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.

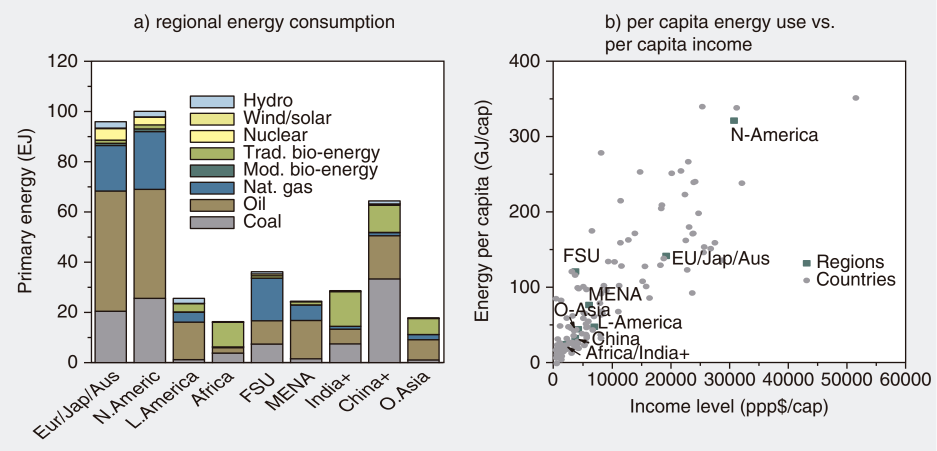

Figure 1.1 Regional differentiation in primary energy use. Primary energy use by energy carrier (a) and the relationship between per capita income and per capita energy use (b). (IEA, 2003b; WorldBank, 2006) (FSU = Former Soviet Union; MENA = Middle East and North Africa).

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

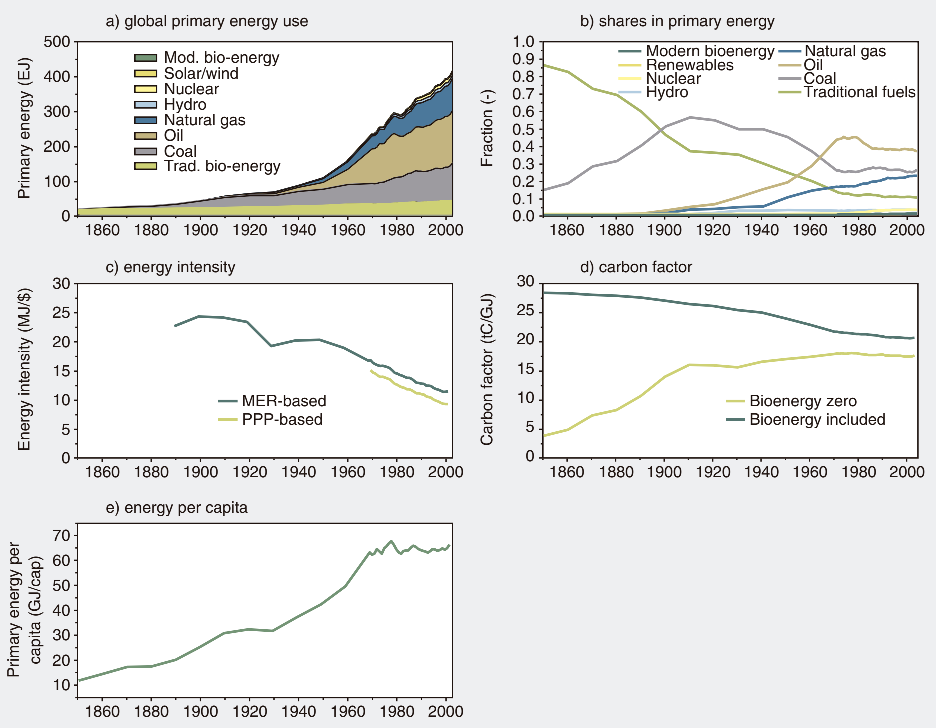

Figure 1.2 Long-term trends in the global energy system (1850-2005). Primary energy consumption by energy carrier (a), fraction of energy carriers in total consumption (b), energy intensity and per capita consumption (c) the carbon content of fuels and (d) (Grübler et al., 1995; IEA, 2006b).

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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.

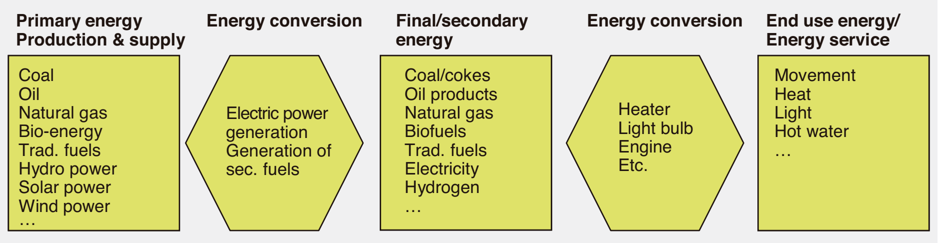

Figure 1.3 Representation of the energy system, moving from primary energy production to end-use energy.

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)

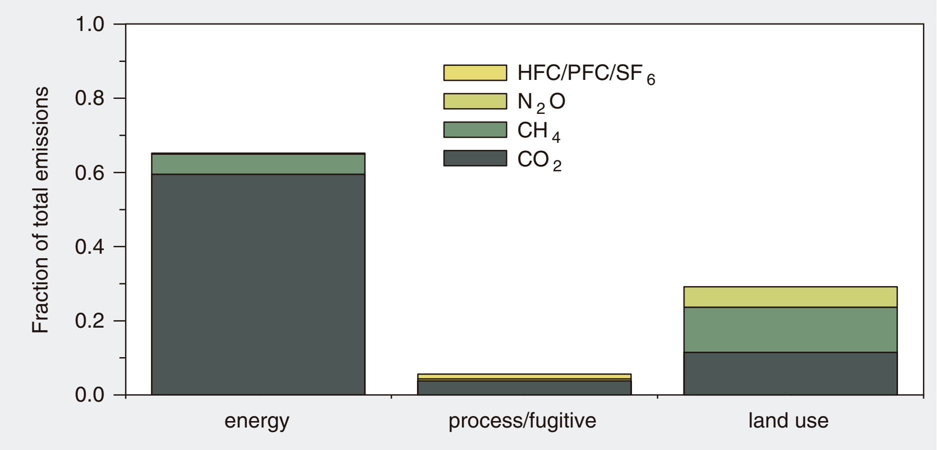

Figure 1.4 Contribution to greenhouse gas emissions (measured as CO_2-equivalents using 100-year GWPs) in 2000 (IMAGE-team, 2001) (the category of process and fugitive emission include, for instance, CO_2 emissions from cement production, CH_4 emissions from steel production and emissions of halogenated 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_2O), 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.

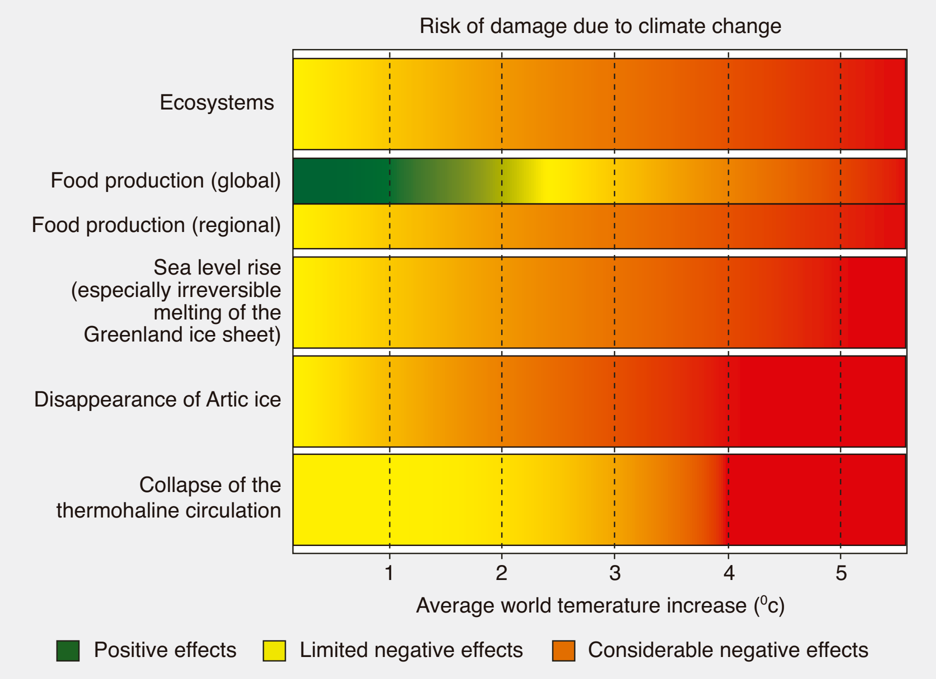

Figure 1.5 Potential impacts of climate change as a function of the increase in global mean temperature compared to pre-industrial levels according to MNP, as based on an earlier assessment in IPCC's Third Assessment Report (IPCC, 2001; MNP, 2005a).

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

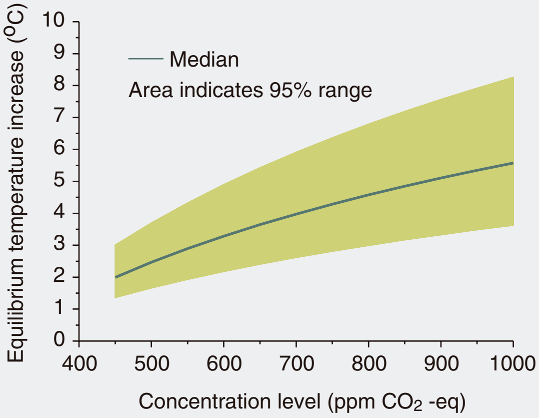

Figure 1.6 Relationship between greenhouse gas concentrations and temperature change at equilibrium (IPCC, 2007) The ranges indicate the 95% probability interval.

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

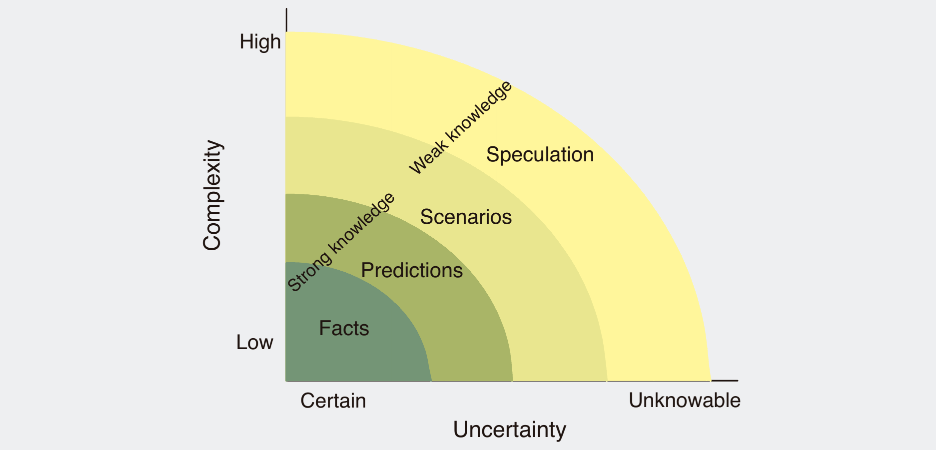

Figure 1.7 Different methods to assess the future in relation to uncertainty and system complexity (based on (Zurek and Henrichs, 2006)).

[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.

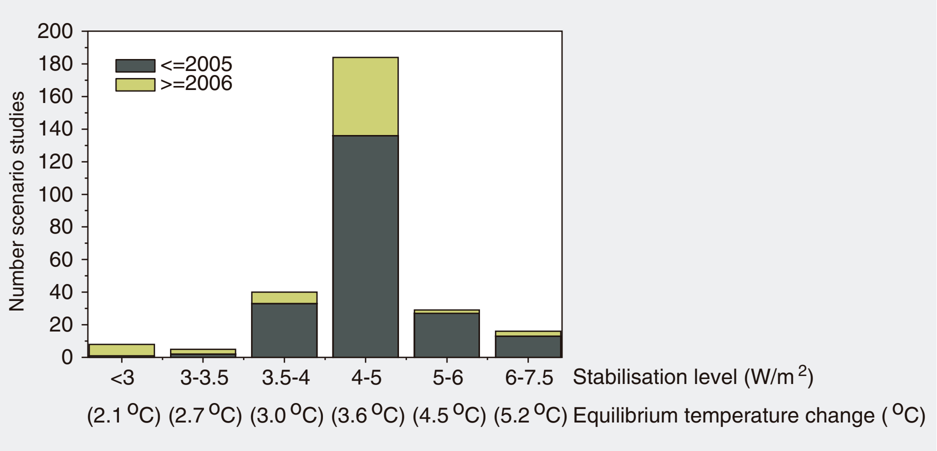

Figure 1.8 Distribution of long-term stabilization scenarios in the literature included in the emissions database (Hanaoka et al., 2006; Nakicenovic et al., 2006). The red column indicates the situation before 2006, and the purple column points to publications in 2006 where two major model intercomparison 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.