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

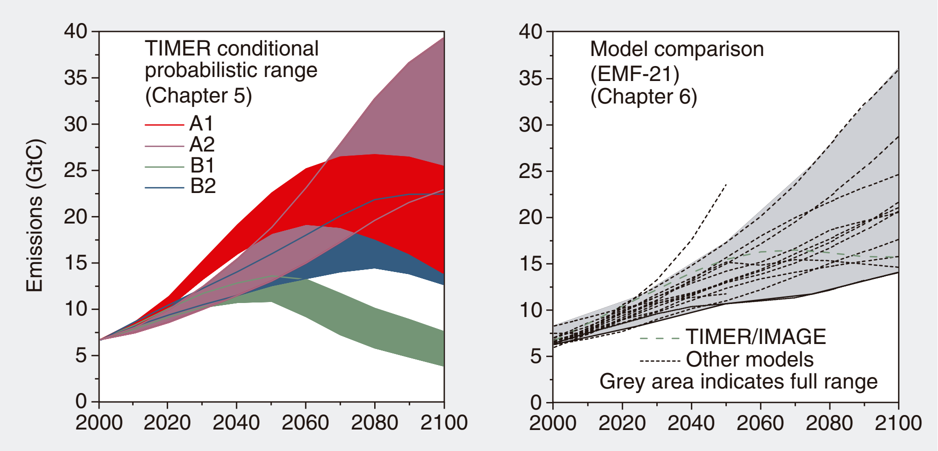

Figure 10.1 World CO_2 emission scenarios in the absence of climate policy.

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.

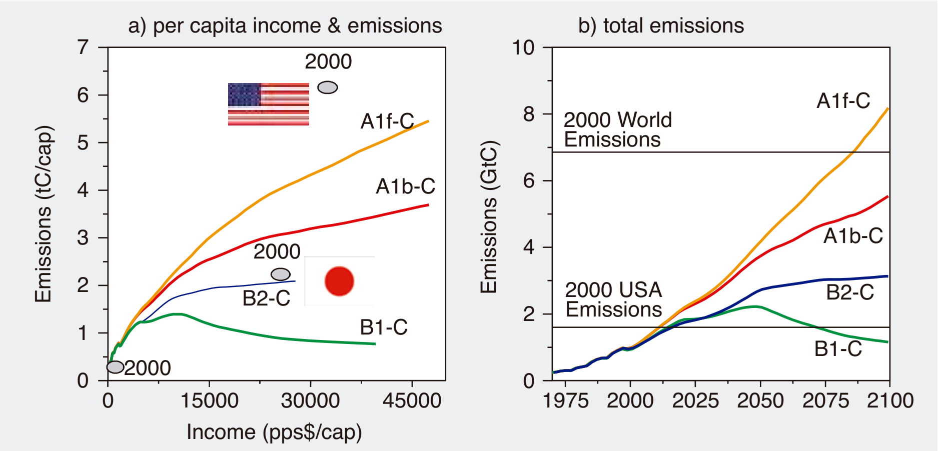

Figure 10.2 Trends in income, per capita emissions and total emissions in China according to the scenarios discussed in Chapter 4. The flag markers indicate the position of USA and Japan in the year 2000.

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.

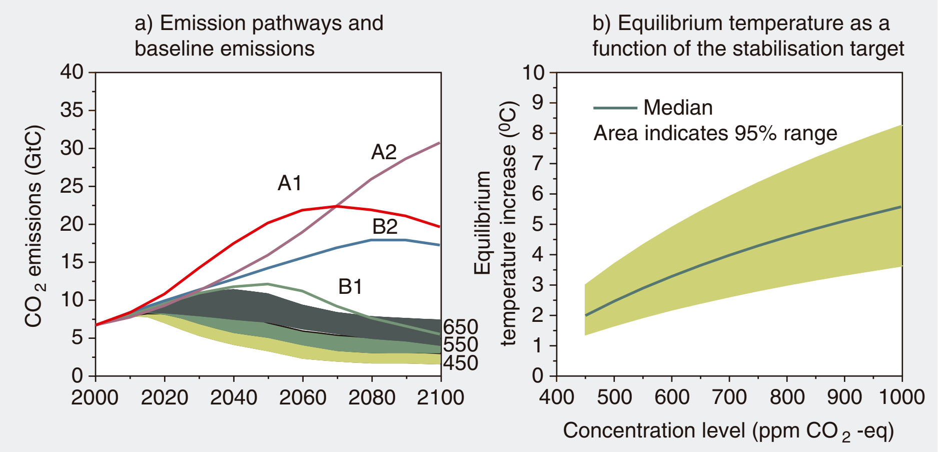

Figure 10.3 Emission pathways leading to stabilization of greenhouse gases at 450, 550 and 650 ppm CO_2-eq compared to emission trends in scenarios without climate policy (mean values of the ranges indicated in Figure 10.2). The right-hand figure shows the likely equilibrium temperature change associated 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

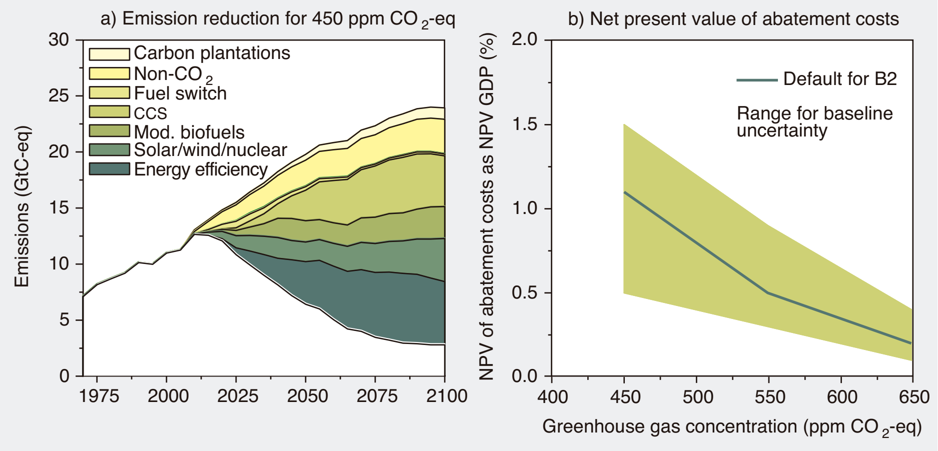

Figure 10.4 Contribution of various options in reducing greenhouse gas emissions from baseline to the 450 ppm CO_2-eq scenario (left-hand) and the costs associated with stabilizing greenhouse gas concentrations (net present value of abatement costs at 5% discount rate as percentage of GDP) (right-hand 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.

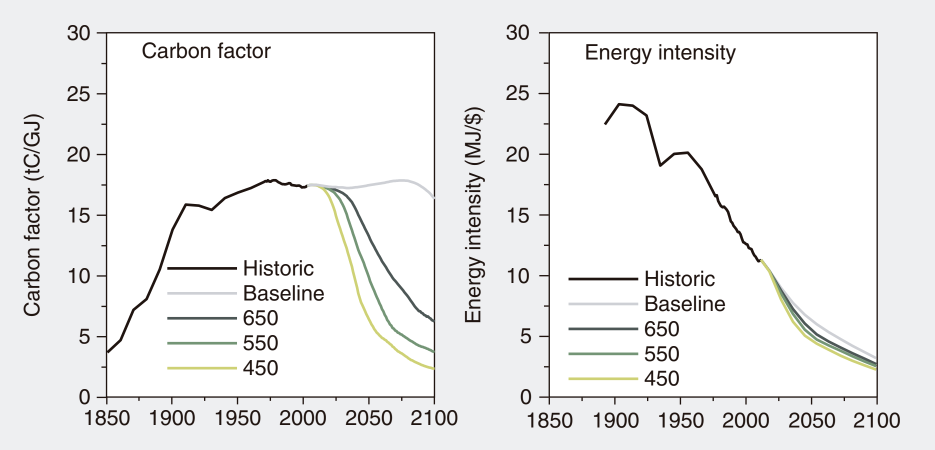

Figure 10.5: Historical development of the carbon factor and energy intensity in the B2 baseline scenario and under the 450, 550 and 650 ppm CO_2-eq stabilization scenarios.

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.