisms to benefit from low-cost reduction options in other European regions. A special issue here is the possibility for trade in so-called "surplus emission allowances" [the term "surplus (emission) allowances" is used throughout this study; a more common but somewhat value-laden term is "hot-air")] (see also den Elzen and de Moor (2002)). The emissions for most countries with economies in transition have substantially declined since 1990 and, as a result, the expected baseline emissions (without additional climate policies) of several of these countries in the First Commitment Period (2008-2012) are significantly lower than the Kyoto targets. According to the provisions of the Kyoto Protocol, these surplus allowances can be traded to other parties. In fact, after the rejection of the Protocol by the USA in 2001, the total required reduction of participating countries under most conceivable baseline scenarios is smaller than the total available surplus allowances in Central Europe and Eastern Europe. In such a case, only trading these allowances would, theoretically, be enough to implement the Protocol. In reality, however, this would not be an attractive strategy for the countries selling emission credits, as this would drive the carbon price down to zero. According to the provisions of the Kyoto Protocol, the surplus allowances can be traded to other parties but can also be banked, i.e. held for use in the years subsequent to the First Commitment Period. Several studies have indicated that banking of surplus allowances could be an attractive strategy for selling countries in order to maximize their revenues (den Elzen and de Moor, 2002).

Obviously, the use of Kyoto Mechanisms will not only have important implications for the total costs of implementing the Kyoto Protocol, but also for the ancillary benefits. In principle, the use Kyoto Mechanisms will not only shift greenhouse gas reductions, but also the ancillary benefits to those regions were measures are implemented. The

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[ii] *Joint Implementation* (JI) allows Annex-1 countries to invest in projects to reduce GHG emissions in other Annex-1 countries. The achieved emission reduction units can be used to meet the reduction commitments of the investing Party. *The Clean Development Mechanism* (CDM) does the same, but now between Annex-1 countries and non-Annex-1 countries. Finally, Emission trading (ET) allows Annex-1 countries to trade emission allowances among themselves. The conditions for using these instruments (i.e. criteria that need to be met) have been developed within the Kyoto Protocol and are available in the related documents.

use of surplus allowances, however, will not result in any ancillary benefits. This means that there are important trade-offs from the design of climate policies for the overall efficiency and effectiveness of Europe's environmental policies. In order assess these trade-offs, three different (hypothetical) climate policy scenarios are analyzed in this chapter.

(1) **Domestic Action:** assumes that Kyoto targets are met solely through domestic implementation, allowing only for internal emission trading (i.e. within each region, such as Western Europe).
(2) **Restricted Trade:** This case assumes full use of the Kyoto Mechanisms, but without using surplus allowances.
(3) **Normal Trade:** Also this case assumes full use of Kyoto Mechanisms, but allows trading of surplus allowances. The use of surplus allowances is chosen at a level that maximizes the revenues from their trade for the Central and Eastern European regions. This "optimal" level of trading has been determined by model analysis (compare den Elzen and de Moor (2002).

In the first scenario, ancillary benefits are expected to occur mainly in the Western European region, the region that also experiences the highest costs of climate policies. In the second and third scenarios, some of the ancillary benefits will have shifted to the other European regions, while ancillary benefits in the Western European region are expected to be less. As the second scenario does not allow for the use of surplus allowances, this scenario could be indicative of the maximum amount of ancillary benefits under trading assumptions. The third scenario is a more cost-optimal scenario (and arguably more realistic). Comparing the results of this scenario against those of the second allows us to assess the consequences of including surplus allowances in climate policies in terms of abatement costs and ancillary benefits. It should be noted that the reduction of CO_2 emissions is not the same in all scenarios as a result of CDM and use of surplus allowances (see Section 9.4).

In all scenarios we included the provisions of the Marrakesh Accords on carbon sinks. Based on a separate analysis, we assumed that the Annex-I countries could use a total of sinks credits[iii] coming to 440 Mt CO_2, of which 270 Mt CO_2 is used by the regions included in our study (see den Elzen and de Moor (2002). Our analysis concentrates exclusively on the reduction of CO_2 emissions, CO_2 being the most important greenhouse gas. The Kyoto Protocol, however, refers to the total set of six greenhouse gases (also CH_4, N_2O, HFCs, PFCs and SF_6), and allows for substitution among them. Other studies, e.g. Lucas et al. (2002), indicate that control costs for non-CO_2 gases for moderate reductions could be lower than those for CO_2. Thus, under an optimal reduction strategy, reduction rates for CO_2 might be lower than the overall reduction targets. In

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[iii] Activities covered by Articles 3.3 and 3.4 of the Kyoto Protocol and agricultural management and sinks under the Clean Development Mechanism; for details see (den Elzen and Lucas, 2003a)

[iv] The consequence could be that there will be fewer changes in the energy system, and therefore less impact on sulfur and nitrogen oxide emissions. At the same time, the increased reductions in CH4 (as a greenhouse gas) will impact the levels of tropospheric ozone.

such a case the ancillary benefits could be somewhat different from those presented here[iv]. However, it is not expected that this will change the qualitative conclusions of our research.

9.2.2 Model framework used

This study integrates the different research areas by linking models that address climate change issues: the climate policy model FAIR (den Elzen and Lucas, 2003b), the energy model TIMER[v] (de Vries et al., 2001) and regional air pollution model RAINS (Amann et al., 1999) (Figure 9.1). Appendix 9.1 provides some description of each of the models and their linkages – while additional information on TIMER can be found in Chapter 2).

Within the total framework, the first step was to use the global energy system model TIMER (de Vries et al., 2001) to determine the changes in energy (and thus CO_2 emissions) under the baseline scenario (see Section 9.3). Next, on the basis of these emissions and a set of marginal abatement costs curves for CO_2 per region, the reduction and abatement costs sub-model of FAIR was used to determine the level of (domestic) action and use of Kyoto Mechanisms required in each region to meet the Kyoto targets under each scenario [see, for a description of this model, the marginal abatement curves and a detailed description of results under comparable scenarios (den Elzen and de Moor, 2002)]. The fundamental assumption here is that on the basis of the marginal abatement curves, regions will implement a least-cost approach, choosing to use Kyoto Mechanisms if costs outside their region are lower, unless constrained by specific rules on emission trading.

Next, the TIMER model implements the outcomes of FAIR in terms of regional emissions by introducing price signals (a tax on carbon dioxide). In response to the carbon tax, the model generates several changes: investments in energy efficiency, fossil fuel

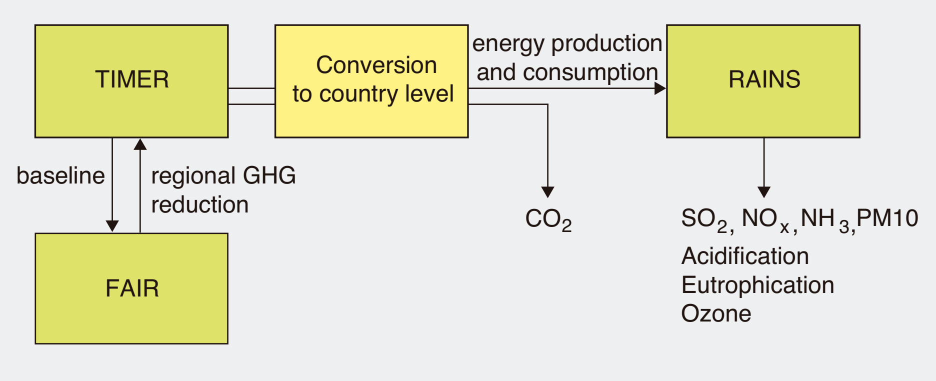

Figure 9.1 Overview of the models used in this study.

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[v] Both FAIR and TIMER constitute part of the IMAGE 2.2 framework (Integrated Model to Assess the Global Environment) – a modeling framework to study global change issues.

substitution, and extra investments in non-fossil options such as wind/solar energy, nuclear energy and biofuels. These lead to changes in the energy system (mitigation scenarios).

Finally, the RAINS model calculates emissions of air pollutants (SO_2, NO_x, VOC, PM10 and NH_3) for the scenarios based on the outputs of TIMER, and explores their environmental impacts and emission control costs. In these calculations RAINS optimizes air pollutant emissions for acidification, eutrophication and formation of ground-level ozone, while at same time emissions of particulate matter (PM) from anthropogenic sources are also estimated. In each scenario, the RAINS model meets the emission standards set under the Gothenburg Protocol and the EU National Emission Ceilings Directive, by means of a cost-minimal combination of measures. Here, regional differences are accounted for in emission control costs and atmospheric dispersion characteristics.

Some assumptions needed to be made to link inputs and outputs of these models. As TIMER and FAIR models make use of a similar regional breakdown, data could be easily transferred between these models. Some minor assumptions needed to be made to deal with the non-Annex I parts of the Former Soviet Union region of TIMER, as described in Appendix 9.1. The link between RAINS and TIMER requires a more elaborate procedure. While RAINS requires energy activity levels on a country basis, the TIMER model calculates energy use for three large regions in Europe. In terms of fuel types too, the RAINS model is more detailed than TIMER [RAINS recognizes various forms of solid (coal) and liquid fuels (oil-based)]. Finally, the data sources used to calibrate the model for the base year are different (TIMER is calibrated against IEA data,while RAINS uses in addition data from national sources). A downscaling method has been developed to translate the TIMER energy results into RAINS input, as described in Appendix 9.1. Use of this method leads to the results on a country level showing very good correspondence to country-based projections, indicating that the method for downscaling was functioning well (van Vuuren et al., 2003b).

9.2.3 Comparing control costs from TIMER and RAINS: compatibility of costs calculated by different models

Estimating costs of future policies is beset with uncertainties. This is already an important issue when comparing costs from different studies within one research domain, but this is even more so when comparing cost calculations from different areas. Some of the differences between several studies result from methodological differences; others simply reflect the uncertainties we are facing (see also IPCC (2001b)). A practical cause of differences is the use of different cost concepts (e.g. welfare loss and the change in energy system costs, compare Syri et al., 2001)). But in addition, there are a large number of other factors that can influence cost calculations such as assumptions about substitutability of fuels and technologies, assumptions on the use of Kyoto Mechanisms, technology development, and the coverage of the study etc. As a result, cost estimates for implementing the Kyoto Protocol in Western Europe range from several billions to even more than a hundred billion Euro (IPCC, 2001a).

The cost estimates of CO_2 policies presented in this chapter are based on the results of the TIMER model. Costs are calculated using the carbon tax that is required to meet the specific reduction target in each region. Costs are calculated by determining the integral of emission reductions and the carbon tax. The cost is not directly related to the costs of a single measure, because each option induces changes in the costs of other parts of the system. In contrast, RAINS calculates, for a given energy scenario, the costs of implementing technologies that limit the emissions of air pollutants. The assumptions used for cost calculations in RAINS and the appropriate databases are described in various documents (see Cofala et al. (2002)). In RAINS, effect of technology development has not been accounted for.

Theoretically, adding the control costs, as estimated by TIMER and RAINS, should yield total technical costs of an integrated CO_2 and air pollution control policy. However, as seen above, the two models use different databases and cost concepts. It was not possible to do a full comparison of the cost calculations in the context of this study. This means that the costs calculated by the two models should not be simply added up. However, in the discussion section of this chapter, we will show that the cost calculations of each model do comply well to other estimates with their respective research domains (climate policy for TIMER and air pollution control policies for RAINS). Moreover, we will show that the TIMER calculations also compare well with those of Blok et al. (2001) a study that estimates costs in a similar, bottom-up manner as the RAINS model. We therefore conclude that the results can be used for qualitative assessment and identification of the directions of changes in costs of policies and indicate the possible order of magnitude of ancillary benefits. In the discussion section, we will pay more attention to this issue.

9.3 The baseline scenario for carbon dioxide emissions and air pollution in Europe for 2010

The baseline scenario of this study assumes no new policies to control greenhouse gas emissions but includes the emission ceilings for regional air pollutants that have already been decided upon (i.e. national legislation (CLE)[vi] and the emission ceilings from the EU National Emission Ceilings Directive and from the Gothenburg Protocol to the CLRTAP). In terms of socio-economic trends (compare Table 9.1), the baseline is characterized by a continuation of trends that were dominant during the 1990s: increasing globalization, further liberalization and average assumptions for population growth, economic growth and technology development. The baseline is in principle consistent

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[vi] The impacts are assessed for the year 2010 and include policies as decided per December 2001.

Table 9.1 Major baseline assumptions

	Population (mill.)			GDP (1995 Euro/cap)			Primary energy use (EJ)		
	1995	2010	AAGR	1995	2010	AAGR	1995	2010	AAGR
WE	384	396	0.2%	16250	22771	2.3%	57.8	66.7	0.9%
CE	121	121	0.0%	2120	4195	4.7%	12.8	15.4	1.2%
EE	293	298	0.1%	1312	1851	2.3%	22.6	23.5	0.3%
World	5706	6891	1.3%	3704	4940	1.9%	371	492	1.9%

Source: RIVM, TIMER model calculations after disaggregation to country level; WE = Western Europe, CE = Central Europe, EE = Eastern Europe (AAGR=Annual Average Growth).

Table 9.2: Changes in the primary energy demand, baseline and policy scenarios

			Baseline 2010		Policy scenarios 2010		
	1990	1995			DA	RT	NT
	EJ	EJ	EJ	Change from 1990, %	Change compared to Baseline, %		
WE:							
Total, of which:	*56.4*	*57.8*	*66.7*	*18%*	*-7%*	*-2%*	*-1%*
Coal	11.7	9.2	6.6	-43%	-38%	-21%	-14%
Oil	22.9	23.2	26.3	15%	-9%	-3%	-2%
Gas	10.8	13.1	19.3	78%	-2%	3%	3%
Other	11.1	12.4	14.5	31%	2%	0%	0%
CE:							
Total, of which:	*15.4*	*12.8*	*15.4*	*0%*	*0%*	*-4%*	*-2%*
Coal	6.6	5.4	4.2	-36%	0%	-23%	-17%
Oil	4.0	3.1	4.0	1%	0%	-2%	0%
Gas	3.5	2.9	5.4	53%	0%	7%	6%
Other	1.3	1.4	1.9	40%	0%	1%	0%
EE:							
Total, of which:	*30.3*	*22.6*	*23.5*	*-23%*	*0%*	*-9%*	*-5%*
Coal	4.9	3.0	1.9	-61%	0%	-32%	-26%
Oil	7.9	4.2	4.2	-47%	0%	-9%	-6%
Gas	14.5	12.6	14.2	-2%	0%	-7%	-3%
Other	3.0	2.8	3.1	6%	0%	-3%	-2%

Note: DA = Domestic Action, RT = Restricted Trade (no hot air) and NT = Normal Trade (i.e. including hot air; but based on optimizing revenues of supplying countries). WE = Western Europe, CE = Central Europe, EE = Eastern Europe.

with several other scenarios currently used for European assessments (Capros, 1999; Criqui and Kouvaritakis, 2000a; IMAGE-team, 2001; EEA, 2002b).

Table 9.2 shows the resulting total primary energy demand by fuel type. In Western Europe, the scenario results in a slow, continuous increase of absolute and per capita energy use. Natural gas shows by far the fastest growth rates, but oil remains the most important energy carrier. The share of coal further declines. In Central Europe and Eastern Europe the energy use changed drastically between 1990 and 1995. In Central Europe, under the baseline scenario the historically dominant position of coal is challenged, both by natural gas (increased use for heating and electricity generation) and oil (fast growth of private transport). Total energy use recovers from the low 1995 levels but will in 2010 only be slightly higher than in 1990. In Eastern Europe, natural gas continues to be the most important energy carrier. Coal use further declines, while natural gas and oil grow modestly after 2000 (but still show a decline over the whole period). Total 2010 energy use in this region remains almost a third below the 1990 level.

9.3.1 Carbon dioxide and air pollutant emissions

Between 1990 and 1995 the CO_2 emissions in Europe as a whole decreased by 10% (from 6.3 Gtons to 5.4 Gtons CO_2) with widely diverging trends in the different regions (Western Europe, a 1% decrease, Central Europe, about a 20% decrease and Eastern Europe, more than a 30% decrease). In contrast to these declining trends, emissions are expected to increase in the baseline in all regions between 1995 and 2010, driven by the growth in energy consumption discussed in the previous section. Under the baseline scenario, the 2010 emissions in Western Europe will be 8% above the 1990 level. The emissions in the Central and Eastern Europe regions, although higher than in 1995, will remain below the 1990 values (by 10 and 32%– compare Table 9.3). Emissions of CO_2 and air pollutants by country for the Baseline are to be found in the report (van Vuuren et al., 2003).

The baseline scenario at the same time indicates significant reductions in the emissions of regional air pollutants throughout Europe (Table 9.3), which is a continuation of the trend that has been seen in the recent past. Between 1990 and 1995, the emissions of all pollutants in all three regions considerably decreased. For the whole of Europe, this decrease was approximately 20% for NO_x and NH_3, 18% for VOC, 38% for SO_2 and even 46% for PM_{10}. The main driver of this decrease in Western Europe was the implementation of add-on control technologies and low sulfur fuels, and to a lesser extent, structural changes in the energy system (a further decline of coal use)[vii]. In the case of the Central and Eastern European regions, a large proportion of emission reduction was achieved through a decrease in energy demand and agricultural production due to economic restructuring. In addition, in some candidate countries (Czech Republic, Hungary, Poland and Slovenia) add-on controls on SO_2 and PM sources played an important role in emission reduction.

Under the baseline, total European emissions of SO_2 are expected to decrease up to 2010 by 74% compared with 1990 (given the implementation of the Gothenburg Protocol). The corresponding reductions of NO_x and VOC are 45% and 44%, respectively. Finally, PM_{10} emissions are reduced by 64%. It should be noted that, for Western Eu-

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[vii] The exception is the eastern part of Germany where closing down obsolete plants and economic reform played a major role in emissions reduction.

Table 9.3 Air emissions 1990 - 2010: baseline and climate policy scenarios (CO2 in 10-6 tons, other pollutants in kilotons)

					Policy scenarios 2010		
	1990	1995	Baseline 2010		DA	RT	NT
				Change from 1990, %	Change compared to baseline (%)		
WE:							
CO_2	3311	3267	3565	8%	-12%	-4%	-3%
SO_2	16402	10254	3153	-81%	-15%	-7%	-4%
NO_x	13769	11796	6617	-52%	-7%	-3%	-1%
VOC	14695	12332	6697	-54%	-1%	0%	0%
PM_{10}	2730	1770	1197	-56%	-5%	-3%	-2%
NH_3	3726	3433	3177	-15%	0%	0%	0%
CE:							
CO_2	1123	914	1008	-10%	0%	-8%	-5%
SO_2	11795	8404	3785	-68%	0%	-16%	-11%
NO_x	3919	3199	2256	-42%	0%	-7%	-4%
VOC	2916	2494	2289	-22%	0%	-2%	-1%
PM_{10}	2360	1177	768	-67%	0%	-9%	-7%
NH_3	1608	1137	1367	-15%	0%	0%	0%
EE:							
CO_2	1869	1259	1284	-32%	0%	-11%	-5%
SO_2	9758	4751	2833	-71%	0%	-19%	-15%
NO_x	5846	3886	4001	-32%	0%	-12%	-8%
VOC	5124	3840	3778	-26%	0%	-6%	-4%
PM_{10}	3945	1954	1276	-68%	0%	-7%	-6%
NH_3	2277	1530	1686	-36%	0%	0%	0%
Total Europe:							
CO_2	6303	5440	5852	-7%	-7%	-6%	-4%
SO_2	37955	23409	9771	-74%	-5%	-14%	-10%
NO_x	23534	18881	12874	-45%	-4%	-6%	-4%
VOC	22735	18666	12764	-44%	-1%	-2%	-2%
PM_{10}	9035	4901	3241	-64%	-2%	-6%	-4%
NH_3	7611	6100	6260	-18%	0%	0%	0%

Source: CO_2 emissions: FAIR/TIMER; other pollutants: RAINS

Note: DA = Domestic Action, RT = Restricted Trade (no hot air) and NT = Normal Trade (i.e. including hot air; but based on optimizing revenues of supplying countries). WE = Western Europe, CE = Central Europe, EE = Eastern Europe.

rope and candidate countries belonging to the Central European region, most of the emission reductions is achieved as a result of implementing the revised EU legislation (standards on mobile sources, revised Large Combustion Plant Directive, Solvent Directive etc.). In Eastern Europe the reductions occur mainly through economic restructuring and a switch to cleaner fuels. Abatement measures play a less important role in these countries.

9.3.2 Emission control costs

The cost of controlling all air pollutants in the baseline scenario for the whole of Europe are expected to increase to about € 89 billion per year in 2010 (Table 9.4). About 57% of the total costs are the costs of controlling emissions from mobile sources (road and off-road transport). PM controls from stationary sources contribute about 11% of the costs to the total and SO_2, 21% of the costs. The Western European region bears 81% of total European costs, the reasons being the large contribution of the region to total European emissions in the base year and the more stringent emission control (and hence more costly) than in other parts of Europe. Implementing the EU legislation by the candidate countries is expected to lead to an increase in the control costs in Central Europe. Compared with the legislation from the mid-nineties, the costs for candidate countries will more than double. More than a half of (rather low) air-pollution control costs in Eastern Europe are the costs of dust control equipment (cyclones, electrostatic precipitators) used on larger stationary sources. Other costs for Eastern Europe result from the necessity to comply with the emission and fuel standards, as specified in the 2nd Sulphur Protocol to CLRTAP.

Regional environmental impacts

Implementation of emission controls as assumed in the baseline is expected to significantly increase the area of ecosystems protected against acidification and eutrophication[viii]. For acidification, the calculations indicate that the share of unprotected ecosystems (i.e. ecosystems exposed above critical loads) could decrease from 16.1% in 1990 (93.4 million ha) to 1.5% in 2010 (8.7 million ha) - see Table 9.5. However, in spite of

Table 9.4 Calculated annual air pollution control costs for the baseline scenario in 2010 (1995 prices)

Region	Cost, billion Euro/year	Distribution of control costs SO2	NOx+VOC(*)	NH3	PM10(*)	Mobile sources
WE	72	22%	11%	1%	8%	59%
CE	14	14%	2%	7%	15%	61%
EE	3	35%	2%	1%	63%	0%
TOTAL	**89**	**21%**	**9%**	**2%**	**11%**	**57%**

(*) Only stationary sources
Source: IIASA (RAINS)
Note: WE = Western Europe, CE = Central Europe, EE = Eastern Europe

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[viii] Ecosystems are assumed to be protected against acidification if the total acidifying deposition is below the critical load. A similar definition holds for eutrophication (Amann et al., 1999).

Table 9.5 Environmental impact, baseline and climate policy scenarios

Region	1990	Baseline 2010	Policy scenarios 2010 DA	RT	NT
Acidification (million ha unprotected)					
WE	42.9	6.5	5.9	6.0	6.2
CE	18.2	0.6	0.6	0.4	0.5
EE	32.3	1.6	1.6	0.9	1.2
Europe	93.4	8.7	8.1	7.3	7.9
Eutrophication (million ha unprotected)					
WE	71.4	48.2	46.7	47.2	47.4
CE	38.4	27.7	27.3	27.0	27.2
EE	56.2	26.8	26.5	24.4	25.2
Europe	166.0	102.7	100.5	98.6	99.8
Health-related ozone (AOT60, ppm.hours)					
WE	3.42	0.95	0.92	0.93	0.94
CE	1.64	0.34	0.32	0.29	0.30
EE	0.43	0.06	0.05	0.03	0.04
Europe	2.30	0.60	0.57	0.57	0.58
Vegetation-related ozone (AOT40, excess ppm.hours)					
WE	6.30	3.26	3.15	3.20	3.23
CE	6.00	2.85	2.77	2.67	2.74
EE	1.50	0.74	0.73	0.61	0.65
Europe	4.10	2.04	1.98	1.93	1.97

Source: IIASA (RAINS model)
Note: DA = Domestic Action, RT = Restricted Trade (no hot air) and NT = Normal Trade (i.e. including hot air; but based on optimising revenues of supplying countries). WE = Western Europe, CE = Central Europe, EE = Eastern Europe.

such an impressive improvement at a regional level there will be still countries where a high proportion of their ecosystems will achieve atmospheric depositions above their critical loads (compare van Vuuren et al., 2003). These countries comprise the Netherlands (49% of ecosystems unprotected), Belgium (15%), Hungary (13%); Germany, Norway and the UK (9 - 10% ecosystems not protected). The areas with excess deposition of nutrient nitrogen, which is responsible for eutrophication of ecosystems, is expected to decrease for Europe as a whole from 30.5% in 1990 (166 million ha) to 18.8% in 2010 (103 million ha). Nevertheless, relatively large areas remain without protection from eutrophication, in particular, those in the Central European region (more than 57% of ecosystems' area). Developments according to the baseline scenario will also substantially reduce population exposure to elevated ozone levels (Table 9.5). The average exposure of a person in Europe (as measured by the so-called AOT60 value) under these conditions is projected to decrease from 2.3 ppm.hours in 1990 to 0.6 ppm.hours

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[ix] The AOT60 value indicates a cumulative exceedance of ozone of the critical (damage) thresholds for human health (60 ppb). Similarly, the AOT40 value indicates a cumulative exceedance of the critical (damage) thresholds for terrestrial vegetation (40 ppb). More details about the indicators used can be found in Cofala et al. (2002).

in 2010[ix]. However, this also means that in 2010 the guidelines of the World Health Organization will still be exceeded. Just as for health effects, the situation will also improve for vegetation, although at a somewhat slower pace. The exposure index for the whole of Europe (as measured by the so-called AOT40 value) is projected to decrease from 4.1 excess ppm.hours in 1990 to 2.0 excess ppm.hours in 2010.

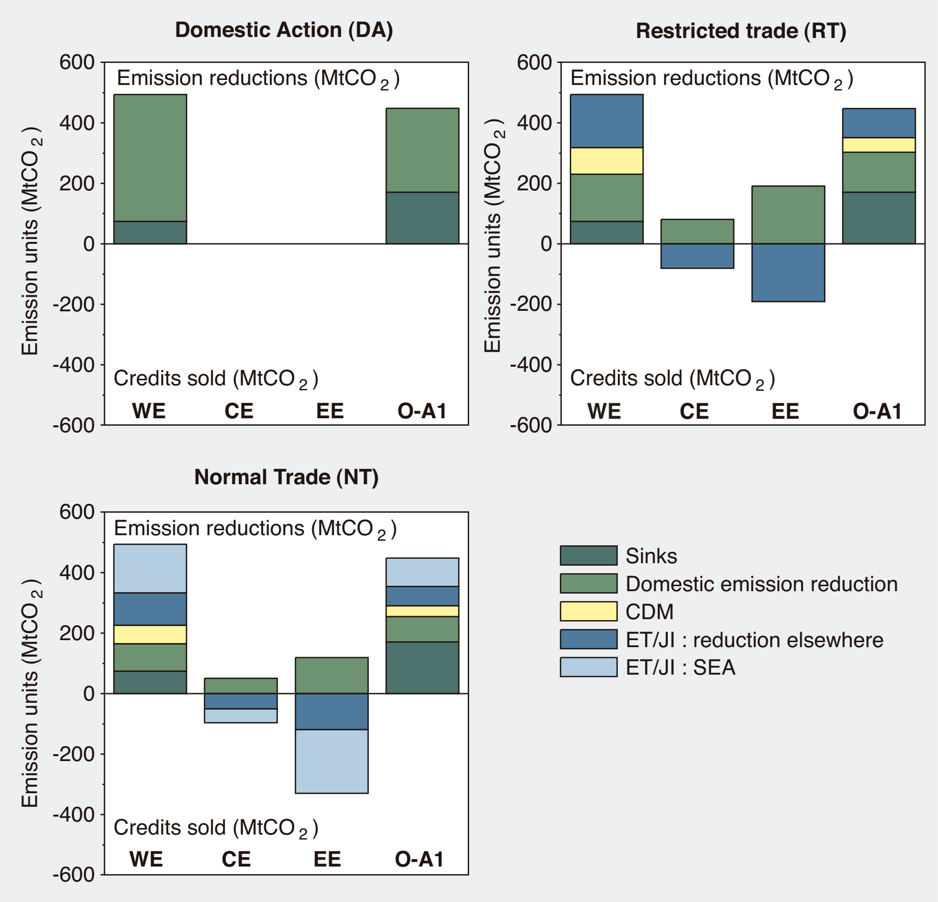

Figure 9.2 Implementation of the Kyoto targets in the three European regions and other Annex-1 countries according to: a) the Domestic Action scenario (DA); b) restricted trade (without the use of surplus emissions allowances, RT), and c) trade with optimal banking of sulfur emission allowances, NT).

Note:

- ET/JI: Emission trading and Joint Implementation. The study does not distinguish between these two instruments. The SEA category only refers to emission trading, as JI cannot lead to implementation of SEA. The category ET/JI (excl. SEA) refers to the use of Kyoto Mechanisms leading to actual physical emission reductions.

- Domestic mitigation refers to reduction of energy-related CO_2 emissions.

9.4 Kyoto scenarios and ancillary benefits for regional air pollution

Different ways of implementing the Kyoto Protocol result in different CO_2 reductions. Figure 9.2 and Table 9.6 illustrate these differences for three European regions (for the complete picture also the reductions of the other Annex-I countries are shown (OA-I = Canada, Japan, Australia and New Zealand[x]). In the *Domestic Action* scenario, of the European regions only Western Europe needs to reduce its CO_2 emissions. As a percentage of the 1990 emissions, the required reduction from baseline is 15 percent point (from 8% above the 1990 level to 7% below). About13 percent age points are achieved by domestic mitigation in the energy system. The balance (2 percentage points) is assumed to be achieved by carbon sinks, as indicated in Section 9.2 (den Elzen and Lucas, 2003b). Energy system CO_2 reduction measures are enhanced energy efficiency and changes in the electricity production structure. a switch from coal to less carbon-intensive generation options occurs in the latter case. Some fuel substitution also takes place in the end-use sectors. The total response in the transport sector is small.

In the *Restricted Trade* scenario (trade without the use of surplus allowances), the Western European and other Annex-I (OA-I) countries use the Kyoto Mechanisms to implement their targets. Domestic CO_2 reduction in Western Europe is reduced by 60% compared to the *Domestic Action* scenario, and replaced by the use of CDM and emission trading (ET). This leads to reductions in Central and Eastern Europe (by 7% and 8% of their 1990 emissions, respectively). Total reductions in Europe in this scenario are approximately the same as in the *Domestic Action* case. This is the net effect of a decrease in reductions as a result of CDM use by Western Europe, and an increase in reductions in Central and Eastern Europe due to emission trading with the group of other Annex-I (OA-I) countries.

The optimal level of surplus allowances had to be determined first for the *Normal Trade* scenario. This was done using a similar analysis as in den Elzen and de Moor (2002) applying the FAIR model. Countries having surplus allowances (mainly Russian Federation and Ukraine) have been estimated to maximise their revenues by supplying only 25% of the available surplus allowances in the First Commitment Period and to “bank” the rest. Compared with the *Restricted Trade* case, the use of surplus allowances increases emission trading and decreases the need for emission reductions from the energy system. In the *Normal Trade* scenario the contribution of the energy system measured is 3 percentage points (of 1990 emissions) in Western Europe, 5 percentage points in Central Europe and 5 percentage points in Eastern Europe. About 4/5 of the necessary reductions in Western Europe is achieved by the Kyoto Mechanisms.

The overall European emissions in this scenario (88% of 1990 level) are higher than in the *Domestic Action* case (85%), which is due to the use of surplus allowances. On

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[x] Only after these calculations were performed, did Australia decide not to ratify the Kyoto Protocol. As the group of Other Annex-I countries is dominated by Japan, this does not have consequences for the results presented in this paper.

Table 9.6 CO_2 emissions and mitigation action as a percentage of 1990 emissions

	WE			CE			EE			Total Europe		
	DA	RT	NT	DA	RT	NT	DA	RT	NT	DA	RT	NT
Baseline	108	108	108	90	90	90	68	68	68	93	93	93
Assigned amounts (Kyoto)	93	93	93	106	106	106	100	100	100	98	98	98
Reduction measures												
- Sinks	-2	-2	-2							-1	-1	-1
- Domestic mitigation (energy system)	-13	-5	-3	0	-7	-5	0	-7	-5	-7	-6	-4
- SEA (ET)	0	0	-5							0	0	-2
- ET/JI (excl. SEA)	0	-5	-3							0	-3	-2
- CDM	0	-3	-2							0	-2	-1
Actual emissions	93	101	103	90	83	85	68	61	63	85	86	88
Sales of A.A.U.												
- SEA (ET)	-	-	-	0	0	-4	0	0	-8	0	0	-1
- ET/JI (excl. SEA)	-	-	-	0	-7	-5	0	-7	-5	0	-1	-1
Available for banking	0	0	0	17	17	13	32	32	24	13	13	10

Abbreviations:
DA = Domestic Action, RT = Restricted Trade (no hot air) and NT = Normal Trade (i.e. including hot air; but based on optimising revenues of supplying countries). WE = Western Europe, CE = Central Europe, EE = Eastern Europe. ET/JI: Emission trading and Joint Implementation. The study does not distinguish between these two instruments. The row on the use of Surplus Emission Allowances (SEA) only refers to emission trading, as JI cannot lead to implementation of SEA. The row ET/JI (excl. SEA) refers to the use of Kyoto Mechanisms, which leads to actual physical emission reductions. CDM: Clean Development Mechanism. A.A.U: assigned amount units.

Note: The Kyoto targets are formulated as percentage reductions from base year. For some sources, the base year is not necessarily 1990. As a result, the assigned amount, expressed as a percentage of 1990 emissions, can differ from those expressed as a percentage of the base year emissions. This is particularly the case in the CE region (6% increase versus a 7% reduction). In the WE region, the difference between 1990 and base year emissions, and the higher assigned amounts (as percentage) of Switzerland, Norway and Iceland, result in an assigned amount of 93% of 1990 emissions (instead of 92% for the European Union compared to base year). The columns for the total European regions indicate under “sales” the trade in A.A.U.’s with Annex-1 regions outside the European region. Rounding-off may cause small deviations in sums.

the scale of Europe as a whole, the emission reductions under the *Domestic Action* case amount to 420 Mton CO_2. In the *Restricted Trade* case, emissions are reduced to 377 Mton CO_2 (or 43 Mton less) as a result of the net balance of CDM use by Western Europe (lower reductions) and emission trading by other Annex-I countries (higher reductions). In the *Normal Trade* case, the net reduction on an European scale amounts to 229 Mton CO_2 (191 Mton less) as a result of both emission trading and the use of surplus emission allowances.

Table 9.2 shows the resulting changes in the demand for primary energy. In the *Domestic Action* case, the necessity of reducing carbon emissions in Western Europe causes a 38% decrease in the use of coal. The consumption of oil and gas decreases by 9% and 2%, respectively. This results in a 7% decrease in the total demand for primary energy.

Since less CO_2 needs to be reduced through domestic action in the trading scenarios, the changes in the energy system of Western Europe do not need to go so far. In the *Restricted Trade* case, Western European energy demand decreases by 2% and coal use decreases 21% from the baseline. Consumption of oil decreases by 3% but - at the same time - the use of gas increases by the same percentage. Measures that need to be implemented in Central Europe and Eastern Europe cause a decline in the primary energy demand by 4% and 9%, respectively. This is largely due to a lower use of coal. In the scenario with full use of Kyoto Mechanisms, including surplus allowances (*Normal Trade*), the amount of CO_2 reductions from the energy system is smaller, and therefore the level and structures of fuel use in all regions are closer to the baseline. Nevertheless, also for that scenario the demand for coal substantially decreases.

9.4.1 Emissions of air pollutants

The right side of Table 9.3 and Figure 9.3 demonstrate how our scenarios of implementing the Kyoto Protocol reduce the emissions of air pollutants in Europe. The actual extent of these ancillary benefits highly depends on the climate policies assumed. In the *Domestic Action* scenario, CO_2 emission reductions are only implemented in the Western European region. Thus also the decline in air pollutant emissions is restricted to that region. The emissions of SO_2 decrease sharply as a result of climate policies: calculations show - to a value of 15% below the baseline levels - a similar reduction as that for CO_2, the primary target of the climate policies. In absolute terms, this amounts to more than 450 kilotons, which is comparable with the Gothenburg Protocol emission ceiling for Italy. The corresponding reductions of NO_x and PM_{10} are 7% and 5%, respectively.

Compared with the unilateral case (*Domestic Action*), the total European emission reductions (and thus ancillary benefits) are higher in the trading scenarios (*Restricted Trade*, *Normal Trade*) (see Figure 9.3). However, since the CO_2 reductions in those scenarios are to a large extent achieved in Central Europe and Eastern Europe, the benefits are shifted to these regions. The strongest impacts occur for SO_2 emissions as a result of switching from coal to gas in power generation and end-use sectors. Reductions in NO_x emissions are smaller because they occur mainly in sectors where energy efficiency options are implemented. Trading also decreases the emissions of particulate matter (PM_{10}, 6% reduction in the *Restricted Trade* scenario compared with 2% for the *Domestic Action* case) [xi], while the ancillary benefits for VOC emissions are relatively low (about 2% reduction from the baseline).

The introduction of surplus emission allowances on the market (*Normal Trade* scenario) results in less reduction of air pollutants. Because part of the reduction now does not require any physical action, fewer changes in the European energy system are nec-

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[xi] The TIMER model does not separately specify different categories of biomass for energy (e.g. waste, modern biomass, wood). Therefore, the assumptions on the use of wood for heat generation have been taken from the RAINS database and are identical in all scenarios. Since the use of wood is an important source of PM emissions from the residential sector, the estimates of the changes in PM emission levels would be different if the increased direct burning of wood were included in the CO_2 control scenarios.

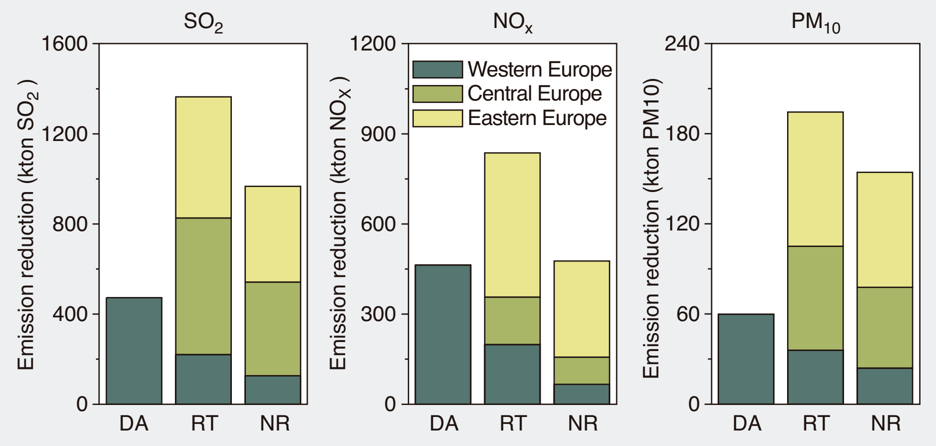

Figure 9.3 Emission reduction of regional air pollutants as a result of implementation of the Kyoto Protocol: a) the Domestic Action scenario (DAO), b) restricted trade (without the use of surplus emission allowances, TNS), and c) trade with optimal banking of sulfur emission allowances, TWS).

essary. For instance, the additional reduction of European SO_2 emissions is only 10% instead of 14% in the *Restricted Trade* scenario.

Emission control costs

Table 9.7 shows the net implementation costs of CO_2 reduction measures in Western Europe. In the *Domestic Action* scenario, the costs are about 12 billion Euro per year in 2010. This is the net result of additional investments in energy efficiency and the use of low-carbon or zero-carbon supply options and cost reductions for other conventional power supply, reduced oil imports and reduced production of fossil fuels. If only the increased investments into energy efficiency and zero-carbon supply options were accounted for, the cost increase would be 30 billion Euro per year.

Table 9.7 Total annual costs in 2010 for reducing CO_2 emissions in Western Europe in line with the Kyoto targets and change in air pollutant emission control costs (billion 1995 Euro/year)

Region	DA	RT	NT
Climate Policies (only WE)			
Domestic measures	12	2	1
Permits	0	5	3
Total	12	7	4
Change in air pollution control costs			
WE	-6.6	-2.9	-1.7
CE	0	-0.9	-0.6
EE	0	-0.2	-0.2
Total	-6.6	-4.1	-2.5

Note: DA = Domestic Action, RT = Restricted Trade (no hot air) and NT = Normal Trade (i.e. including hot air but based on optimising revenues of supplying countries). WE = Western Europe, CE = Central Europe, EE = Eastern Europe.

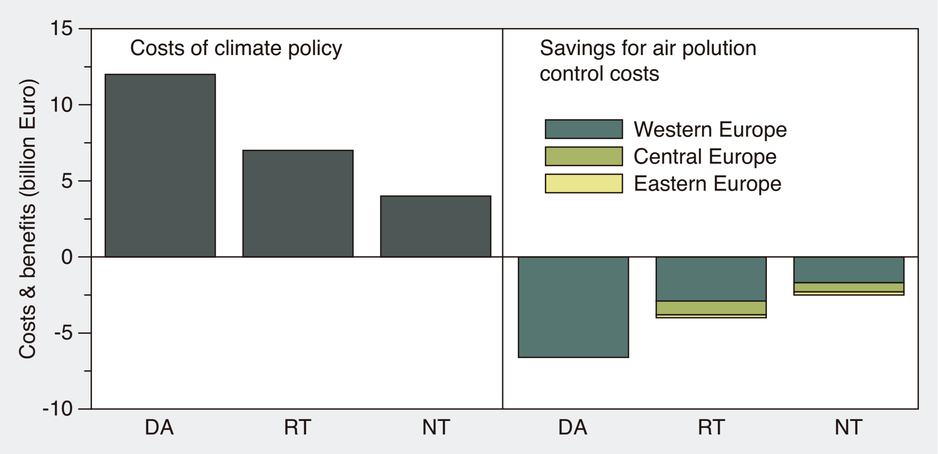

Figure 9.4 Costs of the different climate policy scenarios and their consequent savings for regional air pollution policies: a) the Domestic Action scenario (DA), b) restricted trade (without the use of surplus emissions allowances, RT), and c) trade with optimal banking of sulfur emission allowances, NT).

The trade scenarios show that the total costs of reducing CO_2 emissions can be more than halved through the use of flexible mechanisms (see also Figure 9.4). In the *Restricted Trade* scenario the costs of domestic energy system measures in Western Europe are projected to decrease to 2 billion Euro. However, at the same time about 5 billion Euro would be needed to be spent on permits, so that the total cost of meeting the Kyoto target for this scenario is 7 billion Euro. In the scenario with “Surplus Emission Allowances” (*Normal Trade*), the expenditures on domestic measures are expected to decrease further to 1 billion Euro; the same goes for the cost of permits to slightly above 3 billion Euro.

The ancillary benefits of CO_2 control policies also occur in terms of reduced costs of regional air pollution (compare the lower part of Table 9.7 and Figure 9.4). In the *Domestic Action* scenario, the expenditures on air pollution mitigation in Western Europe are projected to decrease by 6.6 billion Euro (or about 9%) from the baseline level. The air pollution control costs are also lower in the trading scenarios. However, the cost savings are not as high as in the domestic action case. For instance, in the *Restricted Trade* scenario, the savings for Western Europe are projected to decrease to 2.9 billion Euro per year. Characteristically, there are important cost reductions in the trading scenarios in the Central and Eastern European regions. The reduction for the whole of Europe,in annual expenditures on air pollution control is about 4.1 billion Euro per year in the *Restricted Trade* scenario. Inclusion of surplus emission allowances reduces the European ancillary benefits to only 2.5 billion Euros per year.

As mentioned earlier, the cost estimates for climate change and regional air pollution are not fully comparable and thus should be treated as an indication of possible synergies rather than the quantitative assessment. The results, however, clearly demonstrate that the gains in reducing air pollution control costs from climate policies can be very substantial. Although the use of flexible mechanisms reduces these ancillary benefits, the lowest total costs might still occur for the scenarios with emissions trading.

9.4.3 Regional environmental impacts

The absolute values of the changes in regional environmental impacts as a result of climate policies are not high, as substantial improvements are already achieved in the baseline (Table 9.5). For acidification, an additional 0.6 - 1.4 million ha of ecosystem area is protected in our scenarios. In case of eutrophication, 2.2 - 4.1 million ha of ecosystems are additionally protected. Nevertheless, about 100 million ha of yet European ecosystems remain threatened by eutrophication. Since our climate policies do not change ammonia emissions, achieving higher protection levels is not possible.

An interesting aspect is the transboundary effects of regional air pollution – which means that the trading scenarios that reduce regional air pollutants in other parts of Europe, may indirectly also reduce environmental impacts in Western Europe. This can be seen by comparing the *Domestic Action* and *Restricted Trade* scenarios. In the latter, only a third of the action is taken in WE compared to what was formerly taken; yet the improvement in acidification impacts is almost similar. The stronger sulfur reductions in Central Europe per Mton CO_2 reduction (coming mostly from less stringent abatement levels) helps to achieve this result. By the same token, the *Domestic Action* scenario also improves the environmental impact indicators in Central Europe, even if no action is taken in this region. For Europe as a whole, the largest ancillary benefits are found for the trading scenarios.

The CO_2 mitigation scenarios reduce impact indicators for ground-level ozone too. For Western Europe, the highest reductions occur in the *Domestic Action* case – more than 3% reduction of the health-related (AOT60) and vegetation-related (AOT40) exposure indices compared with the baseline. For Europe as a whole, the highest effects are brought about by the *Restricted Trade* scenario (5% improvement of both indices). Just as for the Baseline, country-specific indicators can be found in the study by Van Vuuren et al. (2003).

9.5 Discussion

Our study has explored the potential ancillary benefits of different ways to implement the Kyoto Protocol in Europe by linking models that had previously been used separately to study the climate change and regional air pollution policies. A few remarks should be made on the interpretation of our results. First, no attempt has been made at this stage to optimize climate change and regional air pollution policies in one integrated framework. Before this can be done it is necessary to fully harmonize the costs concepts used by the different models. Moreover, optimization will not be straightforward, given the different trade-offs within the system. Second, given the preliminary stage of this type of research, climate policies in the analysis concentrated solely on carbon dioxide. In a multi-gas strategy, reduction rates for CO_2 are likely to be smaller than the average reduction. In this case, both the costs of climate policies and the gains for ancillary benefits could be somewhat lower.

Overall, the study clearly shows that implementation of the Kyoto Protocol will have important ancillary benefits in reducing regional air pollution. This was found earlier in studies focusing on Western Europe only. The results of our Domestic Action (*Domestic Action*) scenario can be compared with those studies. The European Environmental Priority study (RIVM et al., 2001) and a related paper (Syri et al., 2001) found that reducing the CO_2 emissions in Western Europe by 15%, compared to the baseline (-8% from 1990 level), would reduce SO_2 emissions by 24% and NO_x emissions by 8%. In our study the emission reductions were somewhat lower (15% for SO_2 and 7% for NO_x resulting from a 12% reduction of CO_2 emissions), which is due to the inclusion of carbon sinks in the reduction target and different assumptions adopted in the baseline (higher fuel efficiency of cars according to the ACEA agreement, stricter emission control legislation resulting from the Gothenburg Protocol and the National Emission Ceilings and Large Combustion Plants Directives). Another study for the Western European region used the E3ME model (Barker, 2000) to estimate the possible ancillary benefits of a 10% reduction of the baseline CO_2 emissions (domestic implementation of the Kyoto Protocol). The results (12-14% reduction for SO_2, 7-8% for NOx and 4% for PM_{10}) compare well with our results. The differences can be explained by different CO_2 baseline projections and the assumptions on policies for regional air pollutants.

In contrast to the earlier studies, this study also encompassed the Central and Eastern European regions – and the specific impacts of emission trading. An important finding is that the link between the reduction in CO_2 emissions and regional air pollution is stronger in these regions than in Western Europe. This is caused by heavy reliance on coal in Eastern Europe and by less stringent emission control legislation.

According to our calculations, implementation costs of the Kyoto target vary between 12 billion Euro per year for the domestic action case and 4-7 billion Euro for the trading scenarios. Overall, the costs presented here seem to be within the broad range of cost estimates used in other studies. For instance, a recent detailed European study (Blok et al., 2001) looking into the costs of domestic implementation of the Kyoto Protocol found costs to vary between 4 and 8 billion Euro, depending on the assumptions about EU-wide trading. Since the study also covered non-CO_2 greenhouse gases (leading to an overall decrease in implementation costs) the costs estimated by Blok et al. (2001) are consistent with those calculated here. The European Environmental Priorities study (RIVM et al., 2001) using the PRIMES model found costs very similar to our estimates for a similar cost concept (13.5 billion Euro for domestic implementation of the Kyoto Protocol). However, the total energy system cost calculated by PRIMES is much higher. This could be due to the sector-specific market interest rates used in PRIMES, which for some categories of energy consumers are quite high. The Priorities study also included an estimate of the net implementation costs, taking into account emissions trading, which is again close to those found here, i.e. 6.3 billion Euro versus 4-7 billion Euro for the two trade scenarios explored in this study.

The results indicate that implementation of the Kyoto Protocol will lead to lower costs for regional air pollution control. For the domestic implementation of Kyoto targets in Western Europe, the changes in the energy system result in a decrease of air pollution control expenditures by 9% or 6.6 billion Euro per year. This result suggests that for the domestic action scenario, about half the total costs for implementing the Kyoto target may be regained in terms of reduced costs for air pollution control. A set of other studies that looked into the potential reduction of regional air pollution control vis-à-vis climate control costs also found significant cost reductions, although generally somewhat lower (around 20-30%). These studies cover the EU (Syri et al., 2001), Netherlands (Smeets and Wijngaart, 2002) and the USA (Burtraw and Toman, 2000)

9.6 Conclusions

Our work resulted in several findings on ancillary benefits for air pollution in Europe by implementing the Kyoto Protocol. The most important conclusions are presented below in conjunction with brief explanations indicating the magnitude of potential benefits.

Implementation of the Kyoto Protocol yields substantial ancillary benefits for air pollution in Europe. The design of climate policies is important for obtaining ancillary benefits. Implementing the Kyoto Protocol in Europe reduces the emissions of air pollutants and results in lower exceedances of critical thresholds for ecosystems and human health throughout Europe. In fact, the additional emissions reductions (from baseline) for SO_2 are mostly larger than those for CO_2 (4 – 15 %). For NO_x and PM_{10}, somewhat smaller emission reductions are obtained (2 - 6 %), while the additional reductions are smallest for VOC (1-2 %).

Implementing the Kyoto Protocol also reduces the control costs for air pollutants. In spite of uncertainties in cost estimates and differences in cost calculation methodologies, the results suggest that about 50% of the costs of the Kyoto target can be re-gained in terms of reduced costs for air pollution control (i.e. air pollution control cost reductions of 2.5 to 6.6 billion Euro per year versus costs of climate policies of 4 to 12 billion Euro per year). Interestingly, the total annual air pollution control costs expected for 2010 (typically for emission control technology) are considerably higher than the expected costs for implementing the Kyoto Protocol (typical for changes within the energy system). As a result, even modest climate policies (in terms of costs) may have relatively large financial ancillary benefits in terms of avoiding the most expensive measures for air pollution control. It should be noted that the larger share of the measures taken for climate policies impact the industry and electric power sectors. In contrast, a very large share of the air pollution control costs (about 60%) occurs in the transport sector. This means that the relative reduction of air pollution control costs in the stationary sectors could, in fact, be much larger than the overall reduction. Moreover, the large potential financial co-benefits in the transport sector may allow for stricter climate policies in this sector than from a perspective of optimising climate control costs only.

The type and size of ancillary benefits depends on if - and how - CO_2 trading is used.
The links between the CO_2 and air pollutant emissions are weaker in Western Europe than in Central and Eastern Europe. This is mainly due to more stringent air pollution control legislation compared with the other two regions. As a result, total European air pollutant reductions can be higher in the scenarios that use the Kyoto flexible mechanisms compared to the domestic action scenario. In turn, savings on pollution control costs are the highest in the *Domestic Action* case, since structural changes in Western European energy system induced by the CO_2 constraint allow avoidance of high-cost air pollution abatement measures in this region.

Reaching the Kyoto targets through domestic action only limits the ancillary benefits to Western Europe (as only this region needs to reduce CO_2 emissions). Since emission trading and joint implementation induce changes in energy systems in other parts of Europe, trading scenarios shift (“trade”) ancillary benefits partly to European regions outside Western Europe. Interestingly, however, while in the trading scenarios most of the CO_2 emission reduction takes place outside Western Europe, the differences for environmental impacts (in particular acidification) are much smaller, as Western Europe can partly benefit from the transboundary effect of reducing the pollution levels in Central Europe.

Thus, the results indicate that the use of emission trading, provided that they lead to real emission reductions in Central and Eastern Europe, can lead to a sharper reduction of regional air pollution in Europe. Using CDM with developing countries foregoes these benefits.

Using surplus emission allowances reduces ancillary benefits, in particular, for the Central and Eastern Europe regions.
Introducing available surplus allowances on the carbon market reduces the need for physical action to reduce CO_2 emissions in those regions and, consequently, the emissions of air pollutants and their control costs are higher. In our scenario with surplus allowances, the SO_2 and NO_x emissions in Central Europe and Eastern Europe are 2-4% higher and the control costs are 1.5 billion Euro/year higher than in the scenario that excludes surplus allowances. This might be a further important reason for the Central European and Eastern European countries (in addition to the direct impacts on the price of CO_2 emission permits) to restrict the amount of surplus allowances put on the market.

Integrated approach to climate change and regional air pollution policies is important for harvesting potential ancillary benefits.

The results presented in this chapter clearly demonstrate that integrating climate change and regional air pollution policies will lead to important efficiency gains. However, further development of tools and methods is necessary. In particular, the assessment models need to be extended to non-CO_2 greenhouse gases. Costing methodologies used in the analysis also need to be harmonized.

Acknowledgements

The authors would like to thank the European Environment Agency and its ETC - Climate Change and Air Pollution for supporting this study. In particular, this holds for Andreas Barkman, whose comments and suggestions have been very helpful in finalising the report underlying this chapter and connected paper. We would also like to thank Marcel Berk (RIVM) for his comments and ideas during different stages of the project.

APPENDIX 9.1 MODEL DESCRIPTION AND LINKAGES BETWEEN THE MODELS

This Appendix describes the three models that have been used in this exercise and their linkages.

The FAIR 2.0 model

The FAIR 2.0 model (Framework to Assess International Regimes for differentiation of future commitments) was designed to quantitatively explore the outcomes of different climate regimes in terms of possible environmental and economic impacts (including emission trading). It is a decision-support tool that uses expert information from more complex models (in particular, IMAGE), such as baseline emissions and marginal abatement cost curves. The basic assumption of the model is that regions will reach their emission reduction commitments on the basis of least cost. These costs are calculated using marginal abatement cost (MAC) curves, which reflect the additional costs of reducing the last unit of carbon. These MACs allow an assessment of the willingness of any party to buy permits or to abate more than is required to meet the Kyoto commitment and sell permits. Extensive documentation of the FAIR model can be found in Elzen and Lucas (2003a).

The TIMER model

The global energy system model, TIMER (The IMage Energy Regional Model), has been developed to simulate (long-term) energy baseline and mitigation scenarios. The model describes the investments in, and the use of, different types of energy options influenced by technology development (learning-by-doing) and resource depletion. Inputs to the model are macro-economic scenarios and assumptions on technology development, preference levels and restrictions to fuel trade. The output of the model demonstrates how energy intensity, fuel costs and competing non-fossil supply technologies develop over time. In TIMER, implementation of CO_2 mitigation is generally modeled on the basis of price signals (a tax on carbon dioxide). In response to the carbon tax, the model generates several outputs, such as investments in energy-efficiency, fossil fuel substitution, and extra investments in non-fossil options such as wind/solar energy, nuclear energy and biofuels. The model does not account for any feedback from the energy system to economic drivers. It should be noted that in TIMER costs are not related to the implementation of one single measure, as its implementation also changes other parts of the system. Investing in energy efficiency, for instance, reduces the costs of energy production and also accelerates the learning of energy-efficiency technology. Costs of air pollution control equipment are not included in the energy system costs of TIMER. The TIMER model has been described in Chapter 2 of this thesis and in De Vries et al. (2001).

The RAINS model

The Regional Air Pollution Information and Simulation (RAINS) model provides a consistent framework for the analysis of emission reduction strategies within Europe for all pollutants relevant for acidification, eutrophication and formation of ground-level ozone (Amann et al., 1999). It also includes a module that estimates the emissions of particulate matter (PM) from anthropogenic sources (see (Klimont et al., 2002))[xii]. Within RAINS, a non-linear optimization is used to identify the cost-minimal combination of measures, taking into account regional differences in emission control costs and atmospheric dispersion characteristics. RAINS covers almost all European countries and incorporates detailed data on their energy consumption. Scenarios for energy development form an exogenous input to the model. For emissions, it is calibrated on the basis of EMEP (compare http://webdab.emep.int), CORINAIR (EEA, 2001) and CEPMEIP data (CEPMEIP, 2002). In RAINS, emission reductions are achieved exclusively by technical measures. Feedbacks of emission controls on economic and energy system are not included. For example, emissions of SO_2 can be controlled through lowering the sulfur content of fuels or through flue gases desulfurization, but not by substituting coal by natural gas. Effects of changing the structure of energy supply and demand need to be analyzed as a separate scenario. Atmospheric dispersion processes for all pollutants are modeled on the basis of results of the EMEP air pollution transport models. The impacts of scenarios are evaluated using a set of indicators reflecting sensitivities of ecosystems and people to pollution (critical loads and levels). More details about the indicators used can be found in Cofala et al. (2002).

TIMER to FAIR

In principle, the TIMER and FAIR models use a similar regional breakdown and data can be easily transferred between them. For the Former Soviet Union (FSU), however, FAIR distinguishes between Annex-I countries that have emission obligations under the Kyoto Protocol (in particular the Russian Federation and Ukraine) and non-Annex-I countries that have no emission obligations. In TIMER, this division does not exist. As the first category contributes the lion's share of the emissions in the region, we have simply assumed the same relative reduction of CO_2 in TIMER as in FAIR. A second limitation in the transfer of data was that FAIR uses data on base year emissions from the CDIAC database (CDIAC, 1999), that are somewhat different from the TIMER modeling results for 1990. Therefore relative changes compared to 1990 were used in the data transfer between these models.

TIMER to RAINS

For RAINS, country-level energy scenarios are necessary as inputs for emission calculations. The TIMER model, however, calculates energy use for three large regions in Europe. In terms of fuel types too, the RAINS model is more detailed than TIMER. Finally, the data sources used to calibrate the model for the base year are different (TIMER is calibrated against IEA data, RAINS uses in addition data from national sources). A methodology had to be developed to translate the TIMER energy results into RAINS input. First, existing RAINS data for each fuel-sector combination are aggregated into the

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[xii] PM is estimated separately for the fine fraction ($PM_{2.5}$ – particles with aerodynamic diameter smaller than 2.5 µm), coarse fraction (particles between 2.5 and 10 µm) and total suspended particles (TSP). The sum of emissions of fine and coarse fractions (PM_{10}) is also calculated.

(lower) level of detail of the TIMER model. This aggregation is done for the base year (1995) and for the target year (2010) using a previous RAINS scenario, with very similar assumptions to the TIMER baseline. Second, for each country, fuel type and sector, the original RAINS data are scaled to the TIMER values using equation 9.1.

$$En\_R_{c,s,f,2010} = En\_R_{old,c,s,f,1995} * (En\_T_{R,s,f,2010} / En\_T_{R,s,f,1995}) * \\ (En\_R_{old,c,s,f,2010} / En\_R_{old,c,s,f,1995}) / (En\_R_{old,R,s,f,2010} / En\_R_{old,R,s,f,1995}) \tag{9.1}$$

Where:
En_R is the fuel use as used in the RAINS model (GJ),
"Old" refers to the data of an earlier RAINS run,
En_T is the fuel use in the TIMER format (GJ),
The prefixes c and R refer to country and region level,
The prefixes s and f are used for sector and fuel type.

Some further assumptions had to be made. First of all, RAINS uses several data for emission calculations on activities not directly related to energy consumption (e.g. production of industrial products and livestock farming). Here data from RAINS were used. This has also been done for energy sources for which TIMER does not include information (the use of solid waste as a fuel). Secondly, equation (9.1) cannot be applied to fuels with very small (or even zero) consumption in the base year, i.e. for "new" renewable energy sources such as solar and wind in power generation and for natural gas use in transport. In these cases, TIMER output has been scaled down to the country level on the basis of a constant percentage, reflecting the contribution of a given country to regional total. In case of renewables, the share of individual countries in total power generation was used. Similarly, data on compressed natural gas (CNG) use in transport was distributed on the basis of total national demand for transport fuels. Finally, using the scaling method of equation 9.1 does not necessarily result in supply meeting demand on a country level. For energy forms for which export/import is possible we assumed that potential surpluses/deficits will be leveled out through international trade within each country group. For district heat we have scaled back the demand per country to its production level.

10. SUMMARY AND DISCUSSION

10.1 Long-term energy projections: both necessary and difficult

Energy plays a crucial role in the aspiration of a more sustainable development. On the one hand, the consumption of energy is a necessary condition for human activities, and thus human well-being. On the other hand, the way energy is currently produced and consumed also causes various environmental problems, such as climate change, regional air pollution, waste generation and nuclear risks. It is also questionable whether energy security can be ensured in the long term. Finally, about a third of the global population has no or very limited access to modern energy sources. Increasing energy supply represents an essential condition for economic growth, but also contributes further to the global environmental problems and energy security issues. Given the situation described above, the world energy system is currently faced with multiple challenges.

One particularly important challenge in the future of the energy system is the response to climate change. Current knowledge indicates that “in order to avoid potentially dangerous anthropogenic changes in the earth’s climate” (objective of the UNFCCC Climate Treaty), atmospheric greenhouse concentrations will have to be stabilized. In fact, low stabilization levels (550 ppm CO_2-eq or below) will be needed, if one is to limit global mean temperature increase to less than 2°C (the EU climate target). This will require dramatic changes in the energy system with respect to development in the absence of climate policy. At the moment, little information is found in the literature on the possibilities of achieving such low stabilization levels.

Many of the processes that govern the behavior of the energy system have a long-term character, certainly those related to climate change. Current decisions on the energy system will influence the energy and climate system for several decades. Therefore, it is important to explore plausible long-term developments. However, assessing the future of the energy system is far from easy. Complex dynamic processes such as demographic and economic development, technological change, resource availability and energy policies all interact as determinants of future energy use – and diverging development patterns for each of these factors could introduce very different futures.

Energy-model-supported scenario analysis is used to provide insights into the future interplay of the energy system, socio-economic developments and the environmental system. In this context, scenarios comprise plausible descriptions 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). In other words, scenarios are used to explore the future – rather than to predict it. In this thesis, we look into scenario analysis for the energy system to address three crucial questions:

1. *What are possible development pathways for the global energy system and associated emissions in the absence of climate policy?*
2. *What types of uncertainties are associated with energy scenarios, and what are promising ways of dealing with these?*
3. *Is it possible to stabilize greenhouse gas emissions at low levels - and if so, what kind of strategies might contribute to this?*

We will examine these questions by analyzing long-term energy scenarios, and using model calculations of the TIMER energy model (described in Chapter 2).

10.2 Long-term projection of baseline emissions and the role of uncertainties

10.2.1 Causes of uncertainty and methods used in scenarios for handling uncertainties

Since there are several causes of uncertainty in scenario projections, various methods will be needed to deal with the uncertainties. Uncertainties play a crucial role in assessing possible future changes in energy use and consumptions. These uncertainties can be classified in different ways. One way is on the basis of their origin. First of all, there is *ontic* uncertainty i.e. the uncertainty present in the system itself (“natural randomness” occurring in complex systems). An example is the variability in economic growth rates. Secondly, there is *epistemic* uncertainty that results from lack of knowledge. Epistemic uncertainty can be further classified on the basis of how it is, and can be expressed: 1) in a statistical way (mostly using Bayesian methods), 2) in terms of conditional expressions (what if) or 3) recognized ignorance. Another important form of epistemic uncertainty is disagreement among experts, possibly originating from differences in value systems. Finally, there is reflexive uncertainty that results from an unknown response to information on the future. Uncertainties can also be classified by scale at the level of: 1) competing theories, 2) the model representation of these theories or 3) parameter values within these models.

Given the large variation in causes of uncertainty, a wide range of methods can be used to deal with uncertainty in assessments on future trends. These include: 1) the alternative scenario method (which in particular responds to the more qualitative forms of epistemic uncertainty and reflexive uncertainty), 2) the fully probabilistic method (strong in addressing ontic and epistemic uncertainty that can be expressed in quantitative terms), 3) model comparison (alternative models and parameter values), 4) validation of scenario results against real trends (addressing all forms of uncertainty) and 5) qualitative statements (such as the pedigree characteristic in the NUSAP method; particularly targeting those uncertainties that cannot be easily quantified). Some of these methods have been applied in this thesis to gain insight into the uncertainty of 21st century greenhouse gas emissions. In Chapter 5, these different methods to handle uncertainty are discussed in more detail.

A lively debate has been held in the literature on how to handle uncertainties in scenario analysis (see Chapter 5). Critics of the alternative scenario approach argue that the lack of probability assignments implies that usefulness for decision-makers is limited, as they lack information on the relevance of the trends presented. At the same time, a criticism for the probabilistic scenario approach it that this method attempts to assign subjective probabilities in a situation of ignorance, thus leading to a dismissal of uncertainty in favor of spuriously constructed expert opinion.

10.2.2 Comparison of earlier scenario exercises with more recent insights

Validation of the SRES scenarios against recent data and projections

One way to gain more insight into relevant uncertainties and their influence is to compare scenario outcomes against actual realizations or more recent projections. In 2000, a set of scenarios was published as part of IPCC's *Special Report on Emission Scenarios* (SRES). The SRES scenarios cover a very long time period (1990-2100) to serve their purpose as input to climate modeling. Uncertainties were handled by applying: 1) a novel method of developing alternative scenarios based on both qualitative storylines and modeling and 2) by using different models. The SRES scenarios have served as a primary basis for assessing future climate change and possible response strategies. More recently, several authors have criticized the scenarios as not only being flawed – but also outdated. As the scenarios were developed between 1996 and 1999, sufficient time (around 6-10 years) has now passed to make it worthwhile to test their consistency with data and more recent projections.

Some key conclusions can be drawn from this comparison:

- ***Overall, the SRES scenarios are still largely consistent with current insights into emission trends and their drivers.*** Some differences between the SRES scenarios and current insights can be noted, most important are the currently lower projections for population and income in developing regions and the lower realization and projections for sulfur emissions (see 3.5). Overall, however, it can be concluded that quantitatively speaking, the SRES projections are broadly consistent with actual trends and current projections. Interestingly, the storylines underlying the SRES scenarios have too been found relevant in more recent assessments such as the Millennium Ecosystem Assessment and UNEP's Global Environment Outlook. The alternative scenario method in SRES has been applied in a way that allowed it to capture relevant uncertainties, even 6-10 years after the period of development.
- ***Scenario updates can help keep scenarios relevant (until more fundamental changes make them irrelevant).*** The fact that the SRES scenarios still compare relatively well to current insights implies, on the one hand, that there is no immediate need for a large-scale IPCC-led update of the SRES scenarios solely based on the SRES scenario performance vis-a-vis data for the 1990–2000 period and/or more recent projections. On the other hand, on the basis of reported findings, individual research teams could make, and in some cases already have made, useful updates of the scenarios. The fact that for these long-term scenarios, the first signs of limited

inconsistency become apparent 6-10 years on, stresses that scenarios are not meant to predict the future, but to explore it on the basis of current knowledge.

10.2.3 Emission scenarios in the absence of climate policy

The possible development of (world) emissions in the absence of climate policy has been explored using a conditional probabilistic approach (Chapter 5), model comparison (Chapter 6) and the scenario method for China (Chapter 4).

Conditional probabilistic approach for world energy emissions

The conditional probabilistic approach to uncertainty uses probabilistic estimates of uncertainty at the parameter level, but within the context of storyline-based scenarios. As such, it aims to combine the strength of probabilistic uncertainty assessment and the alternative storyline approach (see the summarized discussion earlier in this summary). The uncertainties that cannot be easily captured in more formal probability expressions (e.g. the existence of a globalizing world) are captured by the storylines, which also ensure consistency. Other uncertainties, however, such as the rate of economic growth within a storyline, are expressed in terms of probability distribution functions. We used this approach to identify uncertainties ranges within TIMER for the SRES scenarios.

The following conclusions can be drawn from the results of the analysis.

- ***The model calculations suggest that (cumulative) 21st century emissions range from around 800 to 2500 GtC in the absence of climate policy. The low end of the range originates in a different storyline than the high end of the range (see Chapter 4).*** The results indicate that CO_2 emissions from the energy system may develop in very different directions, with emissions ranging from 4-40 GtC in 2100 or, in terms of cumulative 2000-2100 emissions, 800-2500 GtC (see Figure 10.1). This wide range results partly from the fundamentally different way in which 21st

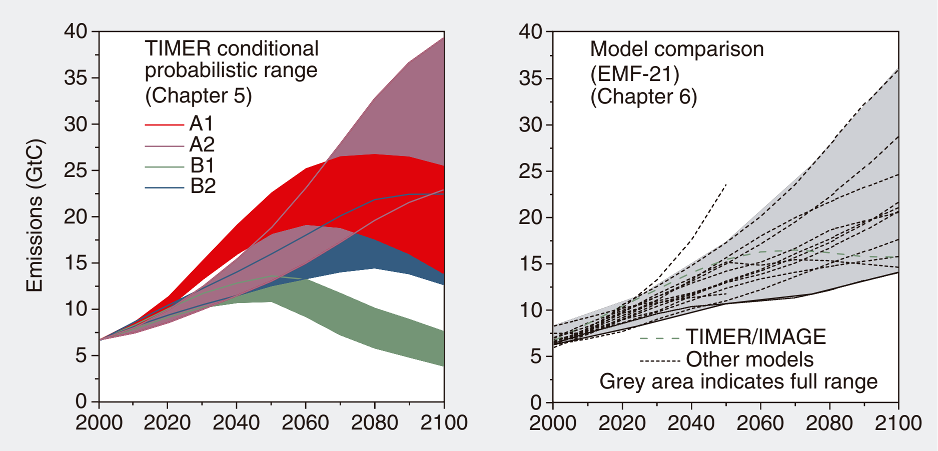

Figure 10.1 World CO_2 emission scenarios in the absence of climate policy.

century society could develop. The B1 scenario, exploring emission pathways under the assumption of sustainable development policies, is clearly separated from the other three storylines. The ranges found are consistent with those in the SRES scenario study (from which the storylines used here are derived), but also with the fully probabilistic study of Webster et al. (2002). Some other fully probabilistic studies showed narrower uncertainty ranges. These broadly coincide with the uncertainty range identified here for the so-called B2 world, based on a more-or-less business-as-usual type of storyline.

- ***Emissions for a clearly defined storyline can still differ over an uncertainty range larger than 40%.*** These ranges originate from stochastic uncertainty and existing ambiguity in each storyline. The most important factors contributing to the uncertainty in CO_2 emission are found to be the uncertainty in population, income, factors determining efficiency in energy consumption, fuel preferences (in particular the degree to which consumers prefer more convenient fuels over coal) and oil resources (Section 5.3). Other important factors are technology assumptions for renewables and for energy demand. The contribution of the different factors depends on the storyline: population, for instance, plays a more important role in the uncertainty range in the A2 scenario, while uncertain fuel preferences play a more important role in the B1 scenario. These findings (consistent with the storylines) show the added value of the conditional probabilistic approach.

Model comparison in the context of EMF-21

Another way to deal with uncertainty is by model comparison. Here, we used the results of a recent model comparison study (EMF-21), performed by the Energy Modeling Forum, which focuses on the role of non-CO_2 gases. Until very recently, most energy models focused exclusively on CO_2 in their analysis. The EMF-21 study encouraged modelers to expand their focus to non-CO_2 gases by offering a harmonized set of information on abatement potential. All model developers used this set in different ways – to fit into the structure of their models (and world views).

- **The model comparison shows that all models projected a strong growth in emissions of both CO_2 and non-CO_2 gases in the absence of climate policy.** On average, emissions of CO_2 (across all models) increase from 7.5 GtC in 2000 to around 20 GtC in 2100. The emissions of non-CO_2 greenhouse gases increase from 2.7 GtC-eq/yr in 2000 to 5.1 GtC-eq/yr in 2100. In other words, most models expect emissions of non-CO_2 gases to grow at a rate slightly below that of $CO_{2,}$ but still the non-CO_2 gases represent about a quarter of the 21st century GHG emissions (Section 6.3).
- **There is a considerable spread in baseline emissions reported by different models – consistent with the spread found earlier for the TIMER model alone.** Figure 10.1 shows that for CO_2 the spread in model outcomes ranges from 14 to 36 GtC/yr in 2100 (or an average growth of 1.1%, ranging from 0.8% to 1.3%). Most of the spread originates in the second part of the century when some models show sustained emissions growth—while others show emission growth slowing down or even going negative (driven by population). This slower emission growth rate occurs in most of the models with a more physical orientation, rather than the econo-

mic models. The average growth rates for CH_4, N_2O and the fluorinated gases are 0.6%, 0.4 and 1.9% per year, respectively. Here too, the models with a more physical orientation seem to lead to a stronger saturation in emissions in the second half of the century than more economically oriented models (Section 6.3).

Alternative scenarios for China's energy future

A crucial uncertainty in the world's energy and climate future are current and future developments in China. As a result of China's large population and its rapidly growing economy, China is likely to surpass the USA to become the world's largest emitter of GHG emissions in a few years' time. At the same time, per capita emissions are far below the OECD level. We used the alternative scenario approach to develop a set of energy and emission scenarios for China. These scenarios were based on the IPCC SRES scenarios and expert elicitation with key Chinese experts. The purpose of the study was to explore possible baseline trends and available options to mitigate emissions.

- **Emissions in China could grow by a factor of 2-4 in the first half of the century in four very different baseline scenarios. The projections could even further diverge in the second half of the century (Figure 10.2).** A crucial uncertainty in China's future concerns the openness of the Chinese economy to international trade and investments. For this reason, scenarios were developed around this uncertainty – with alternative scenarios focusing on an alternative sustainable development orientation and stronger fossil fuel orientation. Despite the substantial differences in the scenarios, all scenarios still result in a rapid growth of carbon emissions in the absence of climate policy. The scenarios follow pathways that can partly be related to the position of current high-income countries (see Figure 10.2). A further outlook beyond 2050 shows that trends in the second half of the century will be largely determined by – uncertain – developments in the economic and social feasibility of non-carbon options such as solar/wind and biomass-derived fuels. It is also in the longer term that the difference between the various scenarios – in terms of sustainable development orientation, openness to fuel trade and the like – starts to make a large difference. This does not mean that larger differences are also possible in the short term. One element might be the development of climate policy (international or within China) (see Chapter 4).
- **In absolute terms, the largest increase in these scenarios is expected to occur in the electric power generation and industry sector.** The high growth in electricity demand and the strong competitive position of coal make electricity generation the fastest growing and, from 2015 onwards, the largest carbon-emitting activity; this is followed by industry. The fastest growth in energy use, however, is in the transport sector, driving rapidly growing oil imports. In the residential and services sector, a phase-out of traditional fuels and (especially in urban regions), of coal, can be expected.

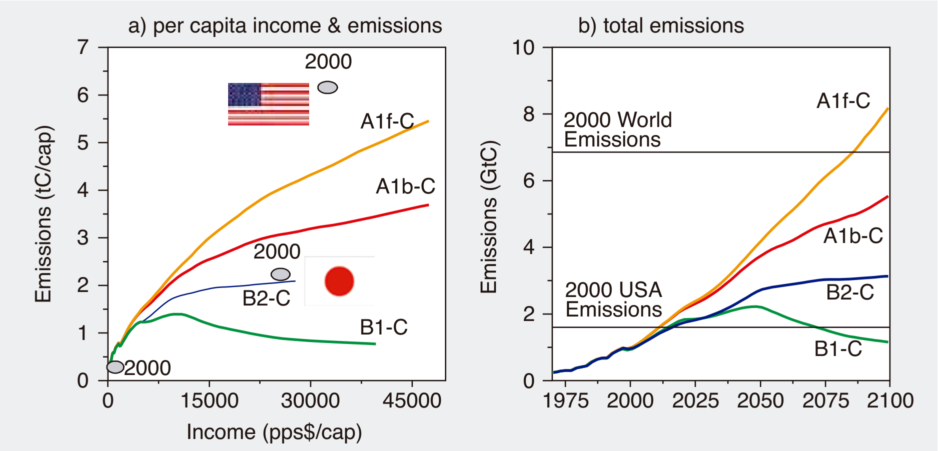

Figure 10.2 Trends in income, per capita emissions and total emissions in China according to the scenarios discussed in Chapter 4. The flag markers indicate the position of USA and Japan in the year 2000.

10.3 Ambitious mitigation scenarios

10.3.1 Integrated mitigation analysis

Mitigation scenarios explore the possible scope of climate policies. Despite the fact that a large number of mitigation scenarios have been developed, only a few focus on low greenhouse gas concentration targets (around 550 ppm CO_2-eq and less). However, current studies indicate that such low concentration levels will be required to achieve the objective of the EU climate policy (limiting climate change to 2°C compared to pre-industrial level). Where stabilization is at a level of 550 ppm CO_2-eq. the probability of staying below the 2 °C level is 20%; where stabilization is at 450 ppm CO_2-eq., this probability will increase to 50% (Figure 10.3). So far, the overwhelming majority of world mitigation studies have focused on stabilization at a level of 650 ppm CO_2-eq. The lack of scenarios for reaching ambitious climate targets forms a serious knowledge gap about the feasibility of these targets. Such scenarios are explored in this thesis. The introduction of a carbon tax was used in the modeling exercises as a generic method to introduce responses throughout the model.

Mitigation analysis has been dealt with in various chapters of this thesis. In particular, attention has been paid to low greenhouse gas concentration stabilization scenarios, the influence of technology change assumptions, the possibilities for integrating climate and air pollution policies, the role of non-CO_2 gases and finally, the reduction possibilities in China.

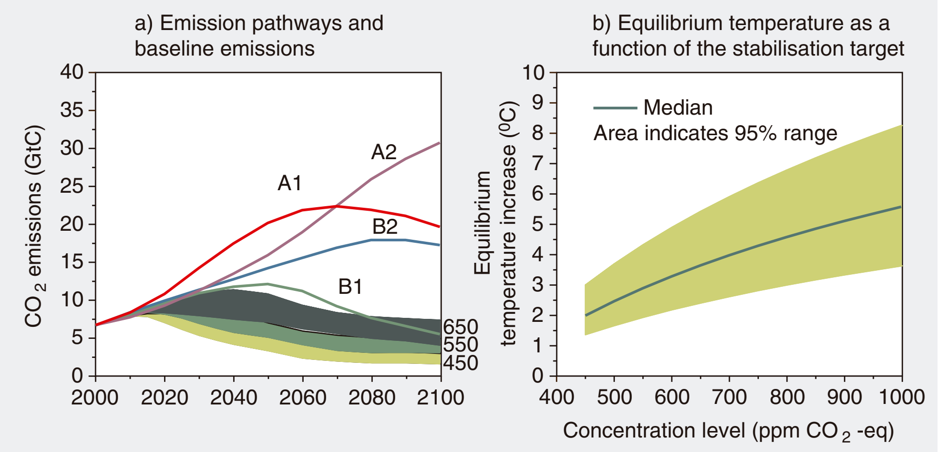

Figure 10.3 Emission pathways leading to stabilization of greenhouse gases at 450, 550 and 650 ppm CO_2-eq compared to emission trends in scenarios without climate policy (mean values of the ranges indicated in Figure 10.2). The right-hand figure shows the likely equilibrium temperature change associated with concentration levels. Grey areas indicate a 95% range, and the black line, the mean value (source IPCC, 2007).

10.3.2 Strategies to reach low stabilization targets

In Chapter 7, we used the TIMER model in conjunction with the FAIR climate policy model and the IMAGE 2.3 model to develop integrated mitigation scenarios targeting low stabilization concentrations. The starting points of the analysis were formed by the mean values of the conditionally probabilistic scenarios presented in Chapter 5 (B2 as standard scenario; A1 and B1 for uncertainty analysis).

- **The study shows that, technically, stabilizing greenhouse concentrations at 650, 550, 450 ppm and, under specific assumptions, 400 ppm CO_2-eq. is feasible from these baseline scenarios on the basis of known technologies.** The 450 ppm CO_2-eq mitigation scenario (in terms different mitigation measures leading from the baseline to the 450 ppm CO_2-eq. reduction pathway) is shown in Figure 10.4. The lowest level of 400 ppm CO_2-eq can only be reached in the TIMER model if the option of bio-energy and carbon capture and storage is included (this option results in net negative emissions in power generation).
- **Strategies were found to consist of a portfolio of measures.** In other words, there is no silver bullet (Figure 10.4). All scenarios apply a wide range of technologies in reducing emissions. Some technologies, however, contribute more than others. Efficiency plays an important role in the overall portfolio. CCS is another important technology under default assumptions – but may be substituted at limited additional costs against other zero-carbon emitting technologies in the power sector.
- **The concentration target forms a trade-off between costs and climate benefits.** The net present value of abatement costs (2010-2100) for the B2 baseline scenario (a medium scenario) increases from 0.2% of cumulative GDP to 1.1%, going from

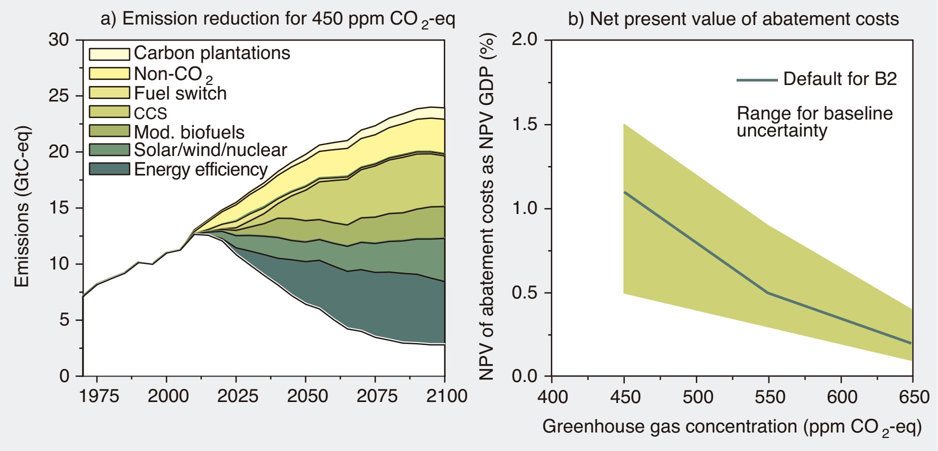

Figure 10.4 Contribution of various options in reducing greenhouse gas emissions from baseline to the 450 ppm CO_2-eq scenario (left-hand) and the costs associated with stabilizing greenhouse gas concentrations (net present value of abatement costs at 5% discount rate as percentage of GDP) (right-hand side). The middle line shows costs from the B2 baseline, while the ranges indicate costs from the B1 and A1b baseline.

stabilization at 650 to 450 ppm (Figure 10.4). On the other hand, the probability of meeting the EU climate target (limiting global mean temperature increase to 2°C) increases from 0-10% to 20-70% (compare Figure 10.3).

- **The types of reductions described will require major changes in the energy system, stringent abatement action in other sectors and related large-scale investment in alternative technologies.** Although the analysis shows that reaching 450 ppm CO_2-eq is feasible, impacts on the energy system are considerable. Figure 10.5 provides some indication by comparing historical development of energy intensity (energy per unit of income), the carbon factor (CO_2 emissions per unit of energy) and the development here required to meet a 450 ppm target. For the carbon factor, the trajectories depicted imply a clear break with the past; for energy intensity, this implies a temporary acceleration of historical trends. Some of these changes are required in the short term (2020) and also global emissions need to peak within two decades. As this will involve many actors with conflicting interests, creating a sense of urgency will be required to achieve this.
- **Uncertainties are also important in mitigation analysis**. Uncertainties play an important role in the whole analysis – and thus are also important for decision-making on mitigation strategies. Uncertainties include: 1) the required reduction levels, 2) baseline emissions, and 3) availability and costs of different technologies. For a given baseline and target, the uncertainty in costs is at least in the order of 50%, with the most important uncertainties originating in input uncertainties in land-use emissions, the potential for bio-energy and the contribution of energy efficiency. Given this dominant role, it is important to develop strategies that are robust with respect to these uncertainties.

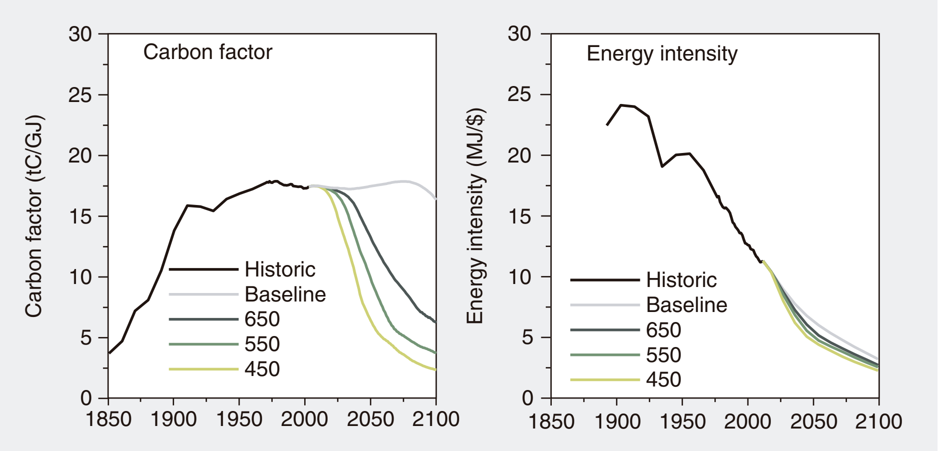

Figure 10.5: Historical development of the carbon factor and energy intensity in the B2 baseline scenario and under the 450, 550 and 650 ppm CO_2-eq stabilization scenarios.

10.3.3 The role of technology assumptions in mitigation scenarios

Technology development forms a critical factor in achieving emission reduction pathways at reasonable costs. In this context, a set of model experiments (presented in Chapter 8) was performed to analyze the role of technology development on energy system responses to a global uniform carbon tax.

- **Technology development was demonstrated to play a crucial role in the mitigation costs by decreasing the gap between the (currently) more expensive low/zero carbon options and their fossil alternatives.** In the TIMER model, technology development is represented by the learning-by-doing formulation (an empirically found relationship between cumulative production and production costs). One can distinguish two forms of technology development:
  - o Technology development as part of the baseline;
  - o Technology development induced by climate policy;

  The first category increases the global CO_2 emission reduction in 2030 as a result of a US$300/tC tax from nearly 40% to 60%. Leaving out the second category reduces the response to a US$300/tC carbon tax in 2030 from 40% to only 30% (all numbers compared to the B2 baseline). These result indicate that it is important to make sure that technology development indeed is able to to reduce abatement costs . Policies to stimulate this may include, for instance, the creating of niche markets to provide learning opportunities (e.g. by feed-in tariffs) and research support (to ensure favorable progress ratios).
- **Model assumptions on policy-induced technology development vis-à-vis baseline technology development determine whether a model favors early action to delayed response.** The relative importance of the two different forms of technology development distinguished above are of crucial importance for the "optimal" timing of abatement efforts. "Baseline learning" might be a reason to postpone

policies, while “induced learning” calls for early action. Under the TIMER default model settings, both processes seem to contribute in an equal way to the 2030 model response to a carbon tax. As inertia in the energy system provide another reason to spread mitigation effort, this implies that within the current model setting, the processes that would support an early-action response seem to dominate over the processes that favor a delayed-response approach—at least, if no discount rate is applied.

10.3.4 Co-benefits of climate policies

An integrated approach to climate change and regional air pollution can harvest considerable ancillary benefits in terms of environmental impacts and costs. The reason for this is that both problems are caused to a large extent by the same activity: fossil fuel combustion. In Chapter 9, we evaluated different ways of implementing the Kyoto Protocol (with respect to emission trading) in terms of co-benefits using the TIMER, FAIR (emission trading) and RAINS (air pollution) models.

- **The ancillary benefits of the Kyoto Protocol are substantial compared to its costs.** The total cost savings for implementing current policies for regional air pollution of the Kyoto Protocol are in the order of 2.5–7 billion euros. In all cases, this is in the order of half the costs of the climate policy (4–12 billion euros). Similarly, while the Kyoto Protocol reduces European CO_2 emissions by 4–7%, it also reduces European emissions of SO_2 by 5–14%, compared to baseline.
- **The magnitude of ancillary benefits depends on how flexible mechanisms and surplus emission allowances are used in meeting the Kyoto targets.** Interestingly, using flexible mechanisms reduces emissions of air pollutants for Europe as a whole even further than domestic implementation, but the reductions are shifted from Western Europe to Central and Eastern Europe, and Russia. The use of surplus emission allowances to achieve the Kyoto targets decreases the ancillary benefits, in particular, for the group of countries selling emission credits (Eastern Europe and Russia).

10.3.5 Non-CO_2 gases

Non-CO_2 gases can also be important in mitigation strategies. Several conclusions can be drawn from the EMF-21 model comparison study.

- **A multi-gas strategy can achieve the same climate goal at considerably lower costs than a CO_2-only strategy.** The cost reduction of a multi-gas strategy (i.e. allowing substitution among different greenhouse gases in climate policy) may amount to about 30–40% for GDP losses compared to a CO_2-only strategy. The largest cost reductions are expected to occur early on in the mitigation policy.
- **To make multi-gas strategies operational, a metric is needed that allows substitution. The choice here plays a crucial role in the results of a multi-gas strategy.** Current climate policies allow for a multi-gas strategy by using the 100-year GWPs as substitution metric. EMF-21 results show that this leads to a very large contribution of the non-CO_2 gases in total reductions in the short term. Later in

the scenario period, the contribution of most gases becomes more proportional to their share in baseline emissions. Using an alternative metric, i.e. inter-temporal optimization under a long-term target within models leads to lower long-term costs and also implies that reductions in CH_4 are delayed to later in the century. It should be noted, however, that substitution metrics also need to work in the real world. In this context, the benefits of using GWPs as a substitution metric (i.e. allowing a multi-gas strategy) seems to outweigh the limited losses against the more idealized cases.

10.3.6 China

A large number of mitigation options have been analyzed in the mitigation analysis for China. As indicated earlier, China's emissions are expected to grow rapidly under baseline assumptions.

- **By combining all options considered, it appears to be possible to reduce 2050 emissions in China by 50% compared to the baseline scenarios.** A large potential has been found to exist for mitigating carbon emissions in China, for example, in the form of energy efficiency improvement (with large co-benefits) and measures in the electricity sector. A large part of this potential was also found to be available at costs which are low in comparison to international standards.
- **Analysis also shows that at least part of this potential can be captured by other policies than climate policy per se.** A policy to reduce GHG emissions can be introduced in existing policies such as the national sustainable development strategy and the national energy development plan. Policy options assessed in this study, such as clean energy utilization, which includes natural gas and non-fossil based energy, could well match the targets described in these national plans. Certainly when taking into account the co-benefits (of reduced of air pollution, this is likely to lead to no-regret strategies.
- **Climate policies need to be evaluated against the scenario storyline.** While considerable attention is paid to the storyline of the scenario in baseline scenario development, in mitigation scenario analysis a simple carbon tax is often introduced to explore model responses. However, the attractiveness of mitigation measures and policies depends on the storyline. Some scenario "storylines" may favor financial instruments more than others, and the same goes for specific options (e.g. nuclear power)., Mitigation measures and policies in China have been evaluated against the scenario storyline.

10.4 Discussion and the steps ahead

10.4.1 Discussion of the main conclusions of the thesis

The analysis of possible developments in greenhouse gas emissions, with and without climate policy, yielded three main messages:

- The baseline scenarios explored in this thesis, which are based on very different storylines and include a wide range of parameter assumptions, all lead to a substantial increase in greenhouse gas concentrations. This is likely to lead to an increase in global mean temperature of at least 3-4°C (see Chapter 5 and Chapter 7, using a mean climate sensitivity for the central B2 scenario).
- It is possible to reduce greenhouse gas emissions in order to stabilize concentrations at low levels such as 450 ppm CO_2-eq. This level provides more-or-less a 50% chance of limiting global mean temperature change to 2°C, compared to pre-industrial levels (the EU climate targets). Abatement costs from a medium emission baseline (B2) are likely to be in the order of 1-2% of GDP (Chapter 7).
- Crucial factors for increasing the feasibility of ambitious climate scenarios include integration of climate policy with other policy goals (air pollution, energy security and sustainable development), technology development and creating a sense of urgency (Chapter 7-9).

A crucial question is obviously whether these modeling results are relevant to the real world. See below for a few remarks in this context:

- First, the TIMER model, calibrated against 30 years of data in the development of the energy system, includes a large amount of empirically derived data on technology parameters, depletion dynamics etc.
- Second, considerable attention has been paid to uncertainty analysis here. The main conclusions of the thesis were found to be robust compared to these uncertainties.
- In addition, comparison of TIMER to model results of other models shows that:
  - the scenarios developed by the TIMER model seem to be consistent with other scenarios for CO_2 emissions (Chapter 5) and non-CO_2 gases (Chapter 6) and
  - in terms of costs, the TIMER calculations are also within the (wide) range of cost estimates, both in the short and long term (Chapters 7 and 9).

As such, we are of the opinion that these findings can be considered as being robust. Nevertheless, there are elements that could be important in long-term energy futures and mitigation scenarios that are either, not at all, or not as well captured in the current analysis.

- Like most energy models, TIMER includes a much more detailed description of energy supply dynamics than energy demand dynamics. An important factor here is that at the moment, activity levels are described in terms of monetary indicators, while in reality physical activities drive emissions. Obtaining a better description of future trends on the basis of physical indicators allows a better understanding of future energy demand trends and the potential to improve energy efficiency.

- Technology development represents a crucial uncertainty, and current understanding of future technology change is still limited. This may lead to under- or overestimation of potential to reduce greenhouse gas emissions, as future technology change may be slower than historical learning rates suggest or, alternatively, totally new technologies may emerge with more favorable characteristics. Especially in the area of energy-efficient technologies a much more rapid development is conceivable in a world with high carbon prices. Other technologies, such as nuclear fusion or decentralized power systems, may also come into play.
- The TIMER analysis focuses on increases in abatement costs. Macro-economic feedbacks have not been calculated. While macro-economic costs measures may be more relevant for the economy as a whole, they are also much more uncertain.
- Current scenarios represent surprise-free worlds and also ignore climate feedbacks. Short-term random events (e.g. disruption of global oil supply) may lead to different futures than the ones depicted in this thesis. Climate change can have significant impacts on development in certain regions, but it is not expected that this will alter the conclusions drawn above.
- Modeling energy–climate scenarios (like the ones in this thesis) tend to focus on economic and technology elements. It should be noted here that this tendency leads to an idealization of implementation issues. New technologies and policies are assumed to be globally applicable and are often introduced over relatively short periods of time. The scenarios here do not generally deal with the question of political feasibility, assuming, for example, that mitigation policies are implemented globally and in all sectors of the economy. To some extent, they also ignore the fact that decisions in the energy system are determined by a large number of actors, with separate or sub-interests , at least, in this context (see, for instance, the impacts on fuel trade discussed in Chapter 7). Implementation issues might be most important in developing countries.

10.4.2 Important steps ahead

On the basis of limitations in current activities, we can visualize a few important areas of progress in the coming years. These are categorized under:1) scenario development, 2) model development and 3) use of model results.

10.4.2.1.Scenario development

Improving current scenarios

Current scenarios are still deficient. Several issues play a role here.

- At the moment scenarios clearly differentiate between baseline and policy scenarios. However, given the current focus on climate change, this difference will, in the coming years, become less easy to make and arguably less relevant. This implies that in future sets of scenarios, one may to decide to work with some form of a continuum starting from existing policies and proceeding to stringent ones.
- Moreover, the feedbacks of climate change to the drivers are generally ignored in current scenarios, implying that the scenarios are in some way inconsistent. The

next generation of scenarios may be expected to further capture climate impacts, and along with this, human adaptation to climate change.
- Mitigation scenarios are currently mostly developed on the basis of a uniform carbon tax as a proxy of different types of climate policies. As different policy instruments may have different consequences, however, future mitigation scenarios might explore a wider range of policy options (requiring more detailed models too).
- Finally, the scenarios are derived from caricature storylines that have continued for over 100 years without surprises. Surprises may occur, however, such as technology breakthroughs (fusion) or major wars. Furthermore, societies may shift from "one storyline to another". Whether it will be possible to capture these issues without making scenarios too complicated is, however, still an open question.

Model development

The TIMER model as described in this thesis has three unique features: 1) a strong focus on technology dynamics, 2) a coupling to the IMAGE model, and thus land-use and climate change issues and 3) a coupling to the FAIR model, and thus international climate policy issues. In terms of model development, it might be important to explore several issues further:
- Geo-graphically explicit processes: for simplicity, models tend to simplify focus on global/regional dynamics. As many relevant processes, however, operate at more detailed levels, it will be important to improve the handling of geographically explicit processes. This may include focusing on urban and rural development, for instance, and also introducing geographically explicit factors into the modeling of energy demand.
- Given the importance of factors related to energy demand in both baseline energy development (see Chapter 5) and mitigation (Chapter 7), it will be important to improve the understanding of the development of energy demand. This involves, for instance, a better understanding of the development of physical drivers of energy demand and an improved description of energy efficiency options.

Model application

Two basic roads are open for improving the understanding of implementation issues in climate policy:
- Including implementation and governance issues in models, e.g. using multi-actor modeling approaches.
- Using models in a context that allows feedback from stakeholders and decision-makers.

At the moment, the first approach might be more relevant in a research mode, especially when focusing on simplified systems. With respect to the second approach, very successful historical examples – both in relation to climate policy (the COOL and Delft Workshops on climate policy) and outside climate policy (the application of the RAINS integrated assessment model for policy-making on air pollution in Europe). It should be noted that there are quite important differences between these examples and their impact. The COOL workshops consisted mainly of an open dialogue between various stakeholders and scientists, strengthening the understanding of climate policy issues among participants, but not directly coupled to a decision-making process. The Delft Workshops formed a more structured dialogue between decision-makers and scientists, instrumental in preparing decision-makers in climate policy negotiations in the context of UNFCCC. The RAINS work has actually been formalized into the decision-making process on air pollution in Europe. Despite these differences, any of these types of interactive workshops between policy makers, policy analysts and modelers can lead to mutual learning on both research outcomes and relevant research questions. This may be especially important considering the pivotal role of the coming years in international climate policy.

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1. Lange termijn projecties: lastig maar noodzakelijk

Energie speelt een cruciale rol in de discussie over duurzame ontwikkeling. Enerzijds is energie nodig voor menselijke activiteiten (en daarmee menselijk welzijn). Anderzijds leidt de huidige energievoorziening tot verschillende milieuproblemen, zoals mondiale, regionale en stedelijke luchtverontreiniging en veiligheidsrisico's. Er bestaan bovendien vragen rond uitputting van goedkope energievoorraden en concentratie van het aanbod in een beperkt aantal landen. Ten slotte geldt dat ongeveer een derde van de wereldbevolking geen, of slechts beperkt toegang heeft tot moderne energiebronnen. Voor hen is het vergroten van het energieaanbod een essentiële voorwaarde voor (materiële) welvaart. Op den duur draagt deze welvaart echter verder bij aan genoemde milieu- en voorzieningsproblemen. Kortom, als samenleving staan we bij de vormgeving van het lange termijn energiesysteem voor forse uitdagingen.

Binnen deze uitdagingen speelt het omgaan met klimaatverandering een cruciale rol. In 1992 is door de meeste landen het Klimaatverdrag afgesloten met als doel stabilisatie van broeikasgasconcentraties in de atmosfeer om gevaarlijke beïnvloeding van het klimaatsysteem te vermijden. De EU heeft voor haar klimaatbeleid deze doelstelling vertaald in een stijging de wereldtemperatuur met maximaal 2°C ten opzichte van het niveau voor de industriële revolutie. Om dit doel (met enige zekerheid) te kunnen halen is volgens huidige inzichten stabilisatie van de broeikasgasconcentratie op zeer lage niveaus noodzakelijk (550 ppm CO_2-eq en minder). Dit vereist verregaande veranderingen (of transities) in het energiesysteem. Of dergelijke lage concentraties ook bereikt kunnen worden is echter zeer beperkt onderzocht.

Veel van de voor klimaatbeleid relevante processen in het energiesysteem hebben een lange termijn karakter. Als gevolg hiervan hebben beslissingen die nu genomen worden nog zeker tientallen jaren invloed. Om beslisprocessen te ondersteunen is het dus noodzakelijk om mogelijke lange termijn ontwikkelingen te verkennen. Dit is echter niet gemakkelijk. Complexe en dynamische processen zoals die met betrekking tot bevolking en economie, technologie, energievoorraden en energiebeleid bepalen samen hoe het toekomstig energiegebruik zich ontwikkelt. Sterk uiteenlopende ontwikkelingen van ieder van deze processen kunnen tot zeer verschillende toekomsten leiden.

Het maken van lange termijn scenario's, mede op basis van energiemodellen, vormt een geschikt instrument om de verscheidenheid aan energietoekomsten en de consequenties hiervan te verkennen. Met het begrip scenario wordt bedoeld "*een plausibele beschrijving van toekomstige ontwikkelingen, gebaseerd op een coherente set aannamen over de belangrijkste relaties and drijvende krachten*". Cruciaal is dat het om een *toekomstverkenning* gaat en niet om *voorspelling*. Dit laatste is gezien alle onzekerheden (en vooral ook de vrijheid van de mens keuzen te maken) weinig zinvol. Gebruik makend van verschillende scenario's gaat dit proefschrift in op drie cruciale vragen in de relatie tussen het energiegebruik en klimaatverandering:

1. Hoe kan het energiegebruik zich in de toekomst ontwikkelen zonder klimaatbeleid en wat zijn hiervan de consequenties voor broeikasgasemissies?
2. Welke onzekerheden spelen hierbij een rol en wat zijn mogelijkheden om met deze onzekerheden om te gaan in scenario's?
3. Is het mogelijk om broeikasgasemissies te stabiliseren op zeer lage niveau's?

Deze vragen zijn bestudeerd door het opstellen van lange termijn energiescenario's, voornamelijk gebruik makend van het TIMER energiemodel. Dit model wordt in hoofdstuk 2 behandeld. In het vervolg van deze samenvatting worden eerst de resultaten met betrekking tot de eerste twee vragen besproken (gebaseerd op hoofdstuk 3-6) en daarna die met betrekking tot de derde vraag (voornamelijk gebaseerd op hoofdstuk 7-9).

2. Lange termijn projecties van het energiesysteem en de bijhorende onzekerheid

2.1 Oorzaken van onzekerheid in projecties, en methoden om hiermee om te gaan

In dit proefschrift wordt een verscheidenheid aan methoden toegepast met betrekking tot omgang van onzekerheden in scenario's om aldus zowel een vollediger beeld te krijgen over mogelijke ontwikkelingen, als om een beeld te krijgen van de mogelijkheden en beperkingen van de diverse methoden. De gebruikte methoden zie verder in deze paragraaf zijn vergelijking met actuele ontwikkelingen (hoofdstuk 3), de alternatieve scenario methode (hoofdstuk 4) en model vergelijking (hoofdstuk 6). In hoofdstuk 5 wordt een nieuwe methode ontwikkeld door combinatie van de alternatieve scenario methode en probabilistische scenario's. Tevens bevat dit hoofdstuk een vergelijking van de verschillende methoden. Zoals uitgelegd in hoofdstuk 1 spelen onzekerheden een cruciale rol bij toekomstverkenningen. Er bestaan verschillende methoden om onzekerheden te classificeren. Eén methode is op basis van hun oorzaak. De twee hoofdcategorieën hier zijn *ontische* en *epistemische* onzekerheid. Bij de eerste gaat het om onzekerheid die fundamenteel aanwezig is in het systeem zelf (natuurlijke variatie). Een voorbeeld is ondermeer de variatie in economische groeisnelheden. Bij de tweede categorie gaat het om onzekerheid door gebrek aan kennis. Deze kan verder worden gekwalificeerd op basis van uitdrukkingsmogelijkheden: 1) in statistische termen (meestal op basis van schattingen) zoals de schattingen van energievoorraden, 2) in termen van conditionele uitspraken ("wat als..."), of 3) in termen van uitdrukkingen over kennislacunes. Een belangrijke vorm van *epistemische* onzekerheid komt naar voren in onenigheid tussen deskundigen, met als onderliggende oorzaak vaak een verschil in expertise en/of waardepatroon (denk bijvoorbeeld aan de verschillende inschatting rond mogelijkheden voor energiebesparing tussen economen en ingenieurs). Ten slotte is er ook nog sprake van reflexieve onzekerheid, namelijk de onbekende reactie van mensen op informatie over de toekomst. Onzekerheden kunnen ook worden gekwalificeerd op basis van niveau. Dan gaat het bijvoorbeeld om 1) volledige theorieën, 2) de modelmatige weergave van deze theorieën, of 3) parameter schattingen.

Het is logisch dat de grote verscheidenheid in soorten onzekerheid ook leidt tot een behoorlijke variatie in methoden om hiermee om te gaan. Hierbij gaat het om ondermeer 1) het ontwikkelen van alternatieve scenario's (zeer geschikt voor de minder kwantitatief in te schatten vormen van *epistemische* onzekerheid), 2) probabilistische methoden (vooral geschikt voor het verkennen van de gevolgen van *ontische* onzekerheid en statistische schattingen van *epistemische* onzekerheid), 3) model vergelijking (vooral geschikt voor het verkennen van tegenstellingen tussen experts en onzekerheden op modelniveau), 4) vergelijking van modelresultaten met werkelijke ontwikkeling (in bepaalde mate geschikt voor alle vormen van onzekerheid) en 5) kwalitatieve uitspraken van onzekerheid zoals in de NUSAP methode (zoals een kwalificatie als 'grote mate van onenigheid onder experts'; geschikt voor minder goed te kwantificeren vormen van onzekerheid).

De verschillende vormen van onzekerheid spelen in de tijd ook een verschillende rol. De meer kwalitatieve en fundamentele onzekerheden (ook wel aangeduid met 'onwetendheid' of 'diepe onzekerheid') worden verder vooruit in de tijd steeds belangrijker. Het belang van methoden die hiermee rekening kunnen houden, zoals alternatieve scenario's en kwalitatieve beoordelingen, neemt dan dus toe. Voor meer korte termijn verkenningen (5-30 jaar) spelen *ontische* onzekerheden en kwantitatief te schatten vormen van *epistemische* onzekerheid een belangrijkere rol. In dat geval is het eenvoudiger probabilistische verkenningen toe te passen. In de wetenschappelijke literatuur wordt een stevig debat gevoerd over dit onderwerp (in hoofdstuk 5 wordt dit debat samengevat). In dit debat geven tegenstanders van de alternatieve scenario methode aan dat deze door een gebrek aan waarschijnlijkheidsaanduiding weinig van nut is: beleidsmakers moeten immers niet alleen weten wat *kan* gebeuren – maar ook wat de *kans* daarop is. Tegelijkertijd is het commentaar op de probabilistische methoden dat deze proberen door middel met subjectieve meningen van deskundigen een schijnbaar objectieve onzekerheidsaanduiding te geven in een situatie waar onwetendheid dit eigenlijk niet toestaat.

2.2 Vergelijking van scenario uitkomsten met recentere inzichten

In hoofdstuk 3 worden de IPCC emissie scenario's (SRES) getoetst aan recentere inzichten, zowel wat betreft feitelijke ontwikkelingen als recentere toekomstschattingen. Deze scenario's zijn in 2000 gepubliceerd en omvatten een zeer lange tijdsperiode (1990-2100) om zo van nut te zijn voor klimaatmodellering. Sinds 2000 is er verschillende malen kritiek geuit op de SRES scenario's: zij zouden zowel onjuist als verouderd zijn. Een daadwerkelijke toets (zoals uitgevoerd in hoofdstuk 3) leidt tot de volgende conclusies:

- ***Samenvattend kan worden gesteld dat de SRES scenario's nog steeds consistent zijn met huidige inzichten van ontwikkeling van emissies en onderliggende drijvende***

krachten. Er zijn enkele verschillen (huidige inzichten tonen lagere populatie en inkomensprojecties in ontwikkelingslanden en lagere projecties voor zwavelemissies), maar over het algemeen zijn de SRES scenario's nog 'in orde' gebleken. Interessant is dat ook het onderliggende raamwerk nog steeds als relevant beschouwd wordt, gezien het gebruik hiervan in recentere verkenningen zoals de '*Millennium Ecosystem Assessment*'.

- ***Het is mogelijk scenario's te 'onderhouden' door updates op parameter niveau, totdat meer fundamentele veranderingen uiteindelijk de scenario's irrelevant maken.*** De beperkte verschillen betekenen dat op basis van de vergelijking zelf het niet echt noodzakelijk is de scenario's te herzien in een nieuwe IPCC exercitie. Individuele modelteams kunnen echter gemakkelijk de geconstateerde gebreken corrigeren (en hebben dit in bepaalde gevallen ook al gedaan). Interessant is te constateren dat deze lange termijn scenario's na 5-10 jaar de 'eerste scheurtjes vertonen'. Dit benadrukt nog eens dat dergelijke scenario's niet bedoeld zijn om te voorspellen, maar slechts dienen als verkenning binnen de context van gestelde (beleids)vragen.

2.3 Ontwikkeling van energiegebruik en broeikasgas emissies zonder klimaatbeleid

De mogelijke ontwikkeling van wereldenergiegebruik en broeikasgas emissies zonder klimaatbeleid is in dit proefschrift bestudeerd in hoofdstuk 5 en 6. De *conditioneel-probabilistische* scenario methode in hoofdstuk 5 maakt gebruik van probabilistische schattingen op parameter niveau binnen de context van op *verhaallijn-gebaseerde* scenario's. Zo kunnen de sterke kanten van de alternatieve scenario methode en de probabilistische methode worden gecombineerd. Een andere manier om inzicht te krijgen in onzekerheden is door model vergelijking. In hoofdstuk 6 is dit gedaan door te kijken naar een vergelijking van model uitkomsten in het kader van het Energy Modelling Forum (EMF), gericht op de rol van niet-CO_2 broeikasgassen. Daarbij moet worden bedacht dat tot nu toe de meeste lange termijn modellen alleen energie-gerelateerde CO_2 emissies bestudeerden, terwijl de overige bronnen zo'n 30-40% van de emissies beslaan. In de EMF-21 studie kregen alle modelleurs dezelfde informatie over de mogelijkheden om niet-CO_2 te reduceren. Deze informatie werd echter op verschillende manieren in het model verwerkt, vanwege verschillen in de modellen en (de wereldvisies van) de modelleurs.

Op basis van de toegepaste methoden kunnen de volgende conclusies worden getrokken:

- **De TIMER modelberekeningen geven aan dat zonder klimaatbeleid emissies van CO_2 waarschijnlijk sterk toe zullen nemen. De verhaallijn voor scenario's aan de onderkant van de range verschilt substantieel van die in het midden of aan de bovenkant van de range.** Afhankelijk van de verhaallijn kunnen emissies zich in sterk verschillende richtingen ontwikkelen (met name het 'duurzame ontwikkelingspad' B1 wijkt fundamenteel af). De gevonden ranges in dit proefschrift komen overeen met de IPCC SRES scenario studie maar ook met de probabilistische studie van Webster et al. (2002). Ten opzichte van IPCC voegt de huidige studie onzekerheidsranges toe, terwijl ten opzichte van Webster et al. een kwalificatie mogelijk is van het soort scenario's binnen de totale range. Een vergelijking met de totale literatuurrange laat zien dat de hoogste concentratie uitkomsten overeenkomt met de range die hier is aangeduid voor het B2 scenario.

- **Emissies voor een eenduidige verhaallijn kunnen zeker nog 40% afwijken.** De onzekerheidsranges voor ieder van de verhaallijnen komen voort uit *ontische* onzekerheid en ambigue aanduiding in iedere verhaallijn. De belangrijkste parameters die op modelniveau bijdragen aan onzekerheid zijn populatie en inkomensontwikkeling, factoren die de energie-efficiënte van energievraag bepalen, voorkeuren voor brandstoffen (met name de rol van kolen) en olievoorraden (zie 5.3). Andere belangrijke factoren zijn technologie-aannamen voor hernieuwbare energie en voor energievraag.
- **In de modelvergelijking blijkt dat alle modellen in hun 'baseline' scenario (zonder klimaatbeleid) een sterke groei van emissies van zowel CO_2 als niet-CO_2 broeikasgassen laten zien.** Gemiddeld over alle modellen groeien de emissies van CO_2 van 7.5 GtC in 2000 naar ongeveer 20 GtC in 2100. De emissies van de niet-CO_2 gassen groeien iets langzamer van 2.7 naar 5.1 GtC in 2100.
- **Er is een zeer sterke spreiding tussen de projecties van de verschillende modellen, in de orde van grootte als eerder gevonden voor het TIMER model.** De spreiding in 2100 emissies is 14 tot 36 GtC (of wel de gemiddelde groei is 1.1% over de hele eeuw, maar ligt tussen de 0.8 en 1.3%). Het grootste deel van deze spreiding komt pas tot stand in de 2^e helft van de eeuw waar sommige modellen doorgroeiende emissies tonen, terwijl andere modellen een stabilisatie of zelfs een afname laten zien. Ook de emissies van de niet-CO_2 gassen tonen een behoorlijke spreiding. Modellen met een meer fysieke oriëntatie lijken meer verzadiging in groei te tonen dan de meer economisch georiënteerde modellen.

Een cruciale onzekerheid voor de wereldwijde uitstoot van broeikasgassen zijn de ontwikkelingen in China. Ten gevolge van de grote bevolking en de stormachtige ontwikkeling van de economie is het waarschijnlijk dat China zeer binnenkort de VS passeert als werelds grootste land in termen van broeikasgasemissies. Hoewel de emissies per hoofd sterk beneden het gemiddelde OECD niveau liggen, heeft het absolute emissieniveau belangrijke consequenties voor zowel klimaatverandering als mondiaal klimaatbeleid. In dit proefschrift is de alternatieve scenario methode toegepast om – samen met Chinese experts – 4 alternatieve scenario's te ontwikkelen voor het Chinese energiegebruik en bijbehorende emissies. Hieruit bleek het volgende:

- **Emissies in China zouden in de komende vijftig jaren nog eens met een factor 2-4 toe kunnen nemen op basis van vier zeer verschillende scenario's.** Cruciale onzekerheden hierbij zijn de openheid van de Chinese economie voor internationale handel en investeringen en een eventuele focus op duurzame ontwikkeling. Het is interessant om de mogelijke Chinese ontwikkelingen te relateren aan de positie van Japan en de VS. Ontwikkeling richting het patroon van de VS leidt tot het hoge emissie scenario en betekent dat de emissies van China alleen hoger uitkomen dan de huidige wereldemissies. Ontwikkeling naar Japanse patronen betekent dat emissies een factor 2 lager kunnen zijn. De sterkste groeiende sectoren (in termen van emissies) in China zijn in absolute termen electriciteitsproductie, de industrie en op de lange duur transport.

3. Scenarios met drastische reductie van broeikasgasemissies

3.1 Geïntegreerde analyse

Ondanks het feit dat een groot aantal scenario's zijn ontwikkeld die kijken naar de vraag hoe emissies kunnen worden beperkt, zijn er slechts zeer weinig die kijken naar de vraag of en hoe zeer lage concentratieniveau's (minder dan 550 ppm CO_2-eq.) kunnen worden bereikt. Een dergelijk niveau is noodzakelijk om met meer dan 50% kans de EU klimaatdoelstelling te halen . Het gebrek aan scenario's vormt een belangrijke kennis lacune voor de vraag of dergelijke doelstellingen te verwezenlijken zijn. In dit proefschrift worden dergelijke scenario's wel bestudeert (hoofdstuk 7). Daarnaast wordt specifiek aandacht besteed aan de rol van technologie (hoofdstuk 8), de nevenvoordelen van klimaatbeleid voor beleid inzake luchtverontreiniging (hoofdstuk 9) en de reductie mogelijkheden van broeikasgasemissies in China (hoofdstuk 4). De scenario's zijn gemaakt door middel van gekoppelde modellen voor energie (TIMER), landgebruik en klimaat (IMAGE) en klimaatbeleid (FAIR).

- **Er zijn forse emissiereducties nodig om broeikasgasconcentraties te stabiliseren op 650, 550 en 450 CO_2-eq. Ten opzichte van de baseline gaat het om een reductie van 65, 80 en 90% in 2100. De studie laat zien dat dit technisch mogelijk is op basis van bekende technieken. Onder specifieke aannamen is ook 400 ppm CO_2-eq. mogelijk.** Het 400 ppm niveau ligt alleen binnen bereik in het TIMER model indien de optie van bio-energie in combinatie met 'koolstofopvang en opslag' wordt toegestaan (waardoor een optie ontstaat die netto CO_2 kan aan de atmosfeer kan onttrekken bij elektriciteitsgeneratie).
- **Optimale reductiestrategieën bestaan uit een brede portfolio aan maatregelen.** Met andere woorden, er is niet één enkele technologie waarmee de gewenste reductie gehaald kan worden. Wel spelen bepaalde maatregelen, zoals energiebesparing, een voorname rol. Ook 'afvang en opslag van CO_2' is onder de standaard aannames belangrijk. Deze technologie kan echter tegen beperkte extra kosten worden vervangen door andere CO_2-neutrale manieren van elektriciteitsopwekking.
- **De concentratie doelstelling kan worden gezien als een 'trade-off' tussen kosten en klimaatbaten.** De kosten van klimaatbeleid nemen gemeten in termen van de netto constante waarde over de eeuw toe van 0.2% tot 1.1% van het wereld BNP wanneer het stabilisatieniveau wordt aangescherpt van 650 tot 450 ppm. Daarbij neemt de geschatte waarschijnlijkheid om de 2°C doelstelling te halen toe van 0-10% tot 20-70%.
- **De noodzakelijke reducties vereisen zeer sterke veranderingen in het energiesysteem – en hieraan gekoppeld grootschalige investeringen in nieuwe technologieën.** In het meest ambitieuze scenario is het tempo van introductie van

nieuwe technologieën in relatieve termen vergelijkbaar met grootschalige transities uit het verleden (bijvoorbeeld de introductie van olie). Omdat het totale energiegebruik in de toekomst veel groter is, gaat het in absolute hoeveelheden om een veel grotere verandering. Dit kan ook worden geïllustreerd aan de hand van de ratio tussen CO_2 emissies en energiegebruikkoolstoffactor. Deze ratio is de afgelopen 100 jaar eerst toegenomen en de laatste 30 jaar stabiel. Elk van de hier doorberekende scenario's vereist een zeer forse daling van deze ratio. Ook voor de verhouding tussen energiegebruik en inkomen geldt dat deze (tijdelijk) sneller moet verbeteren dan historisch het geval. Daarbij komt dat deze ontwikkelingen al op korte termijn (voor 2020) moeten worden ingezet. Omdat dit de betrokkenheid vereist van een groot aantal actoren met zeer uiteenlopende belangen, is het vereist dat er een gevoel van noodzaak en urgentie ontstaat.

- **Onzekerheden spelen een cruciale rol.** Voor een gegeven ontwikkeling van emissies zonder klimaatbeleid en concentratiedoelstelling kunnen kosten nog steeds met minstens een factor 2 variëren als gevolg van ondermeer onzekerheden met betrekking tot landgebruikemissies, het potentieel van bio-energie en de bijdrage van energiebesparing. Gezien de dominantie van onzekerheden is het dus van belang om strategieën te ontwikkelingen die enigszins robuust zijn.

3.2 De rol van technologie-aannamen

Technologische ontwikkeling is noodzakelijk om forse emissiereducties betaalbaar te maken. Om een beeld te krijgen van de invloed hiervan is in hoofdstuk 8 een analyse gemaakt van de reactie van het energiesysteem op verschillende koolstofprijzen. Hieruit blijkt dat:

- **Technologische ontwikkeling speelt een cruciale rol bij het verlagen van de kosten van klimaatbeleid.** Onderscheid moet worden gemaakt tussen de standaard technologische ontwikkeling zonder klimaatbeleid ('*baselin*e') en die specifiek *geïnduceerd* door klimaatbeleid. In het TIMER model worden beiden gerepresenteerd door '*learning-by-doing*' (een beschrijving waarbij de kosten van een technologie afnemen wanneer deze veel wordt toegepast). In model experimenten kan getoond worden dat '*baseline ontwikkeling*' er voor zorgt dat de response op 300US$/tC tax in 2030 toeneemt van een reductie van 30% tot 40% (wereldemissies), terwijl '*klimaatbeleid geïnduceerde*' ontwikkeling dit verder vergroot tot 60%. Het ondersteunen van technologische ontwikkeling is belangrijk en kan ondermeer door het creëren van niche markten om zo ontwikkeling te bevorderen en het ondersteunen van onderzoek.
- **Model aannamen over de twee vormen van technologische ontwikkeling zijn cruciaal in de keuze tussen 'vroeg' en 'laat' klimaatbeleid.** '*Baseline technologische ontwikkeling*' kan een reden zijn om beleid uit te stellen (technologie wordt vanzelf goedkoper in de tijd), terwijl '*klimaatbeleid geïnduceerd leren*' juist een reden is om vroeg te beginnen (om technologisch ontwikkeling tijdig te bevorderen). Onder de standaard model aannamen lijkt het erop dat beide factoren rond 2030 van vergelijkbare grootte zijn.

3.3 Neven-voordelen van klimaatbeleid

Een geïntegreerde benadering van klimaatbeleid en regionale luchtverontreining kan tot behoorlijke 'nevenvoordelen' leiden voor zowel effectiviteit als kosten. De reden hiervoor is dat beide milieuproblemen in belangrijke mate dezelfde oorzaak hebben: de verbranding van fossiele brandstoffen. Het meewegen van de baten van het beperken van luchtverontreiniging kan extra belangrijk zijn omdat deze onmiddellijk optreden, terwijl de voordelen van klimaatbeleid vaak pas decennia later belangrijk worden. In hoofdstuk 9 is gekeken hoe groot de nevenvoordelen kunnen zijn van het Kyoto Protocol (als voorbeeld van klimaatbeleid). De analyse laat zien dat:

- **De nevenvoordelen van het Kyoto Protocol zijn in de orde van 50% van de kosten.** Terwijl de jaarlijkse kosten van het Kyoto Protocol worden geschat op 4-12 miljard Euro zijn de bijhorende besparingen in termen van luchtverontreiningsbeleid in de orde van 2.5-7 miljard. De grootte van deze nevenvoordelen hangt af van hoe de handelsmechanismes uit het Kyoto Protocol worden gebruikt.

3.4 Niet-CO_2 gassen.

Wat betreft reductie scenario's met betrekking tot niet-CO_2 gassen kunnen de volgende conclusies worden getrokken (hoofdstuk 4):

- **Een strategie gericht op alle broeikasgassen kan dezelfde klimaatdoelstelling bereiken als een CO_2-alleen strategie, maar tegen veel lagere kosten.** De kosten reductie ligt voor de meeste modellen in de orde van 30-40% van de GDP verliezen van een CO_2-alleen strategie.
- **Om een multi-gas strategie mogelijk te maken zijn meetlatten nodig die een afweging tussen de verschillende gassen mogelijk maken. Keuze voor een meetlat bepaalt de resultaten van een multi-gas strategie.** In het huidige klimaatbeleid wordt als meetlat de 100-jaar gemiddelde Global Warming Potential (GWP) gebruikt. EMF-21 resultaten laten zien dat in dat geval er een sterke bijdrage van vooral methaan zal zijn aan de emissiereductie. Een alternatieve benadering, toepasbaar binnen modellen, is optimalisatie over de tijd. In dat geval worden reducties van CH_4 uitgesteld tot het einde van de eeuw (vanwege de beperkte levensduur). Hoewel optimalisatie tot iets lagere kosten leidt is de vraag of deze methode ook kan worden toegepast in de werkelijkheid. Het lijkt dan ook dat de voordelen van gebruik van GWPs opwegen tegen de nadelen.

3.5 China

In hoofdstuk 4 is ook gekeken naar reductie mogelijkheden in China door middel van reductie scenario's. Deze leiden tot de volgende resultaten:

- **Door alle opties in het TIMER model te combineren is het mogelijk de emissies in 2050 met 50% te reduceren ten opzichte van de baseline.** In China bestaat een groot potentieel aan emissiereductie opties – ondermeer in de vorm van energiebesparing en maatregelen in de electriciteitssector. Reducties in China zijn vaak goedkoper dan de reducties in OECD landen. Analyse toont aan dat bovengenoemd

potentieel gedeeltelijk ook kan worden benut door andere vormen van beleid dan klimaatbeleid.
- **Voorstellen voor klimaatbeleid moeten ook worden geëvalueerd tegen de scenario verhaallijn.** In scenario-analyse wordt vaak veel aandacht besteed aan de verhaallijn bij het uitwerken van de baseline, maar wordt bij mitigatie analyse slechts gewerkt met een enkele generieke maatregel: een koolstof belasting. In werkelijkheid hangt de voorkeur van bepaalde opties wel degelijk af van de verhaallijn (denk aan de rol van nucleaire energie).

4. Discussie en volgende stappen

Discussie ten aanzien van de belangrijkste conclusies

Uit de analyse in dit proefschrift komen 3 kernboodschappen naar voren:
- De scenario's zonder klimaatbeleid leiden, ondanks sterk verschillende aannamen, allen tot een sterke toename van broeikasgasemissies en daardoor een waarschijnlijke toename van de mondiale temperatuur (in 2100 in de orde van 3-4°C bij een gemiddelde klimaatgevoeligheid).
- Het is mogelijk om de emissies sterk te reduceren zodat broeikasgasconcentraties kunnen worden gestabiliseerd op 450 ppm CO_2-eq. Dit niveau komt overeen met ongeveer een 50% kans op het halen van de 2°C doelstelling. De kosten hiervan liggen in het energiemodel gemiddeld op zo'n 1-2% van het GDP.
- Cruciale factoren bij het vergroten van de realiteit van ambitieuze klimaatbeleid scenario's zijn de integratie van klimaatbeleid met andere beleidsterreinen (luchtverontreiniging, voorzieningszekerheid, en duurzame ontwikkeling), technologische ontwikkeling en het creëren van een gevoel van noodzaak.

Een belangrijke vraag is of deze model resultaten voldoende robuust zijn. In dat kader moet worden overwogen dat: a) het TIMER model is gekalibreerd tegen 30 jaar energiegebruik gegevens en veel informatie bevat over technologische ontwikkeling, b) er in dit proefschrift veel aandacht aan onzekerheids- en gevoeligheidsanalyse is besteedt en c) de vergelijking met andere studies laat zien dat zowel de emissie scenario's en kostenberekeningen hiermee consistent zijn. De bovenstaande kernboodschappen kunnen dan ook als robuust worden beschouwd. Desondanks zijn er ook beperkingen aan de analyse:
- Net als de andere energiemodellen heeft TIMER relatief weinig detail in de beschrijving van energie-vraag. Verbetering is hier mogelijk.
- Technologische ontwikkeling is zeer onzeker. Dit kan leiden tot zowel een over- als onderschatting van het werkelijke reductiepotentieel.
- Als kosten indicator wordt in dit proefschrift naar bestrijdingskosten gekeken. Hierin worden macro-economische feedbacks niet meegenomen.
- De onderzochte scenario's gaan uit van een verrassingsvrije wereld en nemen klimaatterugkoppelingen op de drijvende krachten niet mee.

- Het modelleren van energie-klimaat scenario's leidt tot een focus op economische en technologische elementen. Dit komt ondermeer tot uiting in slechts een beperkte aandacht voor implementatie. Er wordt bijvoorbeeld niet ingegaan op het feit dat de ontwikkelingen in het energiesysteem worden bepaald door een groot aantal actoren met zeer uiteenlopende belangen.

Belangrijke stappen vooruit

Gebaseerd op dit werk, is er nog behoorlijk wat progressie mogelijk. Hier worden een aantal mogelijkheden kort aangegeven, ingedeeld onder 1) scenario ontwikkeling, 2) model ontwikkeling en 3) model toepassing.

Scenario ontwikkeling

- Op dit moment bestaat een duidelijke tweedeling tussen 'baseline' scenario's (zonder klimaatbeleid) en beleidsscenario's. Door de huidige ontwikkeling van klimaatbeleid wordt dit verschil echter steeds moeilijker te maken – en mogelijk ook minder relevant. In plaats daarvan kan worden gewerkt met een continuüm van bestaand beleid tot aangescherpt beleid.
- Met toenemende aandacht voor, en kennis over klimaatgevolgen en aanpassingsmogelijkheden zouden terugkoppelingen van klimaat op scenario aannamen in een volgende generatie scenario's beter moeten worden meegenomen.
- Beleidsscenario's worden op dit moment vooral gemaakt door in een model een uniforme koolstofbelasting te introduceren als ruwe indicatie van een breder beleid. Beleidsrelevantie van scenario's kan worden verhoogd door in te gaan op de mogelijke beleidsinstrumenten. Dit vereist echter meer gedetailleerde modellen.
- Tenslotte, scenario's worden ontwikkeld op basis van karikaturale verhaallijnen die over lange tijd worden volgehouden. In werkelijkheid zullen er verrassingen zijn en reacties op de verhaallijn. In hoeverre dergelijke zaken kunnen worden ingebouwd in scenario's zonder deze ondoorzichtig te maken is nog een open vraag.

Model ontwikkeling

Het TIMER model dat als basis dient van veel werk in dit proefschrift heeft 3 unieke eigenschappen: 1) een sterke focus op lange termijn (technologie) dynamiek, 2) de koppeling aan het IMAGE integrated assessment model, en 3) de koppeling met FAIR en dus internationaal klimaatbeleid. In termen van verdere model ontwikkeling lijken de volgende opties nuttig:

- Verdere focus op geografisch expliciete processen. Hierbij gaat het vooral om het weergegeven van relevante processen die plaats vinden op een gedetailleerder schaalniveau (en dus een meer gedetailleerde beschrijving vereisen). Dit betreft ondermeer plattelands en stedelijke ontwikkeling, en het meenemen van geografisch expliciete factoren in energievraag.
- Het is belangrijk om de ontwikkeling van de energie-vraag beter te begrijpen. Dit vereist ondermeer een beter begrip van de ontwikkeling van de drijvende krachten van de energievraag in fysieke termen en een verbeterde beschrijving van besparingsmogelijkheden.

Model toepassing

Er zijn 2 wegen open om beleidsvorming en -implementatie (en sociaal wetenschappelijk onderwerpen in bredere zin) beter mee te nemen in energie/klimaat scenario's:

- Het uitbreiden van de modellen met expliciete modellering van deze onderwerpen, ondermeer door multi-actor benaderingen
- Het gebruik van modellen in een context die terugkoppeling van belanghebbenden en beleidsmakers toestaat.

Op dit moment gaat het eerste pad vooral om onderzoek, gericht op niet al te complexe modellen. Wat betreft het tweede pad zijn er zeer succesvolle voorbeelden uit het verleden beschikbaar – zowel op het gebied van klimaatbeleid (de Delft en COOL workshops) en daarbuiten (het gebruik van het RAINS model binnen het beleid). Natuurlijk bestaan er tussen deze voorbeelden grote verschillen, maar er mag worden gesteld dat elk van de genoemde interactieve processen heeft geleid tot een beter begrip van beleidsmakers, analisten en modelleurs in de relevante vragen en uitkomsten. Dergelijke kennis zou wel eens zeer belangrijk kunnen zijn in de komende, cruciale periode, waar in het internationaal klimaatbeleid vorm krijgt.

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the attention you deserve. Hopefully, things will normalize a bit now – and can I see a bit more of you at badminton, game evenings or other social events. With respect to my family, Mam, Dad, Aico and Natilja, many thanks for all your support at various times in the past. In fact, that also goes for you, Tjeerd and Ankie. My thoughts obviously also go out to you, Petra and Mette, my two “lovely ladies” at home. We have had anything but dull moments lately... with PhD and job projects and our other recent undertakings. Petra –it has not always been easy to keep pace with your academic level, but I hope to have made a small step in this direction. Mette – many chapters in this book discuss the next 100 years – and as I have shown in one of the chapters – futures tend to change a lot. While I could check the first 10 years of some of the scenarios, I hope you can check how close we have come in our projections over a longer period of time: let’s be hopeful that the future you will experience will be closer to the low climate change scenarios of our analysis than to the high ones, keeping this world a worthwhile place to live in. But until you reach an age that this book might interest you a bit, I will just carry on reading bedtime stories to you from Nijntje.

CURRICULUM VITAE

Detlef van Vuuren was born on 21 December 1970 in Beverwijk. In 1989 he graduated from Berlingh secondary school. In that same year, he started his studies in Chemistry at Utrecht University (UU). As part of this study, he followed courses in Energy and Sustainable Development at the UU's Department of Science, Technology and Society, receiving his MSc in 1995 with a dissertation on modeling trends in world metal use (*c.l.*). In 1991 he enrolled for MSc studies in Environmental Sciences, also at Utrecht University. As part of this study, he followed courses in environmental management and environmental system analysis, graduating in 1995, with a dissertation on the treatment of polluted sediment (*c.l*). In the meantime (1991) Detlef had also qualified for his "propedeuse" examination (first year) (*c.l.*) in Public Administration at Leiden University.

In 1995, he took up a position as researcher in the Department of Science, Technology and Society at Utrecht University, specializing in bottom-up analysis of energy end-use efficiency. In 1996, he joined the National Institute for Public Health and the Environment (RIVM) to work as researcher and coordinator of a project on indicators of sustainable development within the Division of International Cooperation. In 2000, he moved to the Division of Environmental Assessment and joined the IMAGE Integrated Assessment team. His focus within that team was on modeling long-term trends in world energy use in relation to global environmental problems, and on scenario development. Since then, he has continued to work within this field, both as researcher and project manager, publishing over 35 papers in scientific peer-reviewed journals. Early 2006, his position was brought under the Netherlands Environmental Assessment Agency (MNP), when the Division of Environmental Assessment separated from RIVM.

Detlef van Vuuren has participated in several international projects in different capacities: for example, as Coordinating Lead Author in the Millennium Ecosystem Assessment (MA) and as Lead Author in United Nations' Global Environmental Outlook (GEO). He is currently Coordinating Lead Author in the World Bank-led International Assessment of Agricultural Science and Technology Development, and Lead Author in the Fourth Assessment of Intergovernmental Panel on Climate Change (IPCC). In addition, he has participated in projects for the European Environment Agency and the European Commission. Since 2001, he has also participated in several projects of the Stanford University-based Energy Modeling Forum (EMF).

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Translation
Fokke and Sukke leak the next IPCC report to the press
“The Global Warming” “Is pretty much very, very likely caused by humans”

Cartoon published in Netherlands newspaper in response to
IPCC’s system of characterizing uncertanties.

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