Energy and Development
A Modelling Approach

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Energy and Development – A Modelling Approach

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Energy and Development
A Modelling Approach

Energie en Ontwikkeling – Een Modelbenadering

(met een samenvatting in het Nederlands)

Proefschrift

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'Life can only be understood backward, but it must be lived forward'
Søren Aabye Kierkegaard

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Contents

Chapter 1: Introduction

1 Energy and Development

1.1 Urgency and understanding

The consumption and production of energy worldwide plays a major role in several sustainability problems. For example, CO_2 emissions from fossil energy combustion form the main cause of anthropogenic climate change (IPCC, 2007a). Emissions from combustion of both fossil fuels and traditional biomass are also major sources of regional, urban and indoor air pollution. Moreover, depletion of energy resources (especially oil) could limit development options, among others by increasing energy prices, reducing the affordability of energy for future generations (Goldemberg, 2000b, 2004).

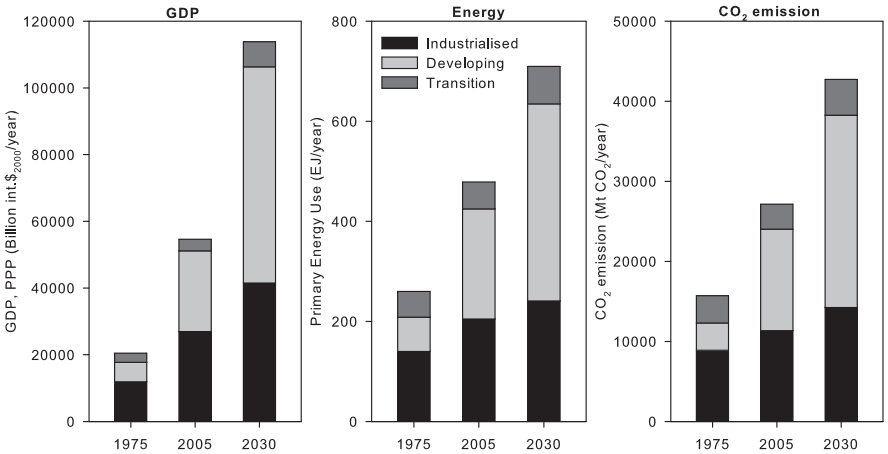

Figure 1.1: Total GDP, energy use and energy related CO_2 emission in Industrialised, Developing and Transition regions in 1975, 2005 and 2030. Historic data from IEA (2007a), future projections from TIMER OECD Environmental Outlook scenario (Bakkes et al., 2008; OECD, 2008).

Since the industrial revolution, global energy use has been dominated by energy consumption in industrialised countries[1]. Initially, energy use increased rapidly with the application of coal for industrial and domestic purposes; later, the energy mix became dominated by oil and natural gas (Smil, 2003). However, the global balance of energy use

[1] In this thesis, we define developing countries as all countries within the World Bank low income, lower-middle and upper-middle income groups, excluding the former Soviet regions and Central-European countries. Figure 1.1 is based on aggregation of countries to IMAGE model regions (see www.mnp.nl/image). Developed regions: Canada, USA, Western Europe, Japan, Oceania; Developing regions: Mexico and Other Central America, Brazil and Other South America, Northern Africa, Western Africa, Eastern Africa, South Africa and Other Southern Africa, Turkey, Middle East, India and other Southern Asia, Korea, China+, South-eastern Asia, Indonesia+; Transition regions: Former USSR (Russia+, Asia-Stan and Ukraine+) and Central Europe.

is changing rapidly. Industrialisation, improvement of living standards and population growth lead to rapidly increasing energy consumption in developing countries. In 1975, developing countries (with 73% of the world population) counted for only 26% of global energy consumption; in 2005 this had number increased to 46% (for 80% of the population, Figure 1.1). The major part of this increase took place in China, Korea, India and the Middle East. This changing balance of energy use influences global sustainability issues. The share of developing countries in global CO_2 emissions increased from 22% in 1975 to 47% in 2005 (Figure 1.1, right graphs). For the future, a further increasing share of developing countries is expected: the OECD Environmental Outlook projects a share 55% for developing countries in global CO_2 emissions for 2030 and states that Brazil, Russia, India and China (so-called BRIC countries) play key-roles for future successful environmental policy (Bakkes et al., 2008; OECD, 2008).

While at the aggregated level, developing countries become an increasingly important factor in global energy use, energy poverty also remains an important issue. At the moment, two billion people have no, or unreliable, access to modern energy forms like LPG and electricity (Goldemberg, 2000b). Indoor air pollution from traditional fuel combustion is still a major health concern for the poorest population groups (Holdren and Smith, 2000). In recent years, increasing energy prices put pressure on the affordability of energy for the poor and hamper the transition towards cleaner fuels (Essama-Nssah et al., 2007). In contrast to the situation in industrialised countries, where energy related sustainability problems refer to impacts of energy use (e.g. pollution or depletion), here, energy use is crucial to fulfil basic needs and increase welfare (Reddy, 1999; Reddy and Goldemberg, 1990). Hence, the energy policy agenda's of developing and industrialised countries diverge (Birol, 2007; Pandey, 2002). Development policies include measures like fuel-subsidies and electrification, whereas energy policies in industrialised regions focus on climate change and security of supply. In recent years, it is increasingly recognised that global climate policy can only be effective if it connects to the policy agenda of developing countries (Metz and Kok, 2008). This includes discussions on centralised fossil and nuclear power generation versus leapfrogging to decentralised renewable energy systems (Kok et al., 2004; Modi et al., 2005) and analysis of climate-benefits from sustainable development policies (Winkler et al., 2008).

Despite this increasing urgency, scientific understanding of the dynamics of energy use in developing countries is limited. Information and knowledge are fragmented over many local case-studies and experts. Global databases often have reliable data on issues important for industrialised countries (like CO_2 emissions) but lack data on energy poverty issues (like access to the electricity grid). In energy analysis, models are used to explore and understand possible future changes in energy systems on the local, regional and global scales. However, only few energy models account explicitly for the specific dynamics of developing countries. Most global energy models are developed in industrialised countries and implicitly assume that the future of developing countries can be derived from experiences in developed countries during the last decades. This has two major limitations. First of all, this hypothesis is not necessarily correct as these models assume the end-product of the development process and ignore the epoch during which multiple and

simultaneous transitions occur (Shukla et al., 2007). Secondly, it simply means that currently important energy issues in developing countries are not included in the models. The focus on energy systems from an industrialised world perspective implies that these models neither describe the transition from a traditional to a modern energy system explicitly nor provide information on issues that are currently important to developing countries. More concrete, these models assume full access to modern energy forms, increasing and equally distributed welfare levels, developed and reliable infrastructure. Moreover, they often ignore differences in market development, institutional arrangements and the existence of traditional economies and energy systems (Pandey, 2002; Shukla, 1995). Hence, future projections on energy use in developing countries could be unreliable and synergies between development and climate policies cannot be identified and addressed by current global energy models.

1.2 Major issues of energy and development

What are these differences between developed and developing regions and what is the relevance to global energy modelling? This question is explored in-depth in Chapter 2 of this dissertation. Major issues are: the transition towards commercial energy sources; access to modern energy forms; distribution of welfare; the informal sector and the changing context of development.

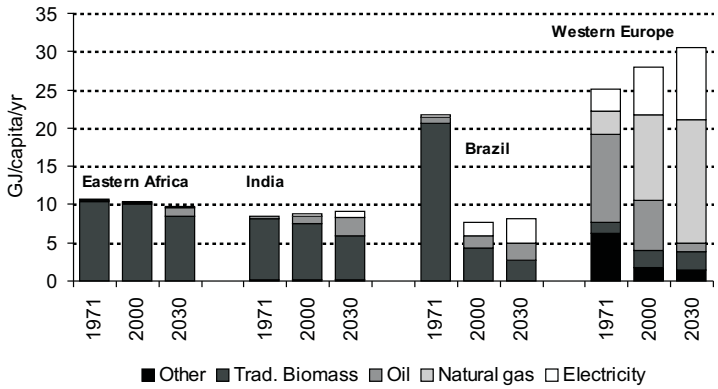

Figure 1.2: The energy ladder: residential sector final energy use per capita per year in several world regions. Generally, GDP per capita increases from left to right in this figure. 'Other' energy includes coal, modern biomass and direct heat. The historic rapid decrease of residential energy use in Brazil is discussed in detail in Chapter 5 of this thesis. Historic data from IEA (2005) and future projections from TIMER OECD Environmental Outlook scenario (Bakkes et al., 2008; OECD, 2008).

With respect to energy use, the energy transition in developing countries is often described in terms of 'climbing the energy ladder': from *traditional biomass* to the direct use of coal and oil, towards modern energy carriers, like electricity and natural gas (see Figure 1.2). This involves 1) the transition away from traditional, non-commercial fuels and 2) increased access to modern energy sources. Traditional fuels, such as fuelwood, dung, agricultural waste and charcoal, constitute a major source of energy in the developing

world[2]. Traditional biomass combustion causes indoor air pollution, leading to various adverse health effects and an estimated 1.6 million premature deaths per year (Niessen et al., 2008; WHO, 2006). However, only three of the six global energy models used in the IPCC Special Report on Emission Scenarios (SRES) (IPCC, 2000a) explicitly account for traditional fuel use and the transition to commercial energy carriers (van Ruijven et al., 2008b). In the year 2000, only 64% of the population of developing countries had *access to electricity* (IEA, 2002b). Access to other modern energy forms, like LPG or natural gas, is limited as well (Martins, 2005). For energy models that mostly assume unlimited substitution among energy carriers, this could mean that the rate of transition towards electricity and other modern energy carriers is easily overestimated (although this cannot be tested as the information is not available). Another issue is that, especially in residential energy use, major differences exist between urban and rural areas. In urban areas, electricity and LPG are predominant types of energy while rural areas depend more on traditional fuels (Goldemberg, 2000a; Reddy, 2000). Though the process of urbanisation is often incorporated in energy models (Urban et al., 2007), explicit modelling of rural and urban energy systems is rare (Shukla et al., 2007).

Developing countries tend to have a more *unequal income distribution* than developed regions. Often a situation exists of elites and poor masses. In such situation, the average income (or GDP per capita) provides a misleading image because energy use of low- and high income groups is considerably different. Hence, developments of income distribution influence the pattern of energy use. Another economic issue is the *informal economy*. This involves activities that also consume energy, but that are not reflected in official economic descriptions. This issue is also often referred to as 'dual economies', i.e. the parallel existence of modern and traditional economies (Shukla, 1995; Shukla et al., 2007). In general, developing economies have much larger informal sectors than developed regions (Chaudhuri et al., 2006; Kahn and Pfaff, 2000; Karanfil, 2008; Schneider, 2005). For energy analysis, this means that the reported economic activity is lower than the real economic activity. This complicates the relations between economic activity and energy use: energy intensity is easily overestimated and future economic projections could become unreliable.

The implicit assumption of many global energy models is that the future of developing regions can be derived from experiences in industrialised regions during the last decades. This ignores that the development-context of these regions is different from industrialised regions in the past century. Current energy prices are higher (partly as result of depletion) and hamper the early energy-intensive stages of economic growth in developing regions. Also, climate change had no impact on the development of energy systems in the past, neither in developed nor developing regions. However, since energy use is responsible for the majority of greenhouse gas emissions, the development of energy systems in developing countries has become part of a global commons problem. Similarly, other environmental problems (such as acid rain or indoor pollution) have become part of the energy agenda in a earlier stage of economic development. Other, and sometimes also positive, differences in

[2] In 2000, 52% of the total population of developing countries relied on traditional biomass as main source of energy for cooking and heating (IEA, 2002b).

the development context are the widespread availability of technologies for energy efficiency and energy production and conversion. For instance, the costs of renewable energy technologies are declining and efficiencies of electric power plants have improved enormously over the last decades.

In a more distant past, currently high-income countries have experienced also large (energy) transitions. Long-term energy-economic history might therefore provide insights that are useful to currently developing countries. For instance, the slowly ongoing transition from fuelwood to coal, oil and natural gas during the 19th and 20th century (Gales et al., 2007) or the long-term decreasing trend of energy intensity (Kander and Schon, 2007). However, these transitions took place in a different social-political context, with less economic interlinkages and less technologies and options for technology transfer. Hence, it is dangerous to infer that these transitions will be the same in current developing countries.

2 Modelling Energy and Development

2.1 Global Energy Models and Classifications

The use of mathematical models as abstractions of the real world stems originally from the fields of economics and military strategies (Benders, 1996). With the studies of the Club of Rome and the development of the World3 model (Meadows et al., 1972; Meadows et al., 2004) the use of models was introduced into the analysis of global environmental change (Kareiva et al., 2005). With expanding computational power during the last decades, many models on the interactions of economy, energy and environment have been developed from different scientific disciplines and paradigms. Overviews of the development of global energy models and integrated assessment models (IAMs) can be found in Dowlatabadi (1995), van der Sluijs (1997), Bakkes et al. (2000) or Kareiva et al. (2005). Several attempts have been made to classify these models; for instance to purpose and role, model structure, methodology or geographical and sectoral coverage (see e.g. Grubb et al., 1993; van Beeck, 1999; van Daalen et al., 2002; van Vuuren et al., 2006c; Weyant, 1996; Weyant, 1997). To indicate the position of the TIMER model, which plays a central role in this dissertation (see Section 4), we here provide an overview of global energy models and IAMs based on four methodological dimensions: the level of integration; the bottom-up, engineering approach versus the top-down, macro-economic approach; optimisation versus simulation models; and, fourth, data-based versus rule-based modelling.

A first classification of energy and IAM models can be based on the *level of integration*: distinguishing dedicated energy models, integrated assessment models (IAMs) and sustainable development models (Kareiva et al., 2005). The former focus on energy systems and their environmental impacts; examples are the RAINS model on regional acidification (Alcamo et al., 1990), the MESSAGE model (Nakicenovic et al., 1998; Riahi and Roehrl, 2000), the MARKAL model family (Loulou et al., 2004) and TIMER (de Vries et al., 2001; van Vuuren et al., 2006b). Integrated Assessment Models place the energy system in a wider context of global environmental change (in most cases climate change), adding dynamic model parts for the environmental system. TIMER, for instance, is part of the integrated assessment model IMAGE. Within the IAM group, two sub-groups can be

distinguished: the first group is rooted in economics and focuses on cost-benefit analysis of emission mitigation costs and climate damages; for instance DICE (Nordhaus, 1993), MERGE (Manne et al., 1995) or FUND (Tol, 1999). The second group of IAMs stems from natural sciences and system-dynamics, involving the larger context of the physical system, for instance IMAGE (Bouwman et al., 2006; IMAGE-team, 2001) and AIM (Kainuma et al., 2003). Sustainable development models have the highest level of integration of social, economic and environmental issues. Their goal is not only to describe environment-economy interactions but also how these interactions are rooted in broader development questions. Examples of such models are International Futures (IF's, see Hughes, 1999), TARGETS (Rotmans and de Vries, 1997), Polestar (Heaps et al., 1998) and GISMO (Hilderink et al., 2008).

The second classification distinguishes between *bottom-up* and *top-down* models. Classically, bottom-up models describe technologies in detail, but do not account for micro-economic decision-making and macro-economic system feedbacks. Examples of these models are AIM (Kainuma et al., 2003) and the MARKAL model family (Loulou et al., 2004) (for more examples and details see Worrell et al., 2004). Especially for developing countries, bottom-up models suggest many no-regret options from energy efficiency improvement. In practice, this potential is often not feasible, because of social, economic and legal barriers to the implementation of these technologies (Shukla, 1995). Top-down models, on the other hand, describe macro-economic structures in a consistent general equilibrium framework, with producer/consumer behavioural equations but aggregate factors for technology development. Examples of such models include MERGE (Manne et al., 1995) and WorldScan (CPB, 1999). With respect to developing countries, top-down models suffer from unrealistic assumptions about the existence of developed market conditions and (apparent) optimality of the present technology mix (Shukla, 1995). In recent years, the distinction between the approaches has been gradually reduced – and the strengths and weaknesses of both approaches are recognised; also, hybrid models have been developed (Hourcade et al., 2006). Nevertheless, many models can still be differentiated on the basis of these two approaches.

Third, there is a difference between *optimisation* and *simulation* models. Optimisation models aim to describe least-cost energy systems under a set of constraints; systems are in "equilibrium" (i.e. operated at the lowest over-all costs) from a centralised perspective. Simulation models describe the development of the energy systems with a pre-defined set of rules that do not necessarily require optimality. While the simulation approach may describe real world systems better, it may be at the cost of reduced transparency (van Vuuren, 2007). Both methods have shortcomings with respect to developing countries. Optimisation models assume perfect market conditions and adequate centralised decision-making; this may be invalid for low-income regions. Simulation models claim to be more realistic, but the relationships used are often from developed economies' data and experiences. Examples of optimisation models are the MARKAL family (Loulou et al., 2004), MESSAGE (Nakicenovic et al., 1998; Riahi and Roehrl, 2000) and GET (Azar et al., 2003); simulation models include POLES (Criqui and Kouvaritakis, 2000), CIMS

(Jaccard and Dennis, 2006; Tu et al., 2007) and TIMER (de Vries et al., 2001; van Vuuren et al., 2006b).

Finally, the fourth dimension is between *data-based* and *rule-based* models, which can be characterised by three stages. First, data-based modelling originates from econometrics and statistical data analysis. This modelling tradition approaches (parts of) the energy system as a black box, identifying correlations between variables without the development of a causal model. In its most concise form, these models exist of single-moment cross-country correlations between indicators. For example, energy use is found to correlate logarithmically with economic activity, the human development index (HDI) or child mortality (see e.g. Smil, 2003) – and hence such a metamodel is often used for energy use projections. More advanced studies use sophisticated regression models to analyse the correlation of many variables with energy use or energy choices. Second, the structure of most global model energy models and IAMs mentioned above is based on intuitive causal relations and rules, either in physical or in monetary terms. The explicit, quantitative implementation of these relations is often derived from econometric studies or extracted from many sources as 'stylized facts'[3]. Third, agent based models are based on behavioural rules that describe interactions between agents or their reaction on information. This type of models can hardly be quantified from data-analysis and focuses on the emergent properties of behavioural rules (see for instance Eriksson and Lindgren, 2005; Jager et al., 2000; Janssen and de Vries, 1998). In general, data-based models are suitable for the interpolation of system behaviour within historically known boundaries; the inclusion of causal mechanisms (i.e. rule based modelling) is crucial for extrapolation of system behaviour (Beck, 2002b).

In this dissertation, we use the TIMER 2.0 model. TIMER is the energy sub-model of the Integrated Model to Assess the Global Environment, IMAGE 2.4, that describes the main aspects of global environmental change (Bouwman et al., 2006). TIMER is a system-dynamics energy model that simulates year-to-year investment decisions based on a combination of bottom-up engineering information and specific rules on investment behaviour, fuel substitution and technology. TIMER 2.0 (van Vuuren et al., 2006b) is an extended version of the TIMER 1.0 model (de Vries et al., 2001), with the main differences being extension of renewable energy modelling (Hoogwijk, 2004), carbon capture and storage (Hendriks et al., 2004), hydrogen (van Ruijven et al., 2007) and a disaggregation from 17 to 26 world regions. In the TIMER 2.0 model, demand for end-use energy is determined from economic activity in five sectors: industry, transport, residential, services and other. The (top-down) demand formulation includes autonomous and price-induced changes in energy-intensity. Energy supply is based on fossil fuels (coal, oil, natural gas), biomass, solar and wind power, hydropower and nuclear power. Fossil- and biofuels can be

[3] The term 'stylized fact' stems originally from social sciences and economics and reflects a simplified representation of empirical findings. It is a broad generalization that emerges from many different data sources. It is mostly used in the context of macro-economic analysis, for instance when describing general relations of economic growth (Agenor et al., 2000; Easterly and Levine, 2001), linkages between economies (AkIn and Kose, 2008) or the behaviour of stock markets (Mazzucato and Semmler, 2002) and currency markets (Guillaume et al., 1997).

traded among 26 world regions. The production of each primary energy carrier includes the dynamics of depletion and learning-by-doing.

2.2 Recent developments in modelling energy and development

As discussed above, most global energy models applied to energy futures in low-income regions are developed in industrialised countries. This weakness is widely recognised. During the last decades, renowned scientists from developing countries pointed out this issue (e.g. Reddy and Goldemberg, 1990; Sathaye et al., 1987) and initiated global scenario studies that involved major participation from developing country experts. For example the World Energy Assessment (Goldemberg, 2000b, 2004). The IPCC aims for substantive participation of experts from developing countries in its assessments, such as the development of new emission scenarios (IPCC, 2006). The Pacific Northwest Laboratory (PNL) organised economic and environmental modelling workshops in China, Korea, India, Mexico and Brazil. These workshops aimed to build technical capacity and exchange information between modellers (PNL, 2008). Gusdorf et al. (2008) use a conceptual model to show that spatial aspects matter in energy policies. In recent years, several international projects have been carried out to explore the nexus between development, energy use and climate change. Some projects focused mainly on analysing the interlinkages between the issues, the development of a standard framework for integrated analysis and identifying policies with multiple benefits (Halsnæs et al., 2008; Kok et al., 2008; Shukla et al., 2003). Other projects are explicitly oriented at improving modelling tools. For example, more detail was added to the IEA World Energy Model for China and India, explicitly including rural and urban areas, income differences and end-use functions (IEA, 2007e). Howells et al. (2005) applied the MARKAL model to a rural village in Southern Africa and Shukla et al. (2007) developed an integrated economy-energy-environment model for developing countries. Complementary approaches include the quantification of co-benefits of sustainable development policies and greenhouse gas mitigation (Winkler et al., 2008).

Another issue is the increased collection and analysis of data on energy use in developing countries by local scientists. For India, the household survey data of the National Sample Survey Organisation (NSSO) were a useful source of information for decades, but increased access and computational power led to many new analyses and insights in the drivers and patterns of residential energy use (Filippini and Pachauri, 2004; Narasimha Rao and Reddy, 2007; Pachauri, 2004; Pachauri and Jiang, 2008; Pachauri et al., 2004; Pachauri and Spreng, 2002; Viswanathan and Kavi Kumar, 2005). Primary collection of survey data on household energy use is increasingly carried out for several regions, for instance Africa (Howells et al., 2005; Louw et al., 2008; Ouedraogo, 2006; Wamukonya, 1995), India (Bhatt and Sachan, 2004; Sudhakara Reddy, 1995a, 1995b), China (Brockett et al., 2002; Jiang and O'Neill, 2004; Tonooka et al., 2006; Xiaohua et al., 2002) and Brazil (Brito, 1997; Ghisi et al., 2007). Due to their mostly rural focus, these studies provide valuable insights in the behaviour of the poorest groups in society, which are not visible in the global databases of the World Bank. These activities recognise that a huge amount of information and knowledge is available with local experts and in regional publications, which does hardly trickle down to the global modelling community.

3 Developing countries and energy transitions

Increased resource depletion, import dependence, climate change and air pollution put pressure on the technology choices in the energy system. It is expected that energy transitions reshape the global energy system in the next decades (IEA, 2007e). New technologies for energy production and conversion are currently being developed and applied, mostly aimed at cleaner and more independent supply of energy. For example, modern biofuels (Smeets et al., 2007) and renewable electricity production from wind and solar (de Vries et al., 2007b) are increasingly applied in developing regions. On the longer term, carbon capture and storage (Damen et al., 2006), or even the transition towards new energy carriers, like hydrogen, might be necessary to develop and maintain affordable, clean and reliable energy systems. Hydrogen is an energy carrier that might play a key-role in such energy system. The variation in production technologies contributes to the need of diversification of energy sources, for example from oil and natural gas to coal and renewables (Edmonds et al., 2004; van Ruijven et al., 2007). Moreover, hydrogen can also level out fluctuations in energy supply from intermittent sources (Schenk et al., 2007).

The transition towards a new energy carrier depends partly on the context of the system in which it is introduced. For industrialised regions, issues like competitiveness (being the first), greenhouse gas emission mitigation and energy security play a major role (McDowall and Eames, 2006). For developing regions, the potential to reduce air pollution emissions and improve energy security – leaving aside the many other, pressing issues – may be more important. Barriers are also likely to be different. While the availability and affordability of technologies may be a limiting factor in developing countries, the rapid growth of infrastructure (e.g. in China and India) may create important opportunities for leapfrogging. Policy measures are another difference: many developing countries hardly tax (or even subsidise) fossil fuels limiting policy options to stimulate efficient energy use and alternative fuels through e.g. tax exemption.

4 Aim, scope and outline of this thesis

The problem formulation, as described in the above sections, can be summarised as follows:

- Energy use in developing countries is increasingly important for many global sustainability issues.
- Global energy models are used to explore possible future developments of the global energy system and provide a basis for sometimes contentious energy and environmental policies.
- Practically all global energy models are constructed in industrialised regions and focus primarily on issues on the political agenda of today's high-income regions. It is implicitly assumed that energy systems in developing regions can be represented by models that are based on experiences in industrialised regions.

- However, energy systems in developing countries involve different dynamics and the energy policy agenda of developing countries includes several issues that were not important for industrialised regions during the last decades.
- Therefore, current global energy models are not necessarily suited to address several key-issues of energy systems in developing countries.

Based on this, the main question for this dissertation is:

How can the performance of global energy models, especially the TIMER model, be improved such that they better represent and forecast energy system evolution in developing regions?

Several research questions have been derived from this:

I. What are the main differences in dynamics between energy systems in developed and developing regions?
II. How can we evaluate the performance of the TIMER model at the regional level and can the model be parameterised such that it simulates energy use in developing regions?
III. How can the model structure of TIMER be improved to better represent mechanisms that drive energy use in developing regions?
IV. What are the differences in potential roles of new energy technologies, especially hydrogen, between developed and developing regions?

In this dissertation, we use the global energy model TIMER 2.0, because of several arguments. Besides practical issues, like access to the model code and initiation of this project, TIMER is a scientific and policy-relevant global energy model. This model has recently been used in several influential scenario studies like the IPCC Special Report on Emission Scenarios (IPCC, 2000a), the Millennium Ecosystem Assessment (MA, 2005), UNEP Global Environmental Outlook (UNEP, 2007) and the OECD Environmental Outlook (OECD, 2008). In combination with the FAIR model (den Elzen and Lucas, 2005) it is used to explore different burden-sharing regimes for greenhouse gas mitigation between developed and developing countries. Finally, the TIMER model simulates energy use for 26 world regions; hence, it explicitly includes many developing countries.

For the purpose of this thesis, we limit our analysis to three sub-modules of the TIMER model: energy demand in the residential and transport sectors and the production and end-use of hydrogen. Increasing energy demand in the residential and transport sectors is closely related to increasing household incomes and changing lifestyles; energy choices and transitions in these sectors play a major role in the energy systems of developing countries. Hydrogen is one of several options for a future cleaner and more reliable energy supply system and is mainly chosen because of its key-role in such a sustainable energy system. The regional focus varies per chapter of this thesis. Two chapters (Chapters 2 and 7) analyse issues at the global level, while others include a series of regions that represent a

broad range of GDP/capita levels: USA, Western Europe, China, India, Brazil and Russia (Chapters 4 and 5). Finally, two Chapters focus specifically on India (Chapters 6 and 8), which we regarded the most suitable developing region for model development. India is the second emerging giant (after China), it contains a broad range of welfare levels, has the advantage of abundant data availability and accessibility and followed a stable development path during the last 30 years. With respect to time, we focus historically on the period 1971-2003 (IEA, 2005) and use future projections towards 2030, 2050 and 2100 in different chapters.

The first part of this thesis explores *research question I* and outlines the backgrounds of energy and development. *Chapter 2* explores the emergence of concepts of energy and development and their use in existing global energy models. First, the results of the IPCC/SRES models are analysed on the emergence of two concepts: the energy ladder and the environmental Kuznets curve. The second part of Chapter 2 focuses on several key-differences between energy systems in developed and developing countries: traditional fuels, electrification, economic structural change, income distribution, informal economies and the changing development context. *Chapter 3* further explores two aspects where currently developing countries experience a different development context than industrialised countries: the depletion of cheap fossil energy and limitations from climate change. This chapter applied the simplified energy-economy-environment model SUSCLIME in a multi-agent analysis.

Chapters 4 and 5 of this thesis focus on *research question II* and evaluate the performance of the TIMER energy demand model for several world regions. *Chapter 4* describes a method to explore uncertainty that stems from model calibration and applies it to transport sector energy use modelling. *Chapter 5* uses this method to explore calibration-uncertainty in the residential sector of Western Europe, USA, Brazil, India and China.

Research question III is analysed in *Chapter 6*. This chapter presents a new model for residential energy use in India, starting from the most important differences between developed and developing countries: urban/rural differences, income distribution, electrification and traditional fuel use.

The final part of this thesis elaborates on *research question IV*, focusing on long-term energy transitions, technology transfer and exploring the potential role of a new energy technology: hydrogen. As an introduction, *Chapter 7* explores the potential role of hydrogen in the global energy system in combination with climate policy. It describes the hydrogen model in TIMER and the development of a set of scenarios, to represent the wide variation in expected future developments of this technology. *Chapter 8* focuses on the role that hydrogen can play in developed and developing countries, given the different arguments for energy transitions and differences in energy policies and economic development.

Finally, *Chapter 9* presents a summary of the chapters and the main conclusions of this thesis.

Chapter 2: Modelling Energy and Development: an Evaluation of Models and Concepts[1]

Abstract
Most global energy models are developed by institutes from industrialised countries, focusing primarily on issues that are important in these regions. Evaluating the results for Asia of the IPCC/SRES models shows that broad concepts of energy and development, the energy ladder and the environmental Kuznets curve, can be observed in the results of the models. However, improvements can be made in modelling the issues that underlie these concepts, like *traditional fuels*, *electrification*, *economic structural change*, *income distribution* and *informal economies*. Given the rapidly growing importance of energy trajectories of developing countries for global sustainability, the challenge for the future is to develop energy models that include these aspects of energy and development.

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1 Introduction

The consumption and production of energy worldwide plays a major role in several sustainability problems, such as climate change and depletion of resources. So far, world energy use has been dominated by energy consumption in industrialised countries. However, that situation is currently changing. Industrialization, improvement of living standards and population growth are leading to rapidly increasing energy consumption in developing countries, with subsequent impacts on global sustainability issues.

Global energy models are used to explore and understand possible future changes in the global energy system. Only very few global energy models account explicitly for the specific dynamics of developing countries. As the majority of these models is developed in industrialised countries, they mainly focus on issues are important for industrialised energy systems, systems that can be characterised by full access to modern energy forms, high (and increasing) welfare levels and a minor role of agriculture in the structure of the economy. Implicitly, it is assumed that the future of developing countries can be derived from experiences in developed countries during the last decades. For a variety of reasons, this is not necessarily the case, as developed and developing countries differ for instance in market development, institutional arrangements and the existence of traditional economies and energy systems (Pandey, 2002; Shukla, 1995).

In 2000, the IPCC published a set of scenarios in the Special Report on Emission Scenarios (SRES) (IPCC, 2000a). These scenarios have been developed using global energy models, to explore future pathways for greenhouse gas (GHG) emissions. Despite the fact that developing countries play an important role in the increase in global energy consumption projected in these scenarios, all modelling teams in the SRES were from the developed world (the number of global energy modelling teams in developing countries is very limited). It should be noted that in the SRES some attempts were made to compensate for this: one modelling team involved modellers from developing countries, while the report as a whole involved several experts from developing countries as non-modelling experts. However, these activities did not change the models that were applied.

This article looks at the question whether current global energy models include several key-issues of energy systems in developing countries. In our analysis, we especially focus on the Asian region. We first evaluate whether two broad concepts of energy and development, the *energy ladder* and the *environmental Kuznets curve*, can be found in the SRES model results (Section 2). Next, we identify several key-issues of energy systems in developing countries that are relevant for global energy models. Section 3 discusses these issues, focusing on the trends and stylized facts and the relevance for global energy models. Section 4 discusses the methods and gives the conclusions.

Some remarks on this study have to be made beforehand. First, we do not claim completeness in the key-issues; we focus on what we consider the most relevant changes in energy systems in developing countries with respect to global energy modelling, based on our own analysis and observation. Second, we focus mainly on Asia, as among all

developing regions this continent has the largest population size, experiences the fastest economic growth and consequently the fastest growing contribution to energy consumption and global climate change.

Many definitions exist for the terms "developing country" and "developing region". In this article, we define developing countries as all countries within the World Bank's low income, lower-middle and upper-middle income groups, excluding the former Soviet regions and Central-European countries (or, in other words, all countries in Latin America, Africa, the Middle East, Asia and Oceania that are not in the high income class). We use the terms developing country and developing region interchangeably.

Metrics for the comparison of economic activity
Most energy models use economic activity (GDP/capita, representing living-standards) as driving force for energy related issues. When internationally comparing economic activity, one has to express local currencies in a common currency. Two options are available for such comparison: market exchange rates (MER, usually US dollars) or purchasing power parity (PPP, expressed as international dollars). MER comparison is based on bilateral exchange rates between different currencies and the US dollar, but this ignores the often large differences in prices of a broad set of goods and services that are not reflected in the value of the exchange rate. The PPP exchange rate is defined as the ratio of prices for a representative basket of goods and services, such that the purchasing power of the currencies is equal (Lafrance and Schembri, 2002). Usually, North American purchasing power in US dollars is set to equal international dollars. Developing countries are usually characterised by a high ratio between PPP income levels and MER-based income levels (the so-callled PPP-ratio), which makes the issue especially relevant for the modelling of energy systems in these regions. In other words, developing countries' economies are larger on PPP basis than suggested on MER basis. In the SRES, economic activity was mainly expressed in MER terms and this has been extensively debated in long-term scenario literature (Castles and Henderson, 2003; Grübler et al., 2004; Nordhaus, 2007; van Vuuren and Alfsen, 2006). In the dynamic context of global models, one of the crucial questions is whether PPP values should be regarded as constant or dynamically converging with increasing welfare levels. Although it was found that models lead to comparable results if calibrated consistently in PPP or MER (van Vuuren and Alfsen, 2006), this aspect contributes to uncertainty in the projection for energy use in developing countries. In this article, we use MER values in the discussion of the SRES results (Section 2) and PPP values for the analysis of data (Section 3), as PPP is more suitable for the comparison of welfare levels between different developing countries.

2 Developing Countries in Global Energy Models

One of the few consistent databases with scenario results from global energy models is the IPCC/SRES (IPCC, 2000a). Due to differences in regional definitions and levels of detail of the models, the reporting of model results in this database rather aggregated. For example,

results are published for only four world regions (of which we focus on the region of Asia[2]) and a limited set of socio-economic and energy data. Due to these limitations, it is only possible to evaluate these models on rather aggregated concepts of energy and development. Here, we focus on the energy ladder and the environmental Kuznets curve (EKC).

The six models involved in the IPCC/SRES process are AIM, ASF, IMAGE/TIMER, MARIA, MESSAGE and MiniCAM (IPCC, 2000a). In the IPCC/SRES, a set of four scenarios was developed, defined by an axis of global versus regional orientation and economic versus environmental preferences. The A1 storyline is a case of rapid globalization and economic development, in which average income per capita converges between world regions. The A2 scenario represents a differentiated world with a focus on materialism, in which protectionism of regions is more important than global interaction and in which significant income disparities continue to exist. The B1 storyline describes a fast-changing and convergent world, aiming at environmental, social and economic sustainability from a global perspective. Finally, the B2 world is one of increased concern for environmental and social sustainability coupled with an emphasis on regional solutions (IPCC, 2000a). Per scenario one model is the marker model, which is illustrative of a particular storyline. The results of other models on several key-variables are harmonised with the marker model.

All data in this analysis are derived from the IPCC/SRES website[3] except for the IMAGE-model data: these are from the IMAGE SRES implementation CD-ROM (IMAGE-team, 2001). Ideally, we would have analysed the source-codes and technical documentation of the models with respect to specific development issues. However, documentation of many of these models is incomplete and source codes are hard to obtain. Therefore, we decided to use the results of the models and the available model documentation. By limiting our evaluation to these models, we are aware that we exclude a range of specific energy models, among them the MARKAL/TIMES family and the IEA World Energy Model (WEM), which were not involved in the IPCC/SRES process. Also, the SRES versions of the models might be outdated as models are continuously improved. For example, the IMAGE model has been considerably improved since the SRES (Bouwman et al., 2006), but no changes have been made to the processes that are relevant for energy and development issues. Also for other models we presume that little has changed on the issues that we discuss in Section 3. Finally, it should be noted that data in the sections are often presented as function of per capita income, an indicator used as a proxy of development level[4].

[2] Due to different regional aggregations of the SRES models, the final report used only four regions: REF (economic reforming countries), OECD 1990, ASIA and ALM (Africa and Latin America).
[3] http://www.grida.no/climate/ipcc/emission/index.htm
[4] For reasons of comparability and to focus on the process of development (i.e. low incomes), we have chosen to limit the graphs to 12000 US$/capita, which is the maximum average Asian income level in the A2 scenario.

2.1 The Energy Ladder in the SRES models

It is a general historically observed pattern that once fuels become available and affordable, populations switch to fuel-stove combinations with a higher quality (Holdren and Smith, 2000). The energy ladder is a generic concept that postulates that household energy use often shows a transition from traditional biomass fuels (wood, dung, crop residues) through direct use of liquid and solid fossil fuels (coal, kerosene) to modern energy forms (LPG, natural gas and electricity) (Barnes and Floor, 1996; Martins, 2005; Smith et al., 1994). Higher ranked fuels on the energy ladder generally tend to be cleaner, more efficient and easy to use, although a switch from traditional fuels to coal is not always an improvement in this sense. On the other hand, capital costs and dependence on centralised fuel cycles also tend to increase. Critiques of the energy ladder state that reality is more complex than a simple transitional theory, for instance, because the pattern is not observed as a sequence and it is driven by more factors than increasing income (Martins, 2005; Masera et al., 2000). Especially issues like household size and location (urban, rural) and availability of wood resources are often found to influence a households' behavior with respect to the energy ladder (Brouwer and Falcao, 2004; Hosier and Dowd, 1987; Kituyi et al., 2001; Top et al., 2004).

To compare the Energy Ladder hypothesis and the results of the SRES models, we used the fraction of non-commercial fuels and electricity in secondary energy use. According to the concept, energy use should move from traditional fuels towards kerosene and electricity. Figure 2.1 shows the fraction of non-commercial fuels in secondary energy use for the four SRES scenarios. Only three of the six SRES models report the use of non-commercial fuels (see also Table 2.1). Generally, the AIM, IMAGE and MESSAGE models project a decreasing share of non-commercial fuels, following an (exogenously determined) exponentially declining path with increasing income levels. However, large differences exist between the models. In the AIM model, non-commercial fuels are rapidly phased out at income level of 6000-10000 US$/capita, while the IMAGE model still shows a share of about 10% at 12000 US$/capita.

Figure 2.2 shows the fraction of electricity in secondary energy use in relation to income for the region of Asia. All IPCC/SRES models project an increasing share of electricity with increasing income. However, large differences on path and share exist between models. The MiniCAM model projects the highest share of electricity, up to 60% in the A2 scenario. On the other extreme, the MARIA model projects hardly any increase in electricity share, in none of the A1, B1 and B2 scenarios it exceeds 15%[5]. The results also show diversity in the rate of growth of the electricity share; especially the ASF A2 scenario involves rapid developments.

[5] For the MARIA model, no A2 scenario was developed

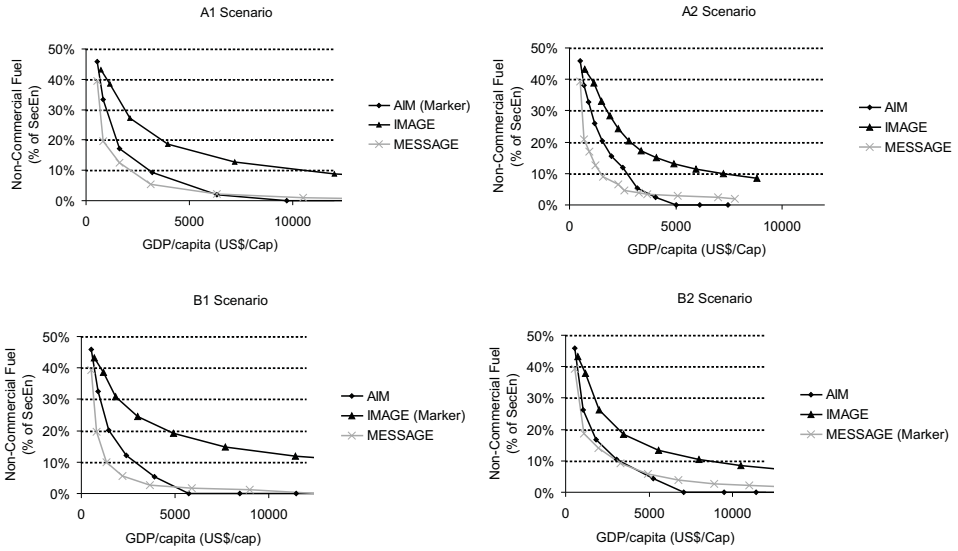

Figure 2.1: Fraction of non-commercial fuels in secondary energy use vs. GDP/Capita in MER for the region of ASIA from the SRES models

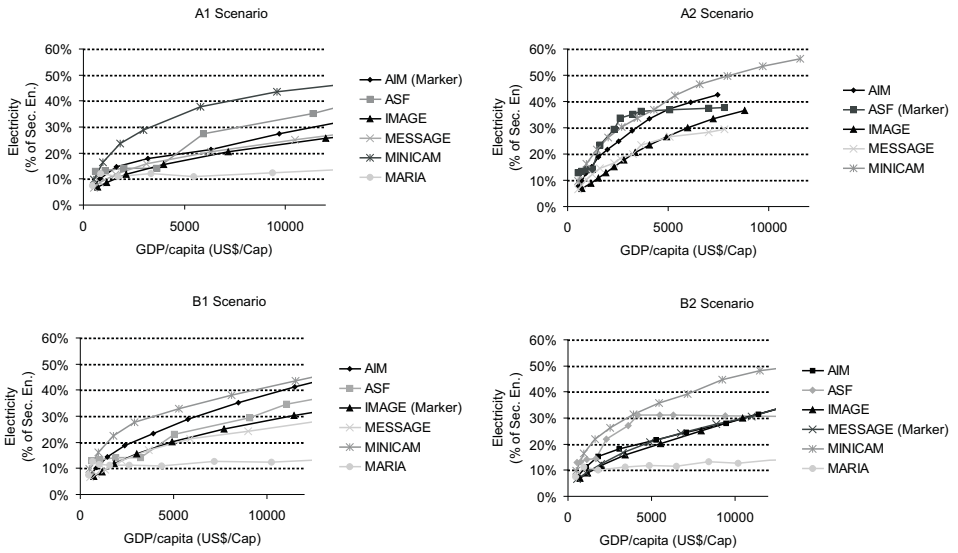

Figure 2.2: Fraction of electricity in secondary energy use vs. GDP/Capita in MER for the region of ASIA from the SRES models

The results for Asia of all IPCC/SRES models involve patterns that correspond typically with the Energy Ladder concept: decreasing shares of traditional fuels and increasing shares of electricity use. However, in reality each rung on the ladder is related to specific

processes and driving forces. For instance, the transition from traditional to commercial fuels has to do with income, household size and wood or fuel availability; the choice between different commercial fuels is influenced by subsidies and taxes and the investment cost for related equipment; and the use of electricity is only possible once households are connected to the grid, or have stand-alone electricity production. There issues, especially traditional fuels and electrification, are often not explicitly incorporated in the global energy models (see Table 2.1).

2.2 The Environmental Kuznets Curve in the SRES models

The concept of the Environmental Kuznets Curve (EKC) generalizes environmental pressure in relation to economic development as an inverted U-shaped-curve, analogous to the income inequality curve described by Kuznets (1955). Based on the concept of the EKC, it is often argued that environmental pressure will decrease once developing countries become more prosperous (Beckerman, 1992). However, the empirical and statistical basis for the EKC is ambiguous: results differ for different type of environmental pressure and time periods. Moreover, critics urge to focus on decomposition of the underlying processes that drive the generic concept (Focacci, 2005; Gales et al., 2007; Stern, 2004). In this context, also the value for modelling energy-related emissions in developing countries is questioned, referring to the heterogeneous income distribution, large presence of poor regions, prevailing rural lifestyle and economic and social barriers to the widespread adaptation of technologies (Focacci, 2005). Diversity and confusion in the EKC-debate stem, among others, from the many definitions that are used to indicate environmental pressure[6] and even the use of underlying drivers such as energy use (or intensity) and carbon emissions (or intensity). While evidence is relatively strong for EKC-type trends in the case of for instance absolute SO_2 emissions, for CO_2 emissions there is hardly any evidence that the EKC holds (see further). The application of the EKC concept for CO_2 is in case of developing countries further complicated because traditional fuels can distort the shape of the curve: the long-term trend of energy intensity can be declining (traditional fuel use is very inefficient), whereas carbon intensity is increasing because fuel wood, which does not result in net CO_2 emissions (depending on the sustainability of the source), is substituted by fossil fuels (Gales et al., 2007) (see also Section 3)[7].

We evaluate the results of the IPCC/SRES models with respect to the EKC using two environmental pressure indicators: sulfur and carbon emissions *per capita*. For sulfur emissions, there is a generic trend in all models to follow an EKC, although the turning point of the inverted U-shape is different (Figure 2.3). The wide variation between the models, even though income, population and energy use projections were coordinated with the marker model, can be explained from different structures in the energy systems (mainly the applied technologies/fuels) or exogenous assumptions on emission intensity. In the A1, B1 and A2 scenarios, the ASF model has the highest SOx emissions, which can be explained from the model's strong focus on coal (van der Sluijs et al., 2001). In the regionalised A2 scenario, the AIM model projects high coal use for Asia, and shows

[6] Emissions: absolute (kg), per capita (kg/cap) or intensity (kg/$), or concentrations (kg/m^3)
[7] In the same way, modern renewable energy can decrease carbon intensity with constant energy intensity.

correspondingly high SOx emissions. Sulfur emissions of the IMAGE and MESSAGE models show wide variations between different scenarios.

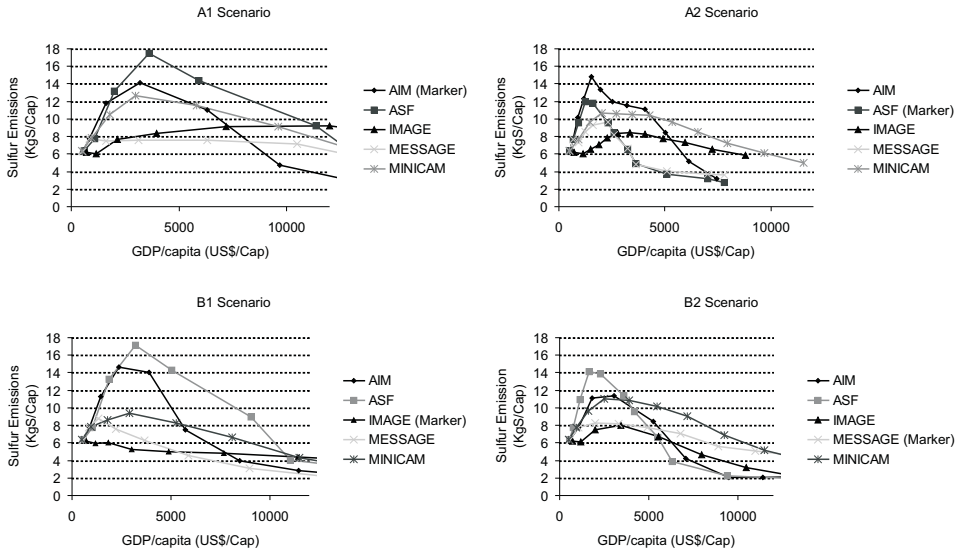

Figure 2.3: Sulphur emission projections vs. GDP/Capita in MER for ASIA from the IPCC/SRES models

There is discussion whether an EKC-type of trajectory could also apply to carbon emissions (Quadrelli and Peterson, 2007; Raupach et al., 2007). For CO_2 so-far there is no evidence of an absolute decoupling of rising incomes and rising CO_2 emissions (so no turning point below current Western income levels): some sectors show signs of saturation of energy use, while in other sectors energy use is still growing rapidly. In this context, we have increased the upper limit of the income axis in Figure 2.4, in order to at least plot the behavior of the model results at higher income levels. Also for carbon emissions, wide variations exist between models and scenarios (Figure 2.4). It should be noted that none of the models have explicitly included the EKC as a theoretical concept to model trends in CO_2 emissions – and trends are driven by factors such as energy demand, exploration and depletion of fossil fuels and technology development. Nevertheless, it is interesting to follow depicted trends in this context. The A2 scenario does not show a turning point of the EKC in the 21st century, while the B1 scenario indicates a turning point well below an Asian average level of 10,000 US$/capita. The ASF model shows the highest carbon emissions in all scenarios, which can be explained from its focus on coal. The AIM model also projects a high share of coal, and thus relatively high CO_2 emissions in regionalizing scenarios. Very low carbon emissions are projected by the MARIA model, due to the substantial amount of nuclear energy projected here (IPCC, 2000b; van der Sluijs et al., 2001).

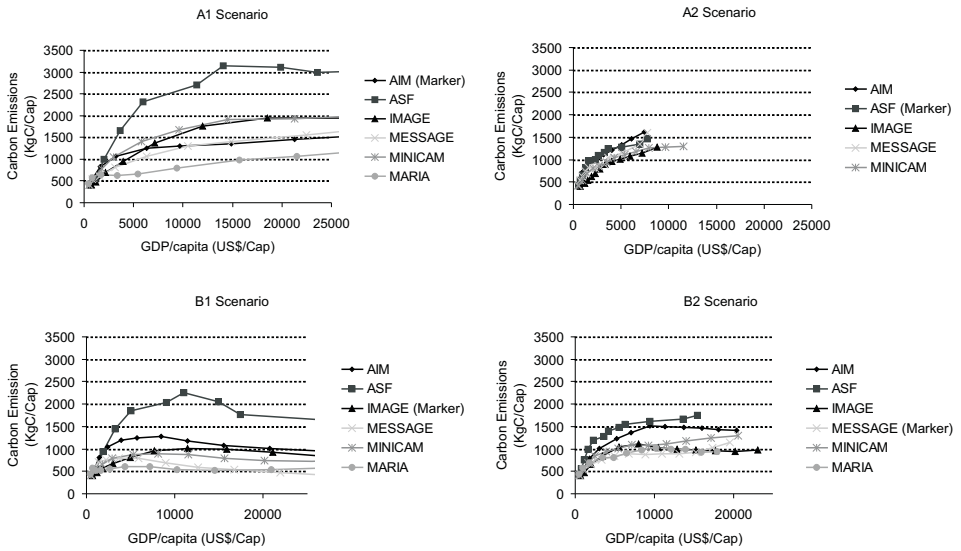

Figure 2.4: Carbon emission projections vs. GDP/Capita in MER for ASIA from the IPCC/SRES models

Generally, all model results show the inverted U-shape of the EKC in the A1 and B1 scenarios for both sulfur and carbon emissions per capita. Higher turning points for the A2 and B2 scenarios were also found in an analysis of the EKC in the IPCC/SRES models at the global level (Fonkych and Lempert, 2005). For SOx emissions, industrialised countries have restrictive policies since the 1970s and end-of-pipe technologies are widely applied. Diffusion of these policies and technologies towards developing countries takes place and is expected to continue (Grubler, 2002; Smith et al., 2005). The SRES results of the A1 and B1 scenarios show a pattern for CO_2 emissions at the Asian level that is consistent with the EKC concept. However, carbon mitigation policies were explicitly excluded from the scenarios and the existence of such curve is debated in literature; it remains at best doubtful whether the EKC is a useful concept to describe trends in CO_2 emissions. The underlying processes that determine whether developing countries follow the EKC, e.g. heterogeneous income distribution, rural-urban divide or socio-economic barriers (Focacci, 2005), but also carbon emission of fuel wood (Gales et al., 2007), are rarely explicitly modelled in the SRES global energy models (see Table 2.1).

Table 2.1: Overview of issues of Energy and Development in the SRES models (Based on IPCC, 2000a; Mori, 2000; van der Sluijs et al., 2001). message that we only analysed the SRES versions of the models.

	Model Acronym	AIM	ASF	IMAGE (TIMER)	MARIA	MESSAGE	MiniCAM
MODELS	Full name	Asian Pacific Integrated Model	Atmospheric Stabilization Framework	Integrated Model to Assess the Global Environment	Multi-regional Approach for Resource and Industry Allocation	Model for Energy Supply Strategy Alternatives and their General Environmental Impact	Mini Climate Assessment Model
	Type of Model	Simulation model / Dynamic	Iterative Search technique (optimization)	Simulation model / Dynamic, non-linear	Optimization model / Dynamic, non-linear	Simulation, Optimization, Dynamic linear	economic equilibrium model
KEY-ISSUES	Traditional Fuels	Included, method unknown	Not included	Included, related to income, urbanization and oil price	Not included	Included, method unknown	Not included
	Electrification	Implicitly included via demand elasticity	Implicitly included via demand elasticity	Implicitly included via demand elasticity	Implicitly included via demand elasticity	Implicitly included via demand elasticity [6]	Implicitly included via demand elasticity [6]
	Structural Change, (available end-use sectors)	Residential, industry, commercial, transport, energy conversion	Residential, industry, commercial, transport and electricity	Residential, industry, transport, services, other	Industry, transport, public and other sectors	Industrial, residential / commercial, transport, non-commercial	Residential / commercial, industry, transport
	Income Distribution	Not included	Not included	Not included	Not included	Not included	Not included
	Informal Economy	Not included	Not included	Not included	Not included	Not included	Not included
	Resource Depletion	Based on assumed exploitation cost. No impact on economic development	Rogner (1997), Naki-cenovic et al. (1998) (fossil), No impact on economic development	Rogner (1997) (fossil) World Energy Assessment (renew-ables). No impact on economic development	Rogner (1997) (fossil), Fuiji (1993) (renew-ables). Impact on economic development	Rogner (1997) (fossil). Consistent with economic development.	
	Climate Change (impact on economy and energy system)	No feedback on economy; mitigation runs possible	No feedback on economy; mitigation runs possible	No feedback on economy; mitigation runs possible	Feedback on economic activity; mitigation runs possible	No feedback on economy; mitigation runs possible	No feedback on economy; mitigation runs possible
	Local Air Pollution (SOx)	Yes	Yes	Yes	Not included	Yes	Yes

3 Key-issues of energy systems in developing countries

Based on the analysis of the model results with respect to the energy ladder and the EKC, we can distinguish three groups of key-issues that were less relevant for energy systems in industrialised regions (in recent history), but are of importance for today's developing countries. First, key-issues in the energy system itself are the use of *traditional fuels* and limited access to modern energy (*electrification*), both related to the energy ladder. A second group of issues, involving *structural change*, *income distribution* and the role of the *informal economy*, has a more socio-economic nature and is related to the demand for energy. A third group of issues is related to the context of development for present-day developing countries compared to Western regions after 1960 and involves *depletion of resources*, *climate change* and *local air pollution*. A final issue is the difference between *urban and rural areas*. Most global energy models do not make a differentiation between urban and rural energy systems, although for most of the above identified key-issues, urban and rural characteristics are different. Therefore, we discuss this with the key-issues below.

Are these key-issues incorporated in the IPCC/SRES models? We assess this question qualitatively, based on the IPCC/SRES report (IPCC, 2000a), the available model documentation from the time of the SRES (de Vries et al., 2001; Kainuma et al., 2003; Mori, 2000) and an overview of the SRES models structure (van der Sluijs et al., 2001) (see Table 2.1). Below, we elaborate on the key-issues, evaluate whether and how they are incorporated in the SRES models and discuss their relevance for global energy models.

3.1 Developments in the energy system

3.1.1 Transition from traditional to commercial fuels

Traditional biomass, such as fuel wood, dung, agricultural waste, crop residues and charcoal constitute a major source of energy in the developing world. In 2000, 52% of the total population of developing countries relied on traditional biomass as the main source of energy for cooking and heating (IEA, 2002b). Traditional biomass combustion causes indoor air pollution which triggers various adverse health effects and an estimated 1.6 million deaths per year (WHO, 2006). Issues related to fuel wood are limited availability and impact on deforestation (Arnold et al., 2006).

Data and Stylized facts

Official statistics on fuel wood include only production, not consumption (FAO, 2005) (but they can easily be considered equal). Unfortunately, however, the reliability of statistics on this topic can be questioned, as most fuel wood is gathered from woodlands and never accounted for in statistics. Another data problem concerning traditional fuel is that global statistic databases account only for fuel wood, not for other forms of traditional biomass; dung, agricultural waste and crop residues are only taken into account by survey studies (FAO, 2005; Xiaohua and Zhenmin, 2005).

Given these caveats, the available data show a generally decreasing trend in fuel wood production per capita with increasing income levels in all world regions and several Asian

countries (Figure 2.5 and Figure 2.6, left graphs). Sub-Saharan Africa also shows a decline in per capita fuel wood production in time, although it faced a decreasing GDP/capita (PPP) in the described period, indicating the relevance of other drivers than income. In contrast to per capita fuel wood production, absolute production increased in most world-regions and in most Asian countries (Figure 2.5 and Figure 2.6, right graphs). This indicates increasing pressure of population growth on the natural environment and the fuel wood supply. As an exception Middle East & North Africa and Indonesia show a declining absolute fuel wood production level (and a rapidly declining per capita level); both regions have abundant oil resources and the Middle East & North Africa have little forest available.

Many studies exist on fuel switching and its relation to socio-economic development. Usually, a decreasing use of traditional fuels in relative measures is observed: per capita, but also as share of total energy use. An extensive data analysis was performed by Victor and Victor (2002). They found that declining fuel wood use can statistically mainly be explained from several factors: changes in income, differences in availability, degree of urbanization and industrialization. Beside these main drivers, other factors that determine the use of traditional biomass are the costs of this energy source (for example costs for feedstock, conversion or alternative fuels), culture and traditions, climate, geography and land use. Culture and tradition are often ignored in energy modelling, as cultural habits are hard to quantify. The relation between income and fuel wood use may be better understood when income distribution is taken into account, as fuel wood is mainly used by lower income households (Victor and Victor, 2002).

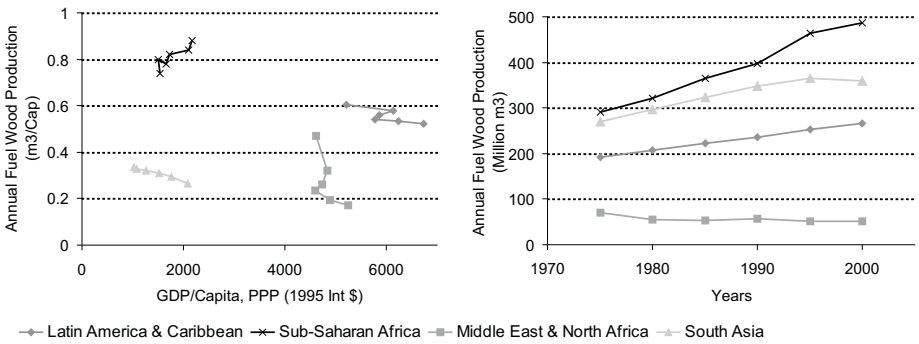

Figure 2.5, left: Fuel wood production per capita vs. GDP/capita (PPP) for several developing world regions, data from 1975 to 2000. Right: Absolute annual fuel wood production for several developing world regions. Data from FAO (2005) and World Bank WDI (2004)

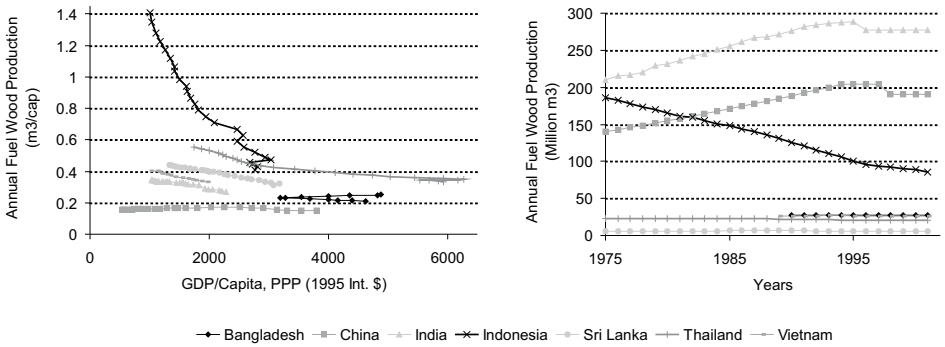

Figure 2.6, left: Fuel wood production per capita vs. GDP/capita (PPP) for several Asian countries for the period 1975-2000. Right: Absolute annual fuel wood production for several Asian countries. Data from FAO (2005) and World Bank WDI (2004)

Relevance for global energy models

Only three of the IPCC/SRES models report the use of traditional fuels, two of them using a non-described method (Table 2.1). This means that the models ignore an essential element of the energy system, potentially underestimating the demand for energy (and energy intensity). Although in terms of global energy use traditional fuels are not very important, there are several reasons to include them in global energy models. First, they constitute a substantial part of energy use in developing countries, especially relevant for people in rural areas. Second, they are not easily replaced as transport and distribution of alternative fuels are expensive in rural areas and cultural habits play a major role. Third, the contrast between declining per capita use and increasing total production of fuel wood in many regions expresses pressure on forests, shortages and a potential fuel wood crisis (see e.g. Arnold et al., 2006). Global energy models could provide added value in this discussion, if they would link demand and supply of fuel wood and identify areas where problems might arise. Also, if fuel wood use is not sustainably harvested it leads to deforestation, a source of carbon emissions. Finally, the importance of traditional energy use for health issues is another reason to include this fuel type in the models.

3.1.2 Electrification

In the industrialised world almost every house is connected to the electricity grid, whereas in developing regions 64% of the population had access to electricity in 2000 (IEA, 2002b). In residential energy use, a major difference exists between urban and rural areas; in urban areas electricity is often the predominant type of energy while rural areas depend more on traditional fuels (Figure 2.7 and Goldemberg, 2000a; Reddy, 2000). Many remote villages, especially those in mountainous areas, are not connected to a central electricity grid.

Data and Stylized facts

Data on electrification are scarce and their usefulness is limited as definitions for 'access to electricity' differ per country (IEA, 2002b). We used data from the World Energy Outlook (2002b) to analyze stylized facts in the relation between development and electrification. This data strongly suggests that the higher the income, the higher the electrification rates. In

fact, the electrification rate increases fast initially and then slows down as only remote areas are left to be electrified (see Figure 2.7 and Figure 2.8).

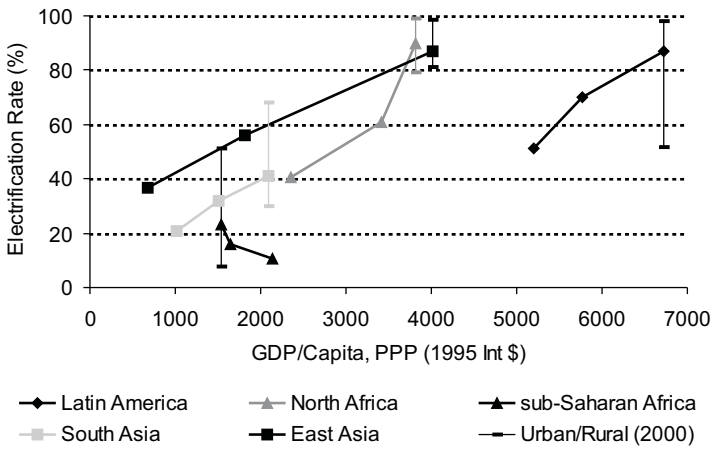

Figure 2.7: Electrification rates in several developing regions vs. GDP/capita (PPP). Data points are for 1975, 1990 and 2000. For the year 2000 information on urban and rural electrification is added, in all regions urban electrification rates are higher than rural. Note that sub-Saharan Africa faced a declining GDP/capita over the described period. Data from IEA (2002b) and World Bank WDI (2004)

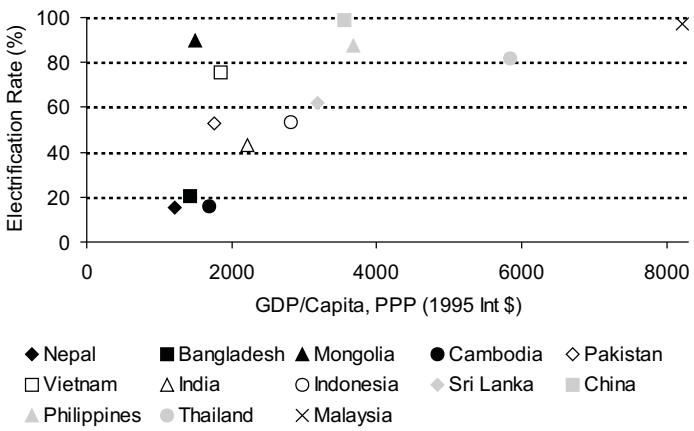

Figure 2.8: Electrification rates in several Asian developing countries vs. GDP/capita (PPP) for the year 2000. Data from IEA (2002b) and World Bank WDI (2004)

Often, a positive feed-back loop is assumed between increased income and growing electricity rates. Increasing income levels lead to an increase of electrification rates, and investments in the electricity sector. At the same time, access to electricity allows to increase income generation as working and manufacturing are possible after dark. Also, more efficient electric machinery and equipment can be used leading to an overall increase

in productivity and income. The last proposition does not necessarily needs to hold: first, many electrification projects don't offer further service or maintenance after the projects end, wiping out the advantages of electrification (Mulugetta et al., 2000). Second, access to electricity is only one of many barriers for economic development; market development and access, financial services (credit) and client's willingness to pay for quality products are also of importance for small manufacturing enterprises (Kooijman, 2005).

Relevance for global energy models
As far as could be extracted from documentation of the IPCC/SRES models none of the models deals explicitly with electrification processes (Table 2.1)[1]. These models implicitly assume that increasing electrification rates are included in the increasing demand for electricity with rising economic activity. This is not necessarily incorrect, but it increases uncertainty of projections for the level of energy demand in developing countries. Electrification (especially if interpreted as grid-expansion) influences primary energy use, since grid or non-grid electricity is generated by different technologies. Non-grid electricity is typically from small-scale renewable energy or oil generators and grid-delivered electricity is from large-scale sources; coal, gas, nuclear. Secondly, the electrification process (grid expansion) is a very capital intensive process and the implicit way of describing electrification in these models may not capture the possible limitations posed by access to capital and economic viability.

3.2 From Economic Activity to Energy Use

3.2.1 Economic structural change and Dematerialization
It is often observed that the nature of economic value added and employment shifts during the development of economies. Typically, developing economies are characterised by a large share of the population working in agriculture (see Figure 2.9, left graph). Historically, developing countries that changed into an industrial economy did this by increasing the production of labor intensive export products. Taiwan, Singapore, Korea and Hong Kong are historic examples; nowadays China and India show a similar pattern. In a later stage the share of the service sector increases in value added and employment. This stage has been observed in developed economies, during the second half of the 20th century. This description of economic structural changes is highly stylized, and it is questionable whether it can be directly applied for individual countries (Jung et al., 2000). Criticism on this concept is recently formulated by historic economists, mainly regarding the shift towards the service sector. For Sweden it was found that, when measured in constant prices per sector, the share of the service sector has been fairly constant over the last two centuries, while the share of industry increased at the expense of the agricultural sector (Kander, 2005). Also, India has a remarkably high share of services (see Figure 2.11 and de Vries et al., 2007a), which influences the prospects for scenario development. Another reason why developing country development might be different is that the decline in the industrial section in developed countries is partly caused by a replacement of (heavy) industry from high to low income countries.

[1] Research on more recent technical documentation and a questionnaire answered by the model developers indicates that in MESSAGE and MiniCAM electrification is modelled explicitly (Urban et al., 2007).

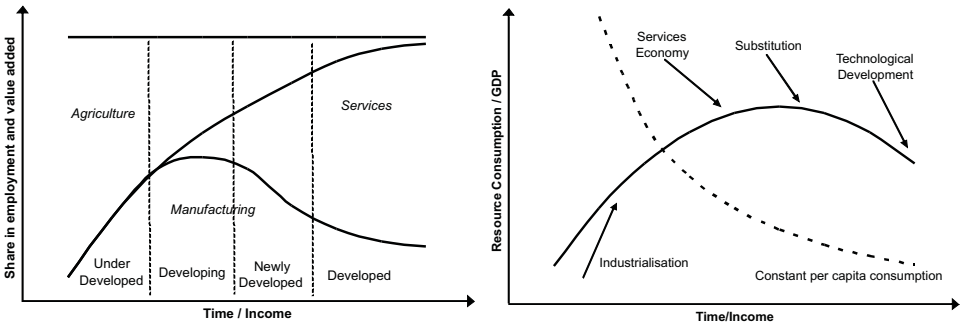

Figure 2.9: Left, typical stages in the share of employment or value added of agriculture, manufacturing and services, based on Jung et al. (2000) and right, the typical intensity of use curve of resources with economic development, based on van Vuuren et al. (1999).

A concept that can be related to economic structural change is the long-term trend of dematerialization. The theory of dematerialization can be summarised in two elements: 1) the intensity of use (in kg/$) of a given material or energy follows a similar pattern for all economies, first increasing with per capita GDP, reaching a maximum and than declining (see Figure 2.9, right graph); 2) the maximum intensity of use declines the later in time it is attained by a given economy (Bernardini and Galli, 1993; Reddy and Goldemberg, 1990). Beside structural change, this pattern is often explained from technical improvements that decrease material input, substitution of new materials with better properties, saturation of bulk markets for basic materials and government regulations (Cleveland and Ruth, 1998). The strength of this concept is its simplicity, the weakness is that technologies and material substitution do not necessarily depend primarily on per capita income and that it does not include the relevant driving forces (van Vuuren et al., 1999). Including or excluding traditional fuels can change the long-term pattern of energy intensity (Gales et al., 2007) and leads to different estimations of energy use in developing countries.

The question is whether these patterns hold for the future of developing regions. These regions may catch up with new, less material- and energy intensive technology (leapfrogging) or show different patterns of economic structural change. One indication that this might happen is that countries which developed their industry and energy system in the 20th century show lower CO_2 intensity curves than earlier industrialised countries, due to leapfrogging over the carbon intensive coal-period (Lindmark, 2004).

Data and Stylized facts

Data analysis for the period 1975-2000 shows that, on average, low-income economies depend largely on agriculture, middle income countries have a relatively high share of industry and high income countries have a high share of services (Figure 2.10, left graph). However, in all income classes the share of industry decreases and services increases. Energy intensity decreases in all classes, which is likely to be related to both the rising share of services and improvements in energy efficiency.

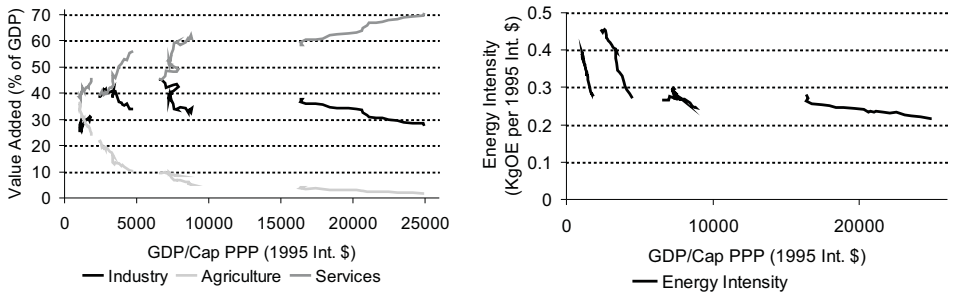

Figure 2.10: Value added (left) and primary commercial energy intensity (right) vs. GDP/capita (PPP) for low income, lower middle income, upper middle income and high income countries, 1975-2000, data from World Bank (2004)

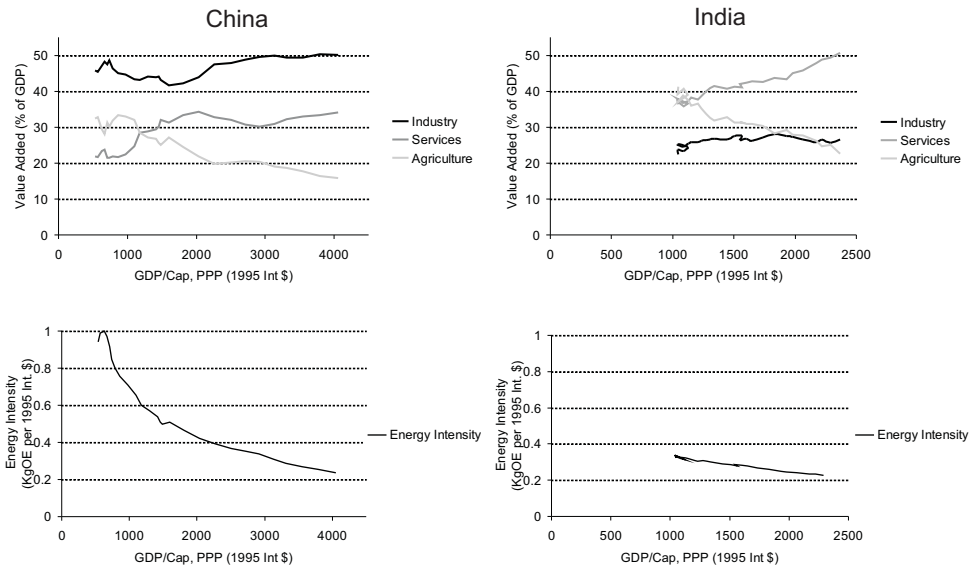

Figure 2.11: value added (upper) and primary commercial energy intensity (lower) vs. GDP/capita for India and China from 1975-2002, data from World Bank (2004)

At the same time, the values for value added and energy intensity of the two major Asian developing countries, China and India, are completely different (Figure 2.11). By 2000, the Indian GDP was for more than 50% based on services, while China relied for 50% on industry. Energy intensity decreased in both countries, in China faster than in India, although the energy intensity for India is already relatively low compared to other low-income countries (see Figure 2.10). Obviously, differences in the energy intensity of the total economy can not only be explained from different economic structures; for instance, the applied technologies and policies, but also climate differences and population density, play a role.

Relevance for global energy models
Economic structural change and energy intensity play a major role in energy demand projections, but differences between countries make it hard to apply these concepts in general in global energy models. All IPCC/SRES models distinguish several economic sectors and therefore it is likely that some form of structural change is included by applying sector-specific economic drivers for energy use (Table 2.1). However, the agriculture sector, which is dominant in economic terms in most developing regions and uses electricity for irrigation, is seldom modelled explicitly. Also, changes in energy intensity within economic sectors are only included in some models, see for example the TIMER model (de Vries et al., 2001).

3.2.2 Income distribution
A difference between developed and developing countries is the distribution of income over the population. Developing countries tend to have a more unequal income distribution, indicating a division in societies between rich elites and poor masses. The classical concept is that with increasing economic development, income inequality would initially increase and, after a top-level, decrease (Kuznets, 1955). Since 1955, studies have been published that reject, affirm or discuss this stylized fact of increasing and decreasing income inequality (see e.g. Glomm, 1997; Saith, 1983).

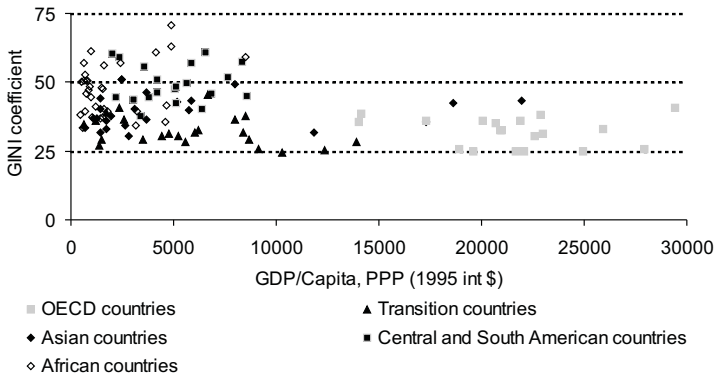

Figure 2.12: GINI coefficients vs. GDP/capita (PPP) for 121 countries. A higher GINI coefficient indicates a more unequal income distribution. Data for different years between 1990 and 2001 from World Bank (2004)

Data and Stylized facts
Data on income inequality are scarce. We used the GINI coefficient as available in the World Bank WDI (2004) as numerical measure for the degree of inequality of income[2]. It appears that income distribution generally tends to become more equal with increasing GDP/capita (Figure 2.12). However, a stylized function for this development, like a

[2] It is determined from two elements: 1) the Lorenz curve which ranks the empirical distribution of a variable and 2) the line of perfect equality in which each element has the same contribution to the total summation of the values of a variable (see e.g. Cypher and Dietz, 1997). Here, the GINI coefficient is given as a percentage and has values between zero (perfect equality) and 100 (perfect inequality).

Kuznets curve, cannot be extracted from these data. What can be noted, though, is that developing countries have a much higher variation in income distribution than developed countries.

Relevance for global energy models
Income distribution is not incorporated in the SRES models (see Table 2.1). Energy demand is mostly modelled as a function of the average GDP per capita and changes in income distribution (e.g. the development of a middle class and matching lifestyle) are not necessarily reflected in this indicator. Initial research indicates that income distribution could be an important factor in transport energy demand but more research is needed to explore this topic for long-term global energy modelling (Storchmann, 2005). In this respect, it is important to realize that independent modelling of high and low income groups may result in very different dynamic behaviour than suggested by the averages (see van Vuuren et al. (1999) for an example with high and low income regions). A tentative indication is that models that ignore income distribution differences in developing countries tend to underestimate energy behaviour that is typically related to low- of high income groups, e.g. the use of traditional energy or the electricity and transport behaviour of high income households.

A complicating factor for including income distribution in energy modelling is the availability and quality of data. Long-term time series are rare, measuring is not consistent and future projections are not provided by macro-economic models. Another pitfall is the possible interference with other developments, like urbanization and decreasing household size. However, it could be worthwhile the attempt because it adds a new dynamic process to global energy models; the available data provide a starting-point and future assumptions can be part of a scenario storyline.

3.2.3 Informal economic systems

Most energy models use GDP per capita as a driver for energy use. Apart from the issue of the underestimation of economies of developing countries using market-exchange rate data (which can be solved by using PPP data, see further), GDP may still not be a good indicator for the energy intensity of activities, as developing countries have a large informal sector. This informal economy involves the unofficial transactions that take place in the real world, but that are not reflected in official economic descriptions. It is a broad concept, for which different scientists use different definitions, including or excluding illegal activities, tax evasion and monetary and non-monetary transactions (Schneider, 2005). The main 'drivers' for the informal economy appear to be the tax burden and social security contributions, the intensity of regulations, social transfer systems, overregulation and high cost on the official labour market (Schneider and Enste, 2000). Informal economies exist all over the world, but in developing countries the informal economy usually forms a much larger share of the total economy (Chaudhuri et al., 2006; Kahn and Pfaff, 2000): on average in 1999-2000 41% of the total official GDP, against an average of 17% in OECD-countries (Schneider, 2005).

Data and Stylized facts
The main problem of informal transactions is that they are hard to measure; data have to be derived from indirect indicators. Several methods exist to assess the size of the informal economy. The direct approach uses surveys and samples, but its reliability might be weak. Indirect methods use discrepancies between several statistics, for instance between national expenditures and income statistics. More advanced methods use the expected amount of transactions in the economy or look into the physical input of the economy (e.g. electricity) as an indicator for the real economic activity. The DYMIMIC model approach (Schneider, 2005) uses multiple input and output indicators to estimate and explain the size of the informal economy.

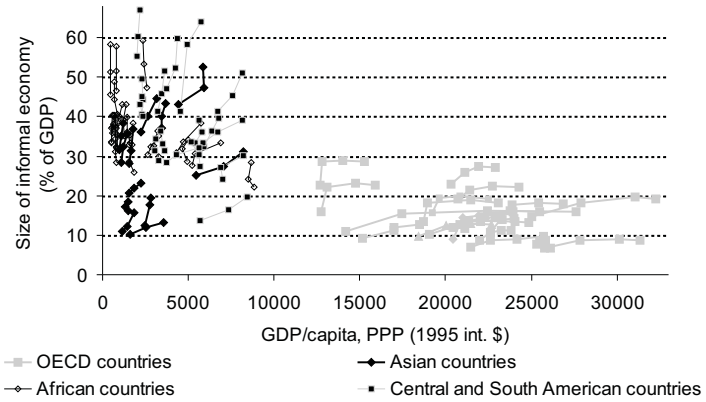

Figure 2.13: Estimations of the size of the shadow economy for several countries vs. GDP/capita (PPP). Data from World Bank WDI, (2004) and Schneider (2005) data points for developing regions: 1990/1991, 1994/1995 and 1999/2000, for OECD regions: 1989/1990, 1994/1995, 1997/1998 and 1999/2000.

Figure 2.13 shows estimations of the size of the informal economy for a global set of countries, clustered in world regions. Also on a country basis, estimations for OECD countries are generally much lower and show less variation than developing countries (as indicated by the arrows). Over time, the size of the shadow economy increased in all countries during the 1990s, also the OECD countries. This may be a consequence of increasing burdens of taxation and social security payments, combined with rising state regulatory activities (Schneider, 2005, 2006).

Relevance for global energy models
The existence of informal economic systems is of importance for global energy modelling as it indicates that the official economic activity (GDP/capita), often used as driving force for energy demand, does not reflect actual economic activity. Usually, the actual economic activity is higher, indicating a different relation between economic activity and energy demand. The cross-country observation of a declining informal economy with increasing income (arrows in Figure 2.13) indicates a process of 'formalizing' the economy. If informal activities are formalised, the official economic growth is artificially high and energy intensity (in GJ per official dollar) decreases rapidly. See for example Figure 2.11,

in which China and India show rapidly declining energy intensities; this might also be explained from formalization (or monetization) of the economy. As energy intensity numbers are often interpreted in terms of energy efficiency – estimates for improvement in developing countries might be overestimated.

Informal economic systems are not included in the SRES models (see Table 2.1). Clearly, there is a relationship between the discussion on the correct metric of GDP data (PPP versus MER, see introduction) and the size of the informal economy. One possible explanation of the large differences in the PPP/MER ratio is that informal economic activities decrease the prices of non-tradable services and goods also on the official market, increasing the purchasing power of consumers. The relation between PPP and the informal economy is unfortunately barely understood (Schneider, 2006) – and alternative explanations for high PPP/MER ratios also exists (van Vuuren and Alfsen, 2006).

3.3 The context of development

An implicit assumption of many global energy models is that the future of developing regions can be derived from experiences during the last decades in industrialised regions. This focus on only the recent past of industrialised regions (for practical reasons), unfortunately implies that potentially valuable information from the times that Western countries were at the economic activity level (but not technology level) of present-day developing countries is not often used to develop insights in developing countries trends. Above, we discussed some characteristics of energy systems and socio-economic developments that mark the difference between developed and developing regions. A final series of issues is related to the context in which energy systems are developing: depletion of fossil resources, climate change and local air pollution. These issues are not unique for developing regions (high energy prices and air pollution were also relevant for Western countries in the 19th century) but they might drive energy systems in developing countries in a different direction than industrialised regions since 1960. Generally, these issues are more elaborately included in global energy models than the issues discussed above (see Table 2.1).

3.3.1 Fossil energy resource depletion

The issue of resource depletion and increasing energy costs is included in all SRES models, mostly based on a single fossil resource assessment (Rogner, 1997) (see Table 2.1). This is the most straightforward impact of resource depletion: some energy sources become more expensive upon depletion, causing a shift towards competitive alternatives. A second impact is the feedback of rising long-term energy costs (or at least a break with the long-term decline) on economic development, a process that can only be modelled in integrated energy-economy models (many of the SRES models are partial equilibrium models and do not capture this feedback). The question here is whether experiences during the oil crisis can be used to model expected future depletion of fossil resources. It should be noted that as oil-importing developing countries have a higher energy intensity, they are much more vulnerable to energy price increases than Western countries (Lucon et al., 2006; Srivastava and Misra, 2007). At the same time, long-term economic history shows that energy prices were also relatively high during the early stages of economic development in Western

countries (Kander, 2002); this period might provide valuable lessons to global energy models.

3.3.2 Climate change

Historically, climate change has hardly had any impact on the development of energy systems, both in developing and industrialised regions. However, since energy use is responsible for the majority of greenhouse gas emissions and climate change is expected to influence economic development (Halsnæs et al., 2007; O'Brien et al., 2004), it becomes a relevant issue for energy systems in developing countries. Climate change can have two major impacts on the development of the energy system. One is that changes in climate can lead to changes in energy demand projections (e.g. higher cooling demand) or to constraints in energy production (e.g. operational requirements in power plants). A much more relevant impact, however, is the impact of climate policy on energy system development. Model studies stress the importance of involving developing countries in international climate policy – in order to avoid high costs and to keep ambitious climate policy targets attainable (e.g. van Vuuren et al., 2007). However, as energy technologies with low or zero greenhouse gas emissions are usually more expensive than their fossil-fuel alternatives this raises the issue who will pay for these additional costs. At the moment, the position of developing countries in international negotiations is that the additional burden of climate policy would damage their abilities for development. Current models are in principle well equipped to assess the additional costs of mitigation trajectories, also on a regional basis (including different proposals for differentiation of commitments among developed and developing countries). There are, however, open issues with respect to additional implementation barriers (e.g. information, risk) in developing countries that are poorly captured by these models. In any case, climate policy might put developing (and developed) countries on a different trajectory than observed historically.

3.3.3. Urban air pollution

One of the major present-day energy-related problems in developing countries is urban air pollution. During the industrial revolution, Western countries also suffered from urban air pollution (Mosley, 2001) and more recently other forms of regional air pollution (e.g. acidification). Especially in the last decades, these problems have been solved using end-of-pipe technology for sulphur emissions, volatile organic compounds and nitrous oxides. Since most of these technologies are affordable and available in developing regions, this issue alone might not be very decisive on the future development of energy systems. However, if combined with climate policy (e.g. van Vuuren et al., 2006a) or if renewable energy is promoted as a solution (e.g. Boudri et al., 2002), urban air pollution can benefit from other developments in the energy system that have an impact on the energy system structure. Interestingly, the link could also work the other way around. While historically, end-of-pipe solutions have been favoured, integrated consideration of both air pollution and climate policy objectives, could lead to a preference for energy efficiency and low-greenhouse gas energy supply options driven primarily by the desire to reduce health impacts of air pollution (Bollen et al., 2007).

4 Discussion and Conclusion

In this article, we have discussed the handling of developing countries in energy-climate models, suggesting that, given the increasing importance of developing countries, these models might need to be reformulated to better capture the dynamics of developing country energy systems. Obviously, the need of focus meant that we have focused on only a selection of the issues that are relevant in this context. Other key-issues like development of infrastructure or technology leapfrogging could have been discussed are well. Also examples of only a limited set of models (the IPCC/SRES models) have been used as they represented a useful consistent scenario database. The choice of models influences the results, but to our experience most discussed issues are not well captured in other global energy models either (Urban et al., 2007). Most data used in this article are derived from global databases: the World Bank WDI, the FAO statistical database, the IEA world energy outlook. These data are harmonised and comparable between countries, but insight in the reliability and collecting methods is generally weak. Finally, global energy models are (also) used to support a wide range of policy-making and weakness in modelling the energy systems of developing countries might lead to inaccuracies in policy-making. However, it is at this stage not possible to speculate about what the inclusion of the developing country issues in global energy models would mean for the results. Many of these issues have implications that work in two directions, both increasing and decreasing energy use and GHG emissions.

In this study, we found that the results of the IPCC/SRES global energy models for Asia are consistent with general "energy development" theories such as the environmental Kuznets curve and the energy ladder. Although some of the driving forces behind these concepts are already included in these models, several improvements for example on traditional fuel use, electrification, structural change, income distribution, the informal economy and a feedback of climate change on the economy can increase their credibility for changes in the energy systems of developing countries.

The modelling of traditional energy, which is currently only done in three of the SRES models, can be improved by including wood-supply. This could be linked to forestation policies and health policies related to indoor air pollution. Explicitly accounting for electrification might improve the quality of projections on energy demand and technology choices for electricity generation. This could be related to electrification policies and the role of off-grid (renewable) energy systems. Economic structural change seems to be included in all SRES models, but the agriculture sector is not explicitly modelled. Modelling income distribution and rural/urban differences gains more insight in the impact of different lifestyles. Establishing a relation between different income groups, their behaviour towards energy use and linking this to income-related energy pricing could be useful. Modelling the role of the informal economy might be useful, but seems not possible with current knowledge. Modelling the impacts of climate policy and climate change on the economy could be valuable to enhance insight in suitable GHG reduction mechanisms and their full effects.

Chapter 3: SUSCLIME: Exploring strategies for resource depletion and climate change[1]

Abstract
Resource depletion and climate change are two factors that influence energy use in such way that the future development trajectory of low-income regions may well be substantially different from the historic development in high-income regions. In this chapter, we use a simple system-dynamics model (SUSCLIME) that describes the dynamics of, and interactions between, population, economy, energy and climate systems in a highly stylized form. We use this model in two variants: 1) using a set of decision rules to allocate investments on the basis of current information and 2) forward looking agents can apply policy measures and assess future effects of their strategies. We conduct a series of experiments, aiming to identify strategies to cope with the potential impact of resource depletion and climate change on the development trajectories of high-income and low-income regions. We find that in SUSCLIME the low-income region is more vulnerable to both issues. This is because this region is more energy intensive and has a lower economic productivity. Therefore, both the potential impacts and the costs of avoidance-strategies put a larger burden on the developing economy. Cheaply imported fossil energy is the preferred option to avoid endogenous resource depletion, although this puts the importing region in a dependent position. With respect to climate change, regions balance between short term emission mitigation and long-term impacts. Our experiments suggest that it is attractive for low-income regions to postpone climate policy until a certain income level is reached. A co-benefit of a long-term focus on minimising emissions and avoiding climate change is that it also slows down fossil resource depletion. A short-term focus to reduce impacts from depletion of endogenous fossil resources will, on the other hand, probably have not much synergy with climate policy because imported fossil energy is preferred over non-carbon energy options.

[1] Co-authors: Chris Roorda, Bert de Vries and Kristian Lindgren. A travel grand from the Netherlands Organisation for Scientific Research (NWO) was gratefully accepted.

1 Introduction

Several key-challenges face the world energy system today. First of all, if societies all around the world decide to significantly reduce greenhouse gas emission, a major transition will be needed from a primarily fossil-energy based system to a system based on zero- and low-greenhouse gas emitting technologies. Second, throughout the century fossil energy resources are likely to become scarcer. The currently high oil prices are seen by some as indicative of such supply-constrained world. These challenges may have very different impacts for low-income than for high-income regions. In energy analysis, global energy models and scenarios analysis are used to explore possible future developments and trajectories. Most of these models, although very detailed with respect to technologies, lack key-dynamics to explore the relationship between energy use, climate change and development. Here, we use a highly stylized system-dynamics model (SUSCLIME) that describes the population, economy and energy system and the processes of resource depletion and climate change.

The SUSCLIME model (de Vries, 1998) was originally constructed to educate students and policy-makers on the dynamics of resource depletion and climate change and to explore the options for policy in a multi-region world with differences in resource base and climate impacts. SUSCLIME simulates development of population, economy and energy systems of a set of (hypothetical) regions. These regions are linked via energy trade, feedbacks from climate change and transfer of knowledge on non-carbon energy technologies. The model was developed as a game, in which human players represent the governments of the regions and allocate every five year investments among different parts of the economy and the energy system. In this chapter we use an adjusted version of this model, with two major adjustments. First, allocation of investments is based on several simple decision rules. Second, human players are replaced by automated agents. These regional agents can apply several policy measures and look forward to assess the consequences of their strategy with respect to depleting resources and climate change.

The aim of this chapter is to identify strategies to cope with the potential impact of resource depletion and climate change on the development trajectories for both high-income and low-income regions. Hence, we run the model for two regions that represent “high and low income regions” in a two-region world. We conduct a series of experiments, involving depletion and import of fossil energy depletion and climate impacts and policies. The aspect of climate change is analysed in a simplified setting: regions only experience impacts from climate change caused by their own emissions. This is to avoid the complex issue of interaction between agents on the negotiation of climate policy, because we only aim to analyse differences in strategies between high-income and low-income regions. From a game theory point of view, this model represents for each region an intertemporal dilemma between short term maximization of consumption with high use of (cheap) fossil energy, and the long-term impacts of depleting the finite fossil energy stocks and climate change. The possibility of realising higher economic growth by importing fossil energy if endogenous resources become depleted adds another element.

Agent-modelling is based on the description of 'human' behaviour by simple rules and can be distinguished between agent-based and multi-agent models. Agent-based models usually contain many (micro-) agents that are characterised by simple behavioural rules and together lead to emergent behaviour on the macro-level. For instance, agents with prescribed strategies to cope with the prisoners dilemma (Eriksson and Lindgren, 2005) or with common's dilemma's (Jager et al., 2000). Multi-agent models contain several agents that are more intelligent or equipped to analyse the (expected) results of their behaviour. For instance, agents that explore strategies within the Fishbanks common's game (Kozlak et al., 1999) or take policy decisions on the basis of the expectations with respect to climate change (Janssen and de Vries, 1998). The multi-agent SUSCLIME model follows the latter tradition: agents optimise their strategy in dealing with resource depletion and climate change. This paper describes the first phase of agent-development, in which the strategies of individual agents are explored with a minimum of interactions. This provides a baseline to interpret agent-behaviour once more interactions are allowed.

In this chapter, we first describe the basics of the SUSCLIME model (section 2) and formalisms that describe the 'agents' (Section 3). Section 4 explores the model's behaviour with respect to fossil energy depletion and Section 5 explores the impacts of climate change. Section 6 analyses the combined case of resource depletion and climate change. Finally, Section 7 discusses and concludes.

2 SUSCLIME model description

2.1 Model overview

The SUSCLIME model simulates the process of demographic and economic development, during which stocks of goods producing capital (K_P, factories, tractors, etc) and consumption capital (K_C, dwellings, schools, roads, hospitals etc.) are built up. Investment in these capital stocks takes place by allocating the produced goods among the different capital stocks. Energy is required to operate the goods production capital and consumption capital stocks. Energy is supplied by a capital stock that produces fossil energy and one producing a non-carbon (or renewable) form of energy (e.g. hydropower, nuclear power, wind or sun). The demand for energy evolves as a function of income in the form of an average energy-intensity, which can be decreased by investing in energy efficiency measures. The use of fossil energy leads to CO_2 emissions, which contribute to the enhanced greenhouse effect and affects the global climate. This influences the life time of all capital stocks (because adaptation often requires early retirement of existing infrastructure) and the productivity of the goods production and consumption capital stocks. Figure 3.1 shows the most important dynamic relations in the SUSCLIME model. For more information on the backgrounds of the SUSCLIME model see de Vries (1998)

The simple model does not permit much meaningful validation with real-world events. Yet, to make simulations somewhat realistic, the model relationships are calibrated to aggregate meta-relations or 'stylized facts', established from time-series or cross-country data as

provided by the World Bank (2007) or IEA (2007a)[2]. All monetary flows and stocks in SUSCLIME are expressed in 'goods', population in 'persons' and energy in 'energy units'. Roughly, one unit of goods can be associated in the order of 1000 Euro or USD and one energy unit approximates PJ.

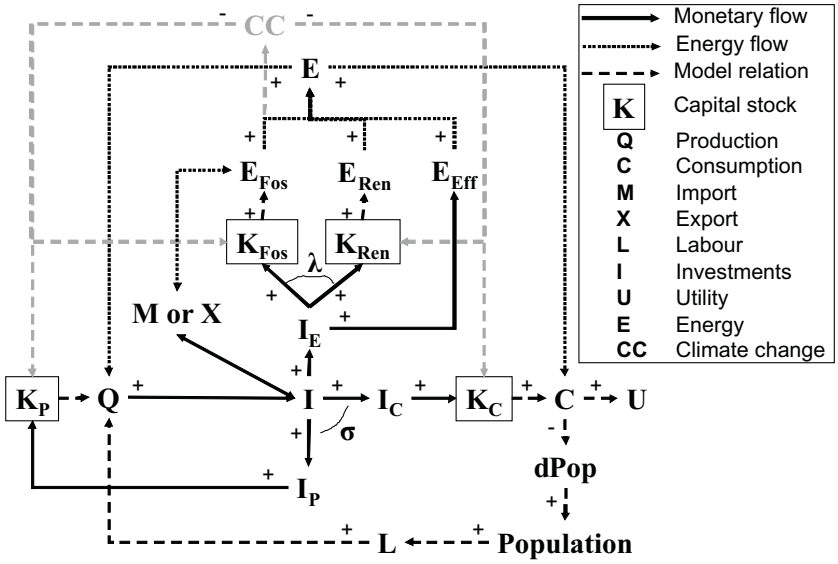

Figure 3.1: Overview of dynamic relations in the SUSCLIME model

2.2 Population

Population growth in SUSCLIME declines logarithmically as a function of income, a stylized form that can be derived from historic data available in the World Development Indicators (WDI) of the World Bank:

$$Population_{(t)} = Population_{(t-1)} \cdot \delta Pop_{(t)} \qquad 1$$

$$\delta Pop_{(t)} = 1 + 0.03 \cdot C_{(t)}^{-0.6} \qquad 2$$

in which *C(t)* represents consumption per capita[3] (i.e. the average income net of investments). It is an aggregate representation of the empirical observation that an increase in development correlates well with lower death rates and, with a delay, lower birth rates. Dynamically, this part of the model contains the positive feedback loop that an increase in per capita income leads to lower population growth, which will further increase available income per capita.

[2] See for instance the IFs model (Hughes, 1999) for a similar use of aggregate relationships based on correlations.
[3] This equation is valid with C>0.5 goods/capita /yr

2.3 Economy

The economic model of SUSCLIME has two major capital stocks: goods producing capital, K_P, and consumption capital, K_C (Figure 3.1). Goods producing capital (K_P) represents raw material exploitation (excluding energy) and the processing and manufacturing of goods. Basically, it is the machinery and factories in the economy: tractors, food processing plants, chemical and car factories etc. Consumption capital (K_C) includes the aggregate of all capital that is used to provide welfare services, from direct consumption of food, paper etc. to mobility (cars, trains, airplanes, but also infrastructure) and shelter (dwellings, offices etc.). The capital stock K_C is associated with the delivery of income or consumption: C, defined as one unit of annual income per unit of capital (see Figure 3.1). This implies that in comparison to some other simple economic models, consumption in SUSCLIME is not directly taken from production – but indirectly via the investments into consumption capital that produces consumption of goods and services. Utility derived from income is a logarithmic function: *ln(C)*. All capital stocks are modelled similarly, with the actual stock being the result of the existing capital stock, plus investment (I) minus depreciation (D):

$$K_{(t)} = K_{(t-1)} + I_{(t)} - D_{(t)} \qquad 3$$

Depreciation of capital is represented as an exponential decay function of capital lifetime (LT), which later on in this paper is assumed to be a function of climate change (see Section 2.5):

$$D_{(t)} = \frac{K_{(t-1)}}{LT_{(t)}} \qquad 4$$

We assume equilibrium in the sense that annual investments in all four capital stocks and expenses on energy import (M) equal economic output (Q) plus income from energy export (X):

$$Q_{(t)} + X_{E(t)} = I_{P(t)} + I_{C(t)} + I_{E(t)} + M_{E(t)} \qquad 5$$

Economic output (Q, i.e. the annual production of goods and services) is a function of labour force (L, fixed at 25% of population) and labour productivity (Λ, in goods per labourer per year). The latter is a function of goods producing capital (K_P), consumption capital (K_C), labour force, energy (E) and climate change impacts (CC), with a maximum value of Λ_{max}:

$$Q_{(t)} = L_{(t)} \cdot \Lambda_{(t)} \qquad 6$$

$$\Lambda_{(t)} = \Lambda_{max} \cdot f(K_{P(t)}, K_{C(t)}, L_{(t)}, E_{(t)}, CC_{(t)}) \qquad 7$$

This function is schematically represented in Figure 3.2. Economic output results from two primary inputs: goods and services producing capital (K_P) and labour (L). In essence, goods production follows a standard two-factor production function in which more manufacturing capital per labourer (thus, the K/L-ratio) increases productivity, but at a declining marginal rate. This formalism of economic production (in Figure 3.2 the chain $K_P \rightarrow K/L$-ratio $\rightarrow \psi \rightarrow \Lambda$) is similar to the Cobb-Douglas two-factor production function in a conventional neoclassical growth model, with an elasticity of output to capital of 0.8. Real-world economic growth is a much more complex phenomenon in which amongst others technology and institutions play an important role (see e.g. Helpman, 2004). These factors, in particular technology which has been found to be a dominant albeit 'black box' determinant, is at present not included in SUSCLIME. As a result, goods production and income stabilise at a maximum level, instead of growing exponentially as a consequence of the assumption of exponentially growing total factor productivity.

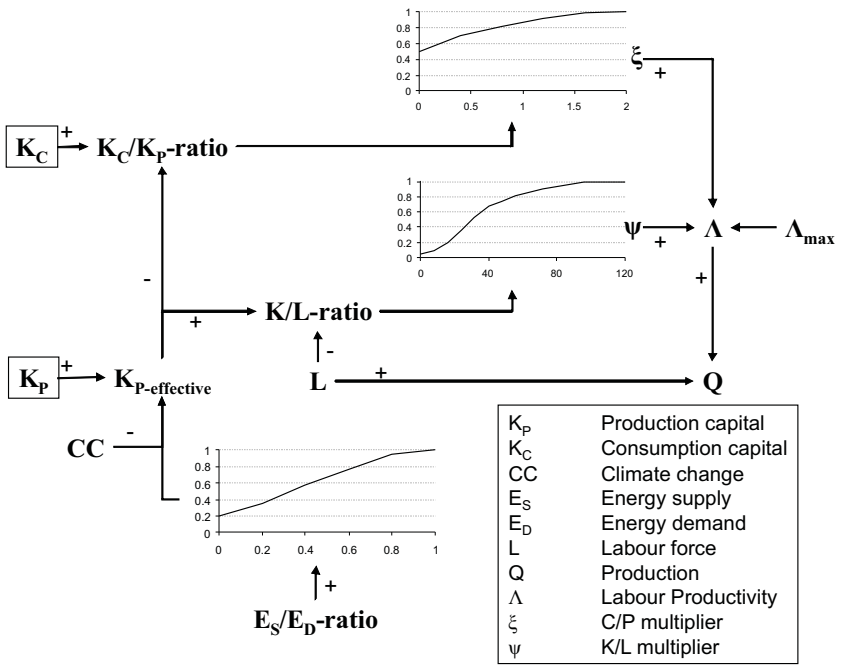

Figure 3.2: Causal-loop diagram of goods production (Q)

In order to add some realism and boundary conditions, three additional features have been added. First, the objective to maximize welfare implies that the consumption capital stock (K_C) is considerably larger than the goods producing capital stock (K_P). We assume that industrialisation only leads to productivity growth if the welfare of the population increases proportionally. This is implemented via a labour productivity loss if the consumption capital stock (K_C) becomes less than twice the goods producing capital stock (K_P). Secondly, both capital stocks also require energy (see Section 2.4). If demand for energy outgrows supply, K_P is reduced with a multiplier, which reduces economic output Q via

eqn. 7. The reduced value of K_P is indicated as $K_{P\text{-}effective}$ in Figure 3.2. Finally, climate change has two impacts on goods production: it shortens the lifetime of K_P and it reduces K_P with an impact similar to the one from energy shortages. Consumption capital has the same relations to energy and climate change as goods production capital. The allocation of investments among the two economic capital stocks is based on a decision rule that maximises labour productivity (Λ) as function of investments in K_P and K_C, using the savings rate (σ, i.e. the share that is invested in K_P):

$$\text{Decision rule 1: } \sigma_{(t)} = \sigma_{(t-1)} + \frac{\psi_{(t)} - \xi_{(t)}}{5} \qquad 8$$

Thus, $\sigma_{(t)}$ stabilises if both multipliers approach 'one' and labour productivity is at its maximum value. The stabilisation factor of 5 is introduced to prevent short-term oscillating behaviour; further, the value of σ is limited between 0.1 and 0.6 (for details see: Roorda, 2008). The investment flows in goods producing capital (I_P) and consumption capital (I_C) are derived from σ, goods production (Q) and investments in energy producing capital (I_E):

$$I_{P(t)} = \sigma_{(t)} \cdot (Q_{(t)} - I_{E(t)}) \qquad 9$$

$$I_{C(t)} = (1 - \sigma_{(t)}) \cdot (Q_{(t)} - I_{E(t)}) \qquad 10$$

2.4 Energy

Energy is needed to operate the capital stocks K_P and K_C. How much depends on the energy-intensity, i.e. the amount of energy required per unit of capital stock. This is assumed to be a function of income (C). To produce the necessary energy, investments into energy capital (I_E) are needed and can be allocated among three options: energy efficiency (I_{Eff}), non-carbon (or renewable) energy production (I_{Ren}) or fossil energy production (I_{Fos}). Besides, economic output can be spent on import of fossil energy (M_E). The balance equation, in monetary units, is:

$$I_{E(t)} = I_{Eff(t)} + I_{Ren(t)} + I_{Fos(t)} + M_{E(t)} \qquad 11$$

We simulate the allocation of investments with a couple of relationships. First, investments in energy efficiency are a direct function of the average cost of energy. Secondly, the market shares of renewable and fossil energy are a function of relative cost differences. Thirdly, a further allocation is made between endogenous production of fossil energy and imported fossil energy, also based on relative cost differences. Investments in energy have priority over investments in economic capital stocks, but we assume they cannot exceed 25% of total economic output in order to stay within real-world ranges. Fossil energy resources experiences depletion: productivity in terms of energy units produced per unit of capital stock declines with cumulated use. Renewable energy includes the dynamics of learning-by-doing: more cumulative renewable energy producing capital leads to higher

productivity. Finally, as said before, if energy demand outgrows total energy supply, K_P and K_C become less effective. The relations in the model are shown in Figure 3.3.

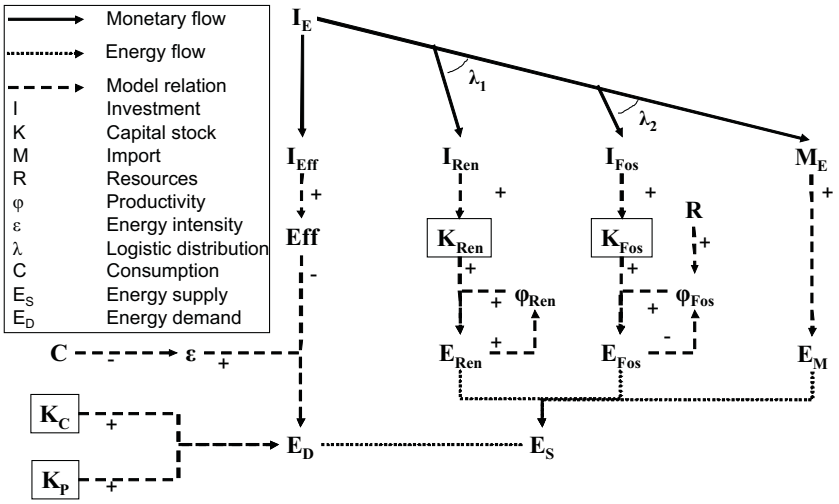

Figure 3.3: Causal-loop diagram of the SUSCLIME energy model

2.4.1 Energy Demand

The demand for energy (E_D) is derived from goods producing capital and consumption capital, with the energy intensity ε determining the ratio between energy demand and production. Total energy demand can be lowered by investing in energy efficiency (*Eff*):

$$E_{D(t)} = (K_{P(t)} + K_{C(t)}) \cdot \varepsilon_{(t)} \cdot (1 - Eff_{(t)}) \qquad 12$$

The energy intensity ε for K_P and K_C changes as function of economic structural change. It is generally observed that with increasing income levels, the share of employment and value added shift from energy extensive agriculture, to the energy intensive industry sector and finally to energy extensive services (see e.g. Jung et al., 2000; van Ruijven et al., 2008b; van Vuuren et al., 1999). In the model, this is reflect by defining energy-intensity as an asymmetric bell-shaped function of per capita consumption, using a formulation from the TIMER model (de Vries et al., 2001; van Vuuren et al., 2006b):

$$\varepsilon_{(t)} = \varepsilon_0 + \frac{1}{\beta \cdot C_{(t)} + \gamma \cdot C_{(t)}^{\ \delta}} \qquad 13$$

with β, γ and δ as shape-parameters (of which δ is assumed negative to maintain a bell-shaped form) and ε_0 the minimum energy intensity[4]. The function is parameterised in such a

[4] The values of the parameters are: β=0.009, γ=1.991, δ=-1, and ε_0=1.5. The derivation of parameters and behaviour of this function is more elaborately discussed in Chapter 4 and 5 of this thesis.

way that ε increases initially with rising consumption levels and then, after a top, decreases towards a constant value equal to ε_0 (Figure 3.4).

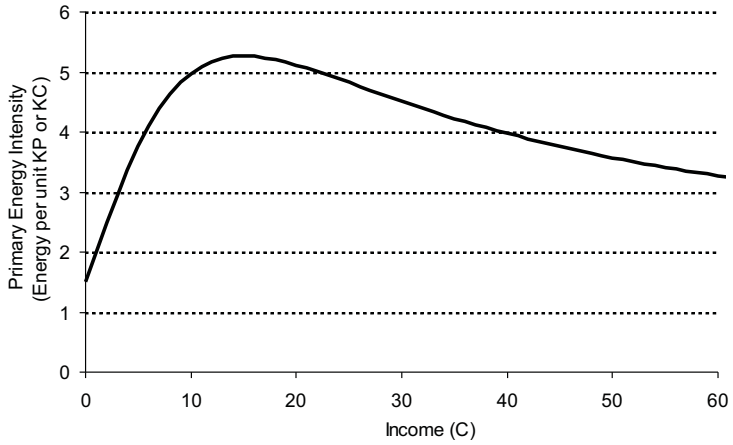

Figure 3.4: energy intensity (ε) as function of income (C), implementation of eqn. 13

2.4.2 Fossil energy production

Energy demand can be met using fossil energy (either imported or locally produced) and non-carbon energy. The productivity of both energy producing capital stocks (K_{Fos} and K_{Ren}) is expressed as the annual production of energy per unit of capital (φ):

$$E_{(t)} = K_{(t)} \cdot \varphi_{(t)} \qquad 14$$

Note that in this formulation the cost of one unit of energy is proportional to the inverse of the productivity: $c \sim E/K$. The initial source of energy supply in SUSCLIME is fossil energy. Resource depletion is introduced in the form of a long term supply cost curve, in which resources are arranged according to their estimated production cost. Many estimations of such curves exist (see e.g. Rogner, 1997). The assumption is usually that the cheapest resources are exploited first until only more expensive resources are left and production costs increase rapidly. The less fossil energy resources remain, the lower the energy productivity (φ_{Fos}) becomes – or the higher the cost of fossil energy becomes. This depletion process is modelled with the following expression for the productivity (i.e. annual fossil energy production per unit of capital):

$$\varphi_{Fos(t)} = \varphi_{max} \cdot \sqrt[3]{R - \sum_{T=0}^{t} E_{Fos\,(T)}} \qquad 15$$

in which φ_{max} is the maximum (i.e. initial) value ($\varphi_{max}=32$). Using the cube root of the fraction of fossil energy remaining means that the cost to produce fossil energy ($\sim 1/\varphi_{Fos}$) initially increases slowly but when the resources get depleted the increase accelerates.

Alternative formulations of fossil energy productivity as function of remaining resources (e.g. square root or exponential) involve similar dynamics. In model-experiments without depletion, fossil energy resources (*R*) are abundantly available and hardly any productivity decrease takes place. In the model-experiments that focus on the impact of fossil energy depletion, the resources are adjusted such that fossil energy is depleted around the year 2020. Because this depends on the size and energy intensity of the economy the following resource base is assumed: in experiments without depletion both countries are initialised with 250e+6 energy units, with depletion, the high-income has initially 5e+6 energy units of endogenous fossil energy and the low-income region 2.5e+6 energy units.

2.4.3 Non-carbon energy production

Non-carbon energy refers to all non-fossil energy carriers such as hydropower, solar and wind power, nuclear or bio-energy. We also refer to this energy source as renewable energy. The dynamics of renewable energy production in SUSCLIME are governed by the process of learning-by-doing. This increases the productivity (cq. decreases the cost) with increasing cumulative production, representing the processes of economies of scale and innovation. Initially, learning only results from cumulative production within the region itself, but with a delay of 15 years cumulative production in other regions is assumed to contribute as well. In mathematical terms, the learning curve is generally described as:

$$\varphi_{Ren(t)} = \varphi_0 * (\sum_{T=0}^{t} E_{Ren\,(T)})^{\pi} \qquad 16$$

in which φ_0 is the base productivity (i.e. annually 12 units of renewable energy per unit capital) and π is the learning coefficient. One interpretation of π is in terms of the progress ratio PR, equal to 2^{π}, which indicates the fractional reduction per doubling of cumulative production (see also Junginger, 2005). We use a moderate progress ratio of 0.9.

2.4.4 Investment allocation and fossil energy import

Investments in energy producing capital stocks are allocated on the basis of a logit function. Based on the ratio of productivities, a higher market share (or investment share) is allocated to the most productive (i.e. cheapest) energy source. We use a nested logit function: in first instance, the market shares of renewable and fossil energy are determined; second, the market share of fossil energy is further divided over endogenous production and imports. The decision rule for market allocation between fossil energy and renewable energy is:

$$\text{Decision rule 2: } MS_{Fos(t)} = \frac{1}{1 + \left(\frac{\varphi_{Fos(t)}}{\varphi_{Ren(t)}} \right)^{-\lambda_1}} \qquad 17$$

$$MS_{Ren(t)} = 1 - MS_{Fos(t)} \qquad 18$$

in which λ_1 is the logit parameter, determining the sensitivity for productivity differences. The higher the value of λ_1, the more sensitive the allocation reacts to productivity differences; if λ approaches zero, both options get a market share of 50%.

Instead of local production, regions may also decide to import fossil energy, which is attractive if differences in fossil energy productivity exist. The advantages are that the importing region has access to the cheaper fossil energy and the exporting region gains extra goods to invest in its economy. We define a world market fossil energy price P_W as the inverse of the arithmetic average of the productivity in the two regions:

$$P_{W(t)} = \frac{1}{(\varphi_{1(t)} + \varphi_{2(t)})/2} \qquad 19$$

If trade is permitted in the model experiment, the actual amount of traded fossil energy is determined by the importing region on the basis of, again, a logit formulation:

$$\text{Decision rule 3: } MS_{M(t)} = \frac{1}{1 + \left(\frac{\varphi_{M(t)}}{\varphi_{Fos(t)}}\right)^{-\lambda_2}} \cdot MS_{Fos(t)} \qquad 20$$

with $\varphi_M = 1/P_W$ the average fossil energy productivity of the exporting and importing regions and MS_{Fos} the market share of fossil energy according to eqn. 17. The fossil energy price in the importing region now equals:

$$P_{Fos(t)} = \frac{MS_{M(t)}}{\varphi_{M(t)}} + \frac{(1 - MS_{M(t0)})}{\varphi_{Fos(t)}} \qquad 21$$

2.4.5 Energy efficiency improvement

If energy costs are high, it may be attractive to invest in energy efficiency measures and decrease the demand for final energy. We assume that energy efficiency investments are initially cheap, but due to diminishing returns further efficiency increases become gradually more expensive. We use a simplified mathematical function from the TIMER model to determine optimal level of energy efficiency investments as a result of weighted average energy cost (*PE*):

$$PE_{(t)} = (MS_{Ren(t)} \cdot P_{Ren(t)}) + (MS_{Fos(t)} \cdot P_{Fos(t)}) \qquad 22$$

$$\text{Decision rule 4: } I_{Eff(t)} = Eff_{Max} - \frac{1}{\sqrt{PE_{(t)} \cdot f}} \qquad 23$$

in which Eff_{Max} is the maximum efficiency level (50%) and f is a scaling parameter[5]. The actual efficiency gain is derived from the share of efficiency investments (I_{Eff}) in total investments:

$$Eff_{(t)} = Eff_{max} - \frac{1}{f \cdot \frac{I_{eff(t)}}{Q_{(t)}} + \frac{1}{Eff_{max(t)}}} \qquad 24$$

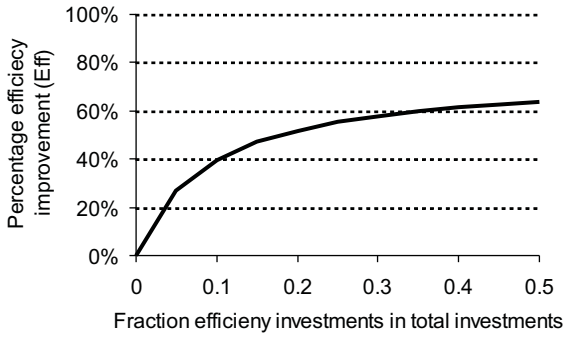

Figure 3.5: energy efficiency improvement (Eff) as function of the share of efficiency investments (I_{Eff}) in total investment (I)

2.5 Climate change

If fossil energy is used, CO_2 is emitted into the atmosphere. Given an average atmospheric lifetime of CO_2 of about 100-year, there is a gradual build-up of this greenhouse gas. This causes a rise in average global surface temperature and sea levels. SUSCLIME contains a greatly simplified climate model as developed by Janssen and de Vries (1998) The atmospheric carbon concentration (p_{CO2}) is based on carbon emissions (E), divided in 5 atmospheric lifetime classes with fractions $c_{1\text{-}5}$ and lifetime $a_{2\text{-}5}$ (the first class has an infinite lifetime), according to the formula (based on Maier-Raimer and Hasselmann (1987)):

$$p_{CO_{2(t)}} = p_{CO_{2(t0)}} + \int_{t0}^{t} 0.47 \cdot E_{(\tau)} \cdot \left\{ c_1 + \sum_{i=2}^{5} c_i \cdot e^{\frac{\tau - t}{a_i}} \right\} d\tau \qquad 25$$

The shares of the different lifetime classes are $c_{1\text{-}5}$ = 0.13, 0.2, 0.32, 0.25 and 0.1 and the atmospheric lifetimes are $a_{2\text{-}5}$ = 363, 74, 17 and 2 years. Based on these concentrations, the potential (equilibrium) change of global mean surface temperature is described by:

[5] f is parameterised at 15, such that efficiency investments become attractive at cost levels above the initial energy cost.

$$\Delta Tp_{(t)} = \frac{\Delta T_{2XCO2}}{\ln(2)} \cdot \ln\left(\frac{p_{CO2(t)}}{p_{CO2(t=0)}}\right) \qquad 26$$

in which ΔT_{2XCO2} is the global mean surface temperature change associated with a doubled CO_2 concentration (the so-called climate-sensitivity, which is currently estimated to be most likely above 1.5 and below 4.5 with a central estimate around 3.0 (IPCC, 2007b)). Inertia in the system (in particular due to the huge heat capacity of oceans that slows down the speed by which a new climate equilibrium is reached) implies that the actual temperature increase will lag behind the potential temperature increase, according to the formula:

$$\frac{d\Delta T}{dt} = \beta \cdot (\Delta Tp - \Delta T) \qquad 27$$

where β is assumed 0.05, causing a delay in reaching the equilibrium temperature that belongs to a given CO_2 concentration of about 20 years.

A more uncertain aspect of climate change is the feedback on the economic system. A commonly applied approach is to use quadratic functions for market damages with increasing temperature, see for instance the DICE (Nordhaus, 1993) and MERGE (Manne et al., 1995). A more refined approach is based on the more optimistic assumption that there is not such a thing as an 'optimal climate' as far as the economy is concerned - an implicit assumption in the quadratic function approach – and that society is able to adapt to climate change (Hallegatte, 2005). Now, the socio-economic system still faces impacts from climate change but only when it is *not* in equilibrium with the climate. In practical terms, this means that whenever temperature stabilizes after a period of change the economic system has the ability to adapt to the new climate regime and the impacts will diminish or even disappear. Such an endogenous adaptation of the economy is modelled after Hallegatte (2005). It starts with the notion of an 'adaptive temperature', i.e. the temperature to which the economic system is adapted (T_a). This temperature equals the surface temperature (T_s) when economy and climate are in equilibrium, but diverges from it when the climate changes faster than the socio-economic system can adapt. The adaptation process is defined by:

$$\frac{dT_a}{dt} = \frac{1}{\mu} \cdot (T_s - T_a) \qquad 28$$

in which μ equals $5 \cdot LT_{(t)}$ (the lifetime of capital stocks), which implies that the economic system adapts to the changing climate in five capital turnover periods. If the adaptive temperature and the climate temperature differ, the unadapted economic system faces two

impacts: 1) productivity losses (*CC*), for instance in agriculture and infrastructure, and 2) shorter capital life times (*LT*) caused by increased wear or destruction due to change in climate or early retirement for reasons of adaptation to climate change. Both impacts are assumed proportional to the maladjustment of T_a to T_s:

$$CC_{(t)} = 1 - \alpha_{CC} \cdot \left| T_{a(t)} - T_{s(t)} \right| \qquad 29$$

$$LT_{(t)} = LT_0 \cdot (1 - \alpha_{LT} \cdot \left| T_{a(t)} - T_{s(t)} \right|) \qquad 30$$

The parameters α_{CC} and α_{LT} respectively represent productivity loss and lifetime change due to 1 degree maladjustment of T_a to T_s. In this chapter, we use the same values for α_{CC} and α_{LT} but distinguish two divergent assumptions on the severity of climate impacts: mild with α=0.05 and severe with α=0.1.

2.6 Baseline development

The model includes several decision rules: σ (eqn. 8) determines the allocation between economic capital investments, two nested logistic functions (eqns. 17 and 20) describe investments in energy producing capital and energy efficiency investments based on energy cost ratios (eqn. 23). Using these decision rules, we can determine a baseline or reference economic development path in which fossil energy resources are abundantly available and climate change has no impact on the economy.

As indicated in the introduction, we have implemented the model for 2 regions – representing a high and low income region. The initial values for these 2 regions for the baseline simulation are indicated in Table 3.1. The two regions are assumed to have the same population size, but the high-income region is assumed to have a ten times higher goods producing capital stock and income than the low-income region.

Table 3.1: initial values (1990) for high-income and low-income region

	High-income region	Low-income region
Population (persons)	1000	1000
Income, C (goods/capita/yr)	16	1.6
Goods Production capital, K_p	16000	1600

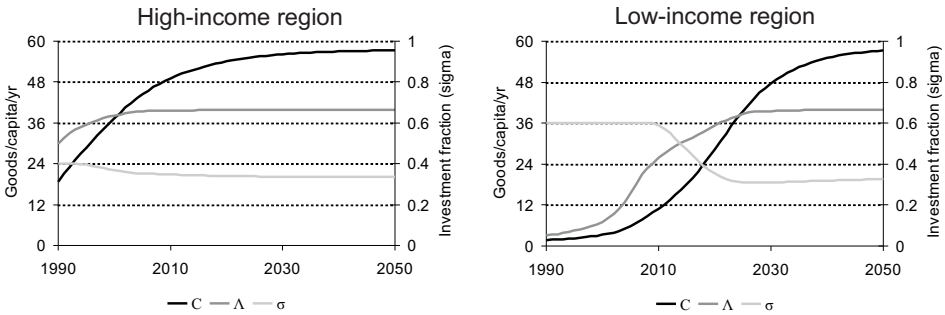

Figure 3.6: Baseline economic development in SUSCLIME without fossil energy depletion, without climate change and without agents (C and Λ are in goods per capita per year and σ is in fraction of investments)

Model results for one feasible parameterization of the unconstrained model and using the initial values in Table 2.1 are indicated in Figure 3.6. The high-income region, initialised at a 1990 income level of 16 goods/capita/yr, continues to increase its labour productivity by building up more goods producing capital. Once labour productivity reaches its maximum level (around 2010), the savings rate (σ) decreases, thus investments in consumption capital increase and income further rises towards almost 60 goods/capita/yr. The growth rate of income decreases from 9%/yr in 1990 towards zero at economic stabilisation. The low-income region, initialised at an income level of 1.6 goods/capita/yr, needs to build up goods producing capital to stimulate economic development. This is done during the first two decades. The savings rate (σ) goes to its maximum level of 60% and labour productivity jumps almost tenfold in a 30-year period as a result of the rising capital-labour ratio. Around 2030, labour productivity reaches its maximum level, investments shift towards consumption capital and income levels keep rising but more slowly. The initially low income growth rates reach a maximum of 14%/yr before the decline towards stabilisation sets in

3 Automated agents

The above model experiment used fixed decision rules without any foresight, expectations or adaptations to future development. As indicated in the introduction, we elaborated the model with automated agents that look forward in the model-world and take policy measures on the basis of their expectations for the future. The premise is that these automated agents act as central planners pursuing the maximum cumulated income within a time horizon T. This implies a trade-off between the highest possible income growth on the one hand and the damages from fossil energy depletion and climate change on the other.

Each agent takes decisions for a single region; hence, our model includes two agents: high-income and low-income.

We provide three policy measures to these agents; all influencing energy investment allocations and only applied if they are relevant for the experiment. First, two policy levers are used to deal with depletion of fossil resources by subsidising alternative options: renewable energy (S_{Ren}) and imports (S_M). These subsidies influence the productivity of these energy options (see eqn. 16 and 20), though only with respect to investment decisions; the actual energy productivity and cost remain unchanged. In this way, the agent can force its region to invest in more expensive energy options. The third policy option is related to climate change, which can be mitigated by limiting fossil energy use. Taxation of carbon containing energy sources (C_{tax}, influencing both endogenously produced and imported fossil energy) decreases their attractiveness and forces the energy system to switch towards renewable energy and energy efficiency. Also this policy measure is only used to influence market allocation, while the actual productivity remains unchanged. The value of these subsidies and taxes is relative to the difference in productivity between fossil energy (φ_{max}, eqn. 15) and renewable energy (φ_0, eqn. 16). The maximum difference between these energy sources is 20 energy units per unit capital per year, which is the maximum value for both subsidies and carbon tax.

The decision of the agent (A) can be formally characterised as a vector of its policy options (S_{Ren}, S_M and C_{Tax}), which are determined as function of its forward looking period (T, 20 or 40 years) and objective function (D):

$$A_{(t)} \begin{Bmatrix} S_{Ren(t)}(T,D) \\ S_{M(t)}(T,D) \\ C_{Tax(t)}(T,D) \end{Bmatrix} \qquad 31$$

The objective function determines what the agent considers to be the most important variable to be optimised. We analysed several objective functions, (combinations of) consumption (C), utility (U), goods production (Q) or import dependence (E_M), both cumulative or in the final year of the time horizon, eventually combined with discounting (see also Roorda, 2008). We found that consumption (C) is the best representation of the performance of the underlying system (i.e. all capital stocks, consumption, goods production and energy, must be balances to maximise income). In this system, introducing a discount rate has the same dynamic behaviour as using a shorter time horizon. Due to the stabilisation of economic activity, the landscape of the objective function is rather flat at high income levels. Therefore, we decided not to use utility, i.e. $ln(C)$, or cumulative functions. Hence, the objective function (D) for this analysis is non-discounted income (C) at the end of the time horizon (T). The value of the objective function is derived from the SUSCLIME model as described above, as function of the policy measures taken by the agent. The agent maximizes its objective function by varying the values of the subsidies and taxes.

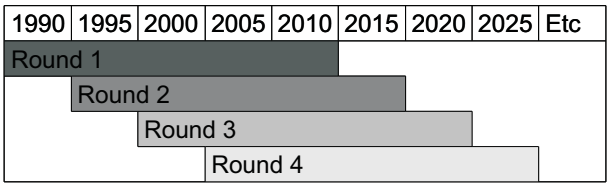

Figure 3.7: Schematic representation of the moving time window with which the agents take their decisions. In this case the time window is 20 years.

The procedure of decision making is as follows: in the starting year (T_{ini}, 1990) the agent looks ahead for a period of T years, in order to maximize the objective function D. During this evaluation the policy measures are assumed constant during the whole evaluation period (T), although in reality it is updated later on when the time window moves to the subsequent rounds. When the agent has found an optimal value of the objective function, the policy measures are set and fixed for the year 1990. Then, the model is run again (with the policy measures fixed for the year 1990) and the agent starts optimizing its decisions for the period 1991-1995. This is done by changing the policy measures for the year 1995 while linearly interpolating the decisions for the years T_{ini}+1 to T_{ini}+4 (i.e. 1991-1994). The objective function is evaluated over the forward looking period T plus the four years of decision-making (e.g. if T=20, the effective evaluation time T_{eval}=1991-2015). When the optimal value of the objective function is reached, the policy measures are set for the period 1991-1995 and the agent moves on to the next round (1996-2000). This moving time window, during which the agent evaluates its decisions, is schematically shown in Figure 3.7.

Each region, high-income and low-income, has its own agent that only takes decisions for its own region. Because we focus on the strategies of high-income and low-income regions, we avoid the aspect of interaction and perform each experiment with one agent at a time. In case of trade, this means that the agent takes decisions for the importing region (which faces depletion of fossil energy resources), while investment allocation in the exporting region takes place on the basis of the above describe decision rules. For climate change, this means that agents only cause and experience impacts from their own emissions and only apply a carbon tax to their own region.

4 Fossil energy depletion and the energy transition

In order to explore how the high- and low income regions respond differently in this system to the challenges posed by climate change and depletion, we have run a set of different experiments (see Table 3.2). These experiments are:

- Experiment 1: Situation with fossil energy constraints, not allowing for trade and without forward looking agents;
- Experiment 2: Situation with fossil energy constraints, allowing for trade and without forward looking agents;
- Experiment 3: Situation with fossil energy constraints, not allowing for trade and with forward looking agents;

- Experiment 4: Situation with fossil energy constraints, allowing for trade and with forward looking agents;

Table 3.2: Assumptions for model experiments on fossil energy depletion

Experiment 1: fossil energy constraint, no trade, no climate change, no agents		
	High-income region	**Low-income region**
Fossil resource (energy units)	5e+6	2e+6
Decision making	Decision rules	Decision rules
Experiment 2: fossil energy constraint, trade, no climate change, no agents		
2a: High-income region fossil energy constraint		
Fossil resource (energy units)	5e+6	250e+6
Decision making	Decision rules	Decision rules
2b: Low-income region fossil energy constraint		
Fossil resource (energy units)	250e+6	2e+6
Decision making	Decision rules	Decision rules
Experiment 3: fossil energy constraint, no trade, no climate change, agents		
Fossil resource (energy units)	5e+6	2e+6
Decision making	Agent (S_{Ren})	Agent (S_{Ren})
Experiment 4: fossil energy constraint, trade, no climate change, agents		
4a: High-income region fossil energy constraint		
Fossil resource (energy units)	5e+6	250e+6
Decision making	Agent (S_{Ren}, S_M)	Decision rules
4b: Low-income region fossil energy constraint		
Fossil resource (energy units)	250e+6	2e+6
Decision making	Decision rules	Agent (S_{Ren}, S_M)

4.1 Experiment 1: the energy transition without trade

As a first experiment, we analyse the behaviour of the autonomously run SUSCLIME model (thus, driven by the decision rules without a forward looking agent) with respect to fossil energy depletion. Both regions are initialised with limited fossil energy resources, trade is not possible and climate change does not occur. The allocation of investments is purely based on the current productivity of the capital stocks, without any forward looking explorations.

As a result of the two dynamic processes, depletion of fossil energy resources and learning of renewable energy production, energy use in SUSCLIME follows a transition from fossil to renewable energy. Initially, fossil energy is the most productive energy source and has a major market share. In the absence of trade, endogenous fossil energy resources become depleted and its costs increase. At the same time, investment in renewable energy becomes more attractive as learning-by-doing increases productivity of the capital stock K_{Ren}. The initial phase of this transition evolves quite smoothly, but when fossil energy depletion speeds up a period of severe tension may occur because not enough renewable energy producing capital may have been installed (Figure 3.8). This energy transition, without trade and only driven by current productivity development, tends to be bumpy because the regions run without anticipation or adaptation full-speed into the depletion of their indigenous fossil energy resources.

Energy efficiency is hardly of any help. During the period that fossil energy resources decrease rapidly, the energy costs increase and investments are allocated towards efficiency measures. However, once the fossil energy resources are depleted, the rapidly declining costs of renewable options absorb most of the available investments into the energy system.

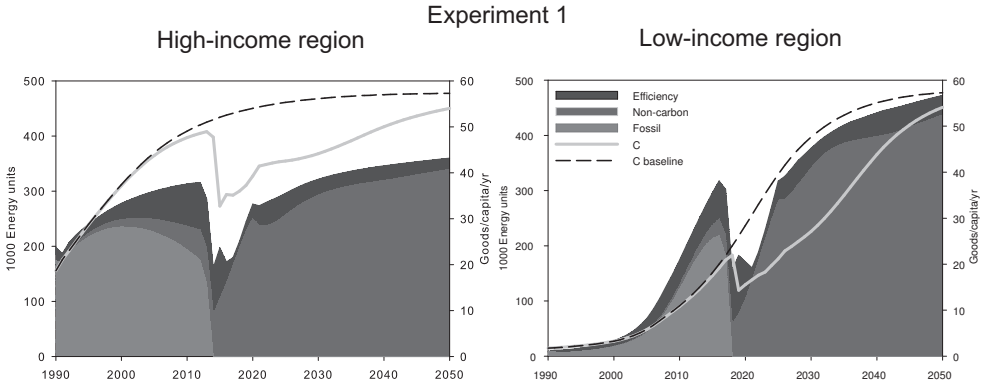

Figure 3.8: A bumpy energy transition: energy supply and income (C) with depleting fossil energy resources without trade and without forward looking agents

What is the difference between the high-income region and the low-income region? Both regions suffer from a major economic disruption once fossil energy resources become depleted and alternatives are not yet adequate (Figure 3.8). The impact in the low-income region is slightly higher than in the high-income region (35% vs. 30% income decrease). Income in both regions deviates downward from the baseline before the actual depletion takes place, because lower energy productivity draws more investments to the energy system.

4.2 Experiment 2: depletion and trade

An alternative to depleting endogenous energy resources is to import fossil energy from other regions. In a way this only postpones the transition to renewable energy sources, because ultimately the resources in exporting regions will be depleted as well. This experiment involves two variants. In experiment 2a, the high-income region has little endogenous fossil energy resources, but has the possibility to import fossil energy from the low-income region, which has abundant resources (Table 3.2 and Figure 3.9, left graph). In experiment 2b, we analyse the opposite situation in which the low income region faces rapid depletion, while it has the option to import energy from the high-income region (Table 3.2 and Figure 3.9, right graph). Both figures also show the impact of extra income from energy exports on income development in the exporting region (with allocation of investments based on the decision rules without agents).

The option to import fossil energy smoothes the transition: it decreases the impact of rapidly declining fossil energy resources and provides time to build up renewable energy producing capital. Ultimately, learning-by-doing makes renewable energy more attractive than imported fossil energy. For the exporting region, trading fossil energy has a minor

positive effect on income. Compared with the bumpy transitions without trade (Figure 3.8), the impact of depletion of endogenous resources on income is much less if trade is allowed. However, there is still a tense transition period and use of more expensive energy over longer periods causes a non-negligible decrease in income after 2030, particularly in the low-income region.

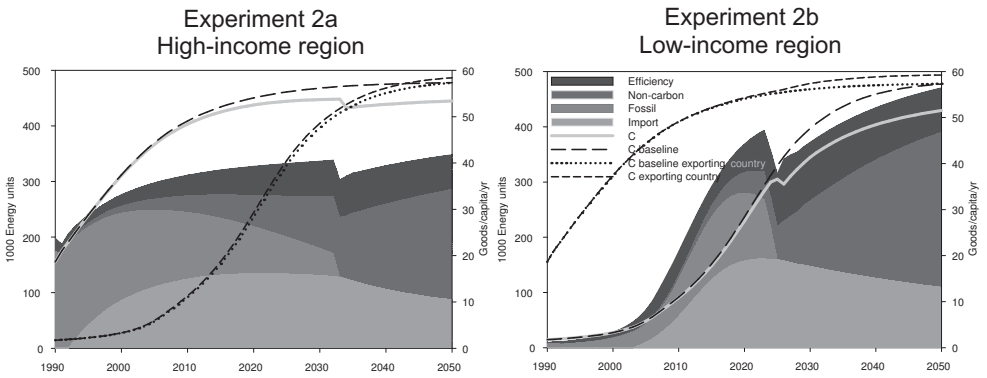

Figure 3.9: Energy supply and income (C) with depleting fossil energy resources with trade without forward looking agents

4.3 Experiment 3 and 4: forward looking agents and fossil energy depletion

We now introduce forward looking agents into the system, conducting two experiments: first, without the option of trade the agents can only subsidise renewable energy; second, with trade the agents can also stimulate the import of fossil energy (Figure 3.10). The agents use a forward looking period of 20 years to assess their policy decisions. Experiment 4 involves two variants in which either one of the regions faces fossil resource depletion (similar to experiment 2).

For the high-income region, the forward looking agent is able to significantly reduce the impact of depletion of endogenous resources on income. Without the option of trade, the agent starts investing early in renewable energy. This smoothes the transition but still, he cannot avoid a decrease of about 10% in per capita consumption levels at the height of the transition (Figure 3.10, upper left graph). If the high-income agent has the option to import energy, he starts subsidizing imported energy and manages in this way to sustain the baseline income growth path (Figure 3.10, lower left graph). There is a gradual and smooth transition to renewable energy without noticeable income loss and without any subsidies for renewable energy.

For the low-income region, the depletion of endogenous fossil energy resources is still a major obstacle to sustained income growth. Without trade, the agent performs better than in the autonomous model run (Figure 3.10, upper right graph vs. Figure 3.8), but the depletion of fossil energy clearly slows down economic development. If trade is possible, also the low-income agent subsidises imported energy and manages in this way to avoid most of the income loss (Figure 3.10, lower right graph). Imported energy becomes quickly the major

energy source, with only after 2020 a gradual market penetration of renewable energy. The latter is not subsidised; its increasing share results from learning-by-doing.

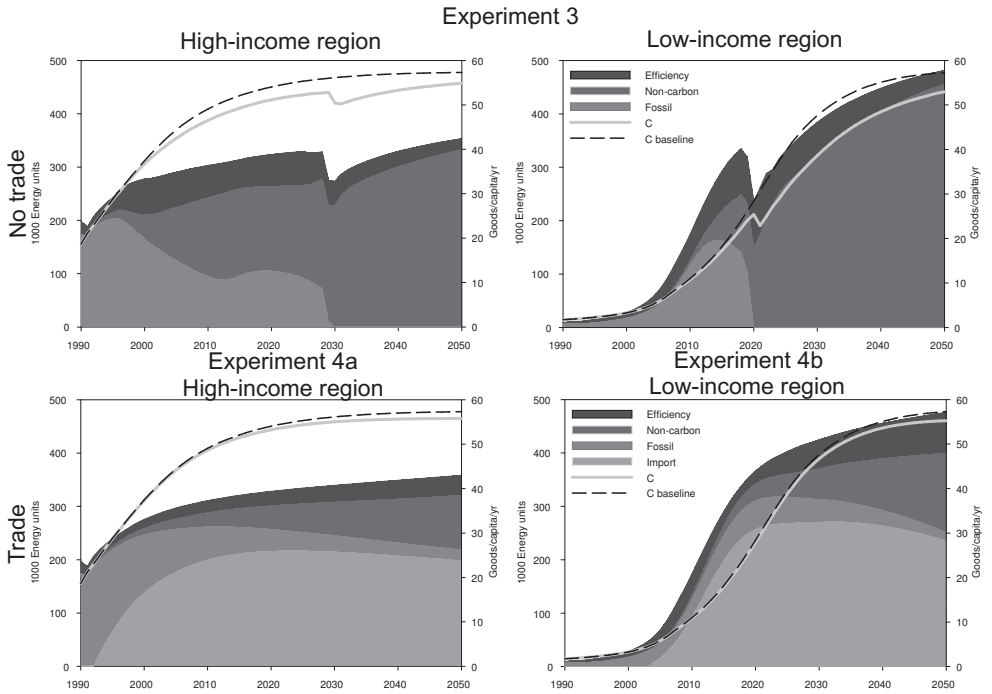

Figure 3.10: Energy supply and income (C) with depleting fossil energy resources with and without trade and with forward looking agents (note that experiment 4a and 4b are separate experiments and only the importing regions are shown)

Evidently, the option of forward looking policy measures improves the performance in terms of (cumulative) consumption. Yet, depletion of endogenous fossil energy resources still has a major impact on the low-income region if energy cannot be imported, due to its higher energy intensity and lower economic productivity. If cheap imported energy is available, depletion does not occur and welfare levels hardly differ from the baseline situation. It has a downside, too: the region becomes quite dependent on energy imports with the associated vulnerabilities in terms of price volatility, trade balance and geo-political risks. In the real world this is a major issue, witness the USA recently considering to increase the exploitation of (more expensive) endogenous resources as reaction to increased costs of imported oil (Stolberg, 2008) and the policy debate in China and India to rely at least partly on indigenous coal (de Vries et al., 2007a).

5 Climate change: balancing between short-term action and long-term impacts

In order to explore the impacts of climate change, two additional experiments were run:

- Experiment 5: Situation without fossil energy constraints, including climate impacts, without forward looking agents;
- Experiment 6: Situation without fossil energy constraints, but including climate impacts, with forward looking agents;

The assumptions for these experiments are shown in Table 3.3.

Table 3.3: Assumptions for model experiments on climate change

Experiment 5: no fossil energy constraint, no trade, climate change, no agents		
	High-income region	**Low-income region**
Fossil resource (energy units)	250e+6	250e+6
Decision making	Decision rules	Decision rules
Experiment 5a: no climate impact ($\alpha_{LT}= \alpha_{CC}=0$)	Ctax: 0, 10, 20 energy units	Ctax: 0, 10, 20 energy units
Experiment 5b: mild climate impact ($\alpha_{LT}= \alpha_{CC}=0.05$)	Ctax: 0, 10, 20 energy units	Ctax: 0, 10, 20 energy units
Experiment 5c: severe climate impact ($\alpha_{LT}= \alpha_{CC}=0.1$)	Ctax: 0, 10, 20 energy units	Ctax: 0, 10, 20 energy units
Experiment 6: no fossil energy constraint, no trade, climate change, agents		
6a: High-income region, severe climate impact		
Fossil resource (energy units)	250e+6	
Climate impact	$\alpha_{LT}= \alpha_{CC}=0.1$	
Decision making	Agent (C_{tax})	
6b: Low-income region, severe climate impact		
Fossil resource (energy units)		250e+6
Climate impact		$\alpha_{LT}= \alpha_{CC}=0.1$
Decision making		Agent (C_{tax})

5.1 Experiment 5: climate change impacts

An important dynamic with respect to climate change as introduced in SUSCLIME is that it only has a serious impact on economic development in the long-term. At the same time, mitigation measures may hamper economic growth on the short term (see for instance Manne et al., 1995; Nordhaus, 1993; Tol, 1999). An important question for the low-income region is whether it should first develop the economy and take mitigation and adaptation measures once it is more prosperous (which is the current strategy in climate negotiations); or whether it should anticipate long-term impacts and start reducing carbon emissions early on with the risk of slowing down income growth in the short term. The same question obviously applies to the high-income region. However, here the lower energy intensity and higher economic productivity make mitigation a more feasible and secure strategy.

The outcome of this delicate balance between short-term mitigation measures and long-term economic damages, depends on the impacts from climate change. Therefore, we first explore income pathways without forward looking agents under different assumptions on climate change and carbon taxes: no, mild or severe climate impact and no, medium or high

carbon taxes[6] (see Table 3.3 and Figure 3.11). Without climate impact, a carbon tax slows down economic development somewhat and mostly in the low-income region due to its higher energy-intensity and lower labour-productivity (Λ, see eqn. 7, Figure 3.11, upper graph). With mild or severe climate impacts (Figure 3.11, lower graphs), there may occur a serious income loss in the longer term. In this case the introduction of a carbon tax tends to have significant long-term benefits because it accelerates the transition to a more efficient, renewable energy based energy system. But, evidently, this demands higher investments in the energy system at the expense of consumption capital, resulting in a lower income growth during the first three-four decades, particularly in the developing region.

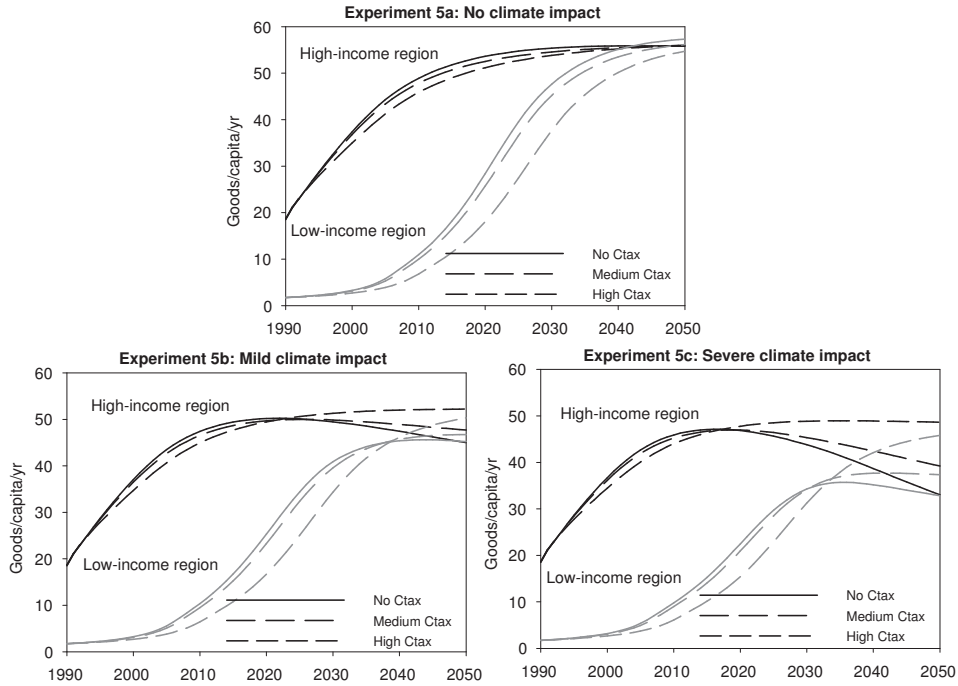

Figure 3.11: Development of income (C) for a low-income and high-income region under different climate impacts and with different carbon taxes (without forward looking agents)

5.2 Experiment 6: Agents and climate change

Next, we perform an experiment where forward looking agents have to deal with severe climate impacts. In first instance, we assume that regions are only motivated to act on the basis of climate change impacts in their own region. This leaves out any consideration of emission trading and interaction on the development of climate policies. In this experiment, the policy option of the agents is to apply a carbon tax on fossil energy (see Table 3.3).

[6] No carbon tax is zero, medium carbon tax is 10 and high carbon tax is 20 energy units (20 units is the initial productivity difference between non-carbon energy and fossil energy, before learning and depletion).

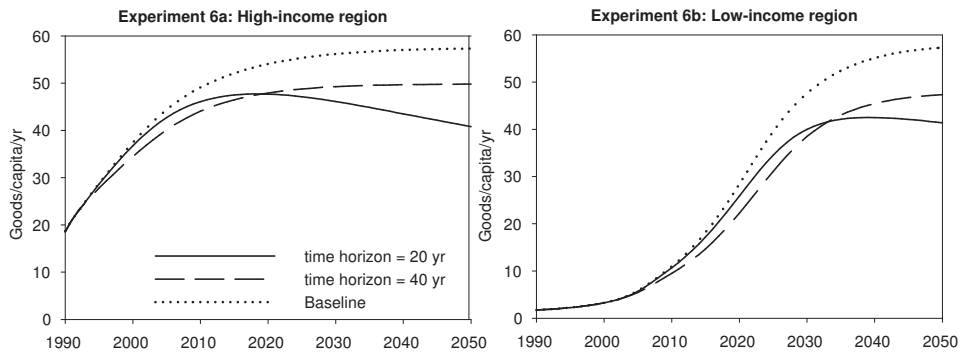

Figure 3.12: Income (C) for low-income and high-income region with forward looking agents dealing with severe climate change and using different time horizons

The results indicate that a forward looking agent can significantly reduce longer-term income loss but that the time horizon, i.e. the forward looking period, is a crucial parameter (Figure 3.12). With a time horizon of 20 years, both the high-income and low-income region agents do not apply a carbon tax. This leads to an initially only small deviation from the baseline – but a significant (~25%) income loss later on. If the agents use a time horizon of 40 years, the high-income agent directly applies the full carbon tax, which initially slows down income development but significantly reduces the long-term impact from climate change. The agent in the low-income region starts applying a carbon tax somewhat later, around 2005, thus striking a balance between short-term economic slow-down and long-term damage (compare Figure 3.12 to Figure 3.11, lower right graph). This is a delicate balance indeed. If applying a climate policy is postponed too long, the impacts of climate change may start to slow down economic development which in turn may aggravate future impacts. This timing issue of climate policy in relation to income levels is analogue to proposals like the multi-stage approach in burden-sharing of greenhouse gas reductions (see den Elzen et al., 2006).

6 Combining fossil energy depletion and climate change

A final experiment explores the impacts of both climate change and energy depletion:

- Experiment 7: Situation with fossil energy constraints and climate impacts, allowing for trade and with forward looking agents (see assumptions in Table 3.4).

Table 3.4: assumptions for model experiments with both fossil energy depletion and climate change

Experiment 7: fossil energy constraint, trade, climate change, agents		
7a: High-income region fossil energy constraint and severe climate impact		
	High-income region	**Low-income region**
Fossil resource (energy units)	5e+6	250e+6
Climate change (cause and severe impact)	Yes	No
Decision making	Agent (S_M, C_{tax})	Decision rules
7b: Low-income region fossil energy constraint and severe climate impact		
Fossil resource (energy units)	250e+6	2e+6
Climate change (cause and severe impact)	No	Yes
Decision making	Decision rules	Agent (S_M, C_{tax})

Agents can deal with depletion by importing and subsidising energy (Figure 3.10, lower graphs) and with climate change by applying a carbon tax using different forward looking periods (Figure 3.12). We only analyse the option with trade and focus, as previously, on the importing region. There are multiple dynamics in this experiment, which provide a useful framework to interpret today's arguments in a longer-term context. Depletion of fossil energy can force a transition to renewable energy, making climate policy less urgent. But it may also lead to increased fossil energy imports, with no or even higher carbon emissions (and impacts from climate change). Climate policy, on the other hand, will stimulate a transition to renewable energy, thus reducing long-term damages with the co-benefits of slowing down the use of indigenous and world fossil energy resources – but it has a short-term cost in terms of lower income growth.

This is nicely illustrated with the model outcomes shown in Figure 3.13. Both high-income and low-income 'short-term' agents start subsidising imported energy in order to postpone the economic impact of resource depletion. The high income agent (Figure 3.13, upper left graph) changes its policy around 2030, gradually decreasing import subsidy while instantly applying a high carbon tax. However, this is not early and intensely enough to avoid significant income losses from climate change. The low-income agent (Figure 3.13, upper right graph) follows a similar strategy but applies its carbon tax even later, in 2045, also too late to avoid a significant income loss.

The 'long-term' agents using a policy time horizon of 40 years perform much better. The high-income agent (Figure 3.13, lower left graph) immediately introduces a high carbon tax, phasing out fossil energy use and avoiding depletion of resources as well as the more severe climate change effects. The low-income agent (Figure 3.13, lower right graph) applies the carbon tax also in an early stage, around 2000, initially using fossil energy to fuel economic growth but also largely avoiding the deleterious effects of depletion and climate change. Again, the long-term low-income agent applies the strategy of postponing climate policy to enhance economic development in the initial period.

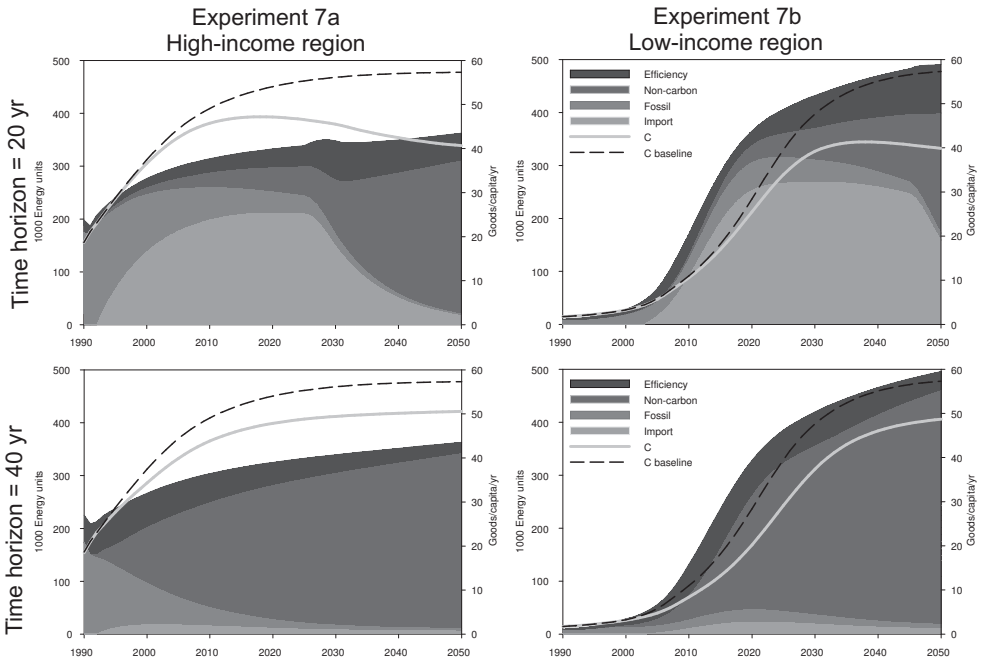

Figure 3.13: results of forward looking agents dealing with fossil energy depletion and climate change with different time horizons (not that experiment 7a and 7b involve separate model runs and only the importing regions are shown)

This experiment shows, in a stylized way, some of the linkages between resource depletion and climate change. A long-term focus on avoiding climate change also slows down cost increases and depletion of fossil energy resources. The reverse is not necessarily true: a short-term focus on avoiding resource depletion may cause the agents to respond by stimulating energy imports – which will for the foreseeable decades be carbon-based. This will therefore aggravate the risks of climate change impacts. The potential co-benefit of an early transition towards renewable energy is therefore not observed in the short-term objective function. This corresponds to the observation in the world nowadays, that rising oil prices cause an increase in the deployment of coal (e.g. coal-to-liquid fuels for transport).

7 Synthesis, discussion and conclusion

We constructed and analysed a simple model (SUSCLIME) to simulate some major dynamic aspects of an economy-energy-climate system. The original model was extended with automated agents that look forward and use policy measures to deal with resource depletion and climate change. We analyse strategic behaviour to cope with these issues given the aspiration for development (cq. income growth). The model is used, more in particular, to explore the role of energy resource scarcity and climate change impacts for the development aspirations in presently low-income regions in the world.

Table 3.5: Overview of cumulative consumption levels, the share of non-carbon energy and imported energy in all experiments (grey indicates the exporting region).

		High-income region 1990-2050 Cumulative: consumption, utility (*U*) and discounted consumption (Cd, 3%) Index, baseline = 100	% ren. 2050	% import 2050	**Low-income region** 1990-2050 cumulative: consumption, utility (*U*) and discounted consumption (Cd, 3%) Index, baseline = 100	% ren. 2050	% import 2050
No agents	**Baseline**	100	18%	N/A	100	17%	N/A
		Depletion & Trade					
	Depletion, no trade	87 (U=97,Cd=89)	100%	N/A	75 (U=93,Cd=75)	100%	N/A
	Depletion HI, trade	96 (U=99,Cd=97)	69%	31%	102 (U=101,Cd=102)	15%	N/A
	Depletion LI, trade	101 (U=100,Cd=101)	14%	N/A	90 (U=98,Cd=92)	72%	28%
Agents	Depletion, no trade	95 (U=99,Cd=95)	100%	N/A	87 (U=97,Cd=88)	100%	N/A
	Depletion HI, trade	98 (U=100,Cd=99)	32%	62%	102 (U=101,Cd=102)	13%	N/A
	Depletion LI, trade	101 (U=100,Cd=100)	11%	N/A	98 (U=99,Cd=98)	37%	59%
		Climate change					
	Time horizon 20y	86 (U=96,Cd=90)	19%	N/A	82 (U=96,Cd=85)	18%	N/A
	Time horizon 40y	89 (U=97,Cd=90)	91%	N/A	82 (U=95,Cd=83)	90%	N/A
		Climate change, depletion and trade[7]					
	Time horizon 20y						
	Depletion HI, trade	85 (U=96,Cd=89)	93%	6%			
	Depletion LI, trade				80 (U=95,Cd=84)	57%	40%
	Time horizon 40y						
	Depletion HI, trade	89 (U=97,Cd=90)	97%	2%			
	Depletion LI, trade				80 (U=93,Cd=80)	96%	2%

In a series of experiments we investigate strategies for low-income and high-income regions. We first constructed a baseline path with model relationships representing aggregate behaviour, adding in sequence the phenomena of depletion, trade and climate change. In a second series, we introduce agents who optimise income over time, applying policy measures to stimulate renewable energy and imported energy or apply a carbon tax on fossil energy sources. The results of both series of experiments are summarised in Table 3.5. It compares cumulative consumption (per person), utility and discounted consumption relative to the baseline economic development. It also summarises the energy situation in 2050 in terms of the shares of non-carbon energy and imported energy.

In case of energy depletion without trade, both high-income and low-income regions experience serious economic disruptions. However, the cumulative income decrease is considerably higher in the low-income region. If trade is possible, the impact of depletion on economic development is reduced. However, also here the low-income region is more vulnerable. Forward looking agents further reduce the negative impact from sudden fossil energy depletion by investing early in renewable energy supply. If agents are allowed to

[7] The exporting regions in these experiments are not shown, because the regions only experience their own climate impact; hence, the situation for the importing and exporting region is not comparable.

import fossil energy, this becomes the preferred option and imports increase to about 60% of total energy use.

Mitigating greenhouse gas emissions has a short-term cost but leads to higher consumption on the long-term. Therefore, an agent with a longer time-horizon shows a better long-term performance. The high-income agent with a long time horizon deploys a carbon tax as of 1990, driving a transition towards renewable energy and energy efficiency. The low-income agent postpones the deployment of a carbon tax as long as possible, to enhance economic growth with cheap fossil energy.

Co-benefits between avoiding climate change and resource depletion are theoretically possible: on the one hand, climate policy can force an energy transition that avoids resource depletion. On the other hand, some strategies to avoid resource depletion also decrease greenhouse gas emissions, although this is not necessarily the case (e.g. when imported fossil energy is used). Our experiments suggest that a long-term focus on minimising climate change also avoids depletion of endogenous resources. However, a short-term focus on resource depletion has little synergy with climate policy, because imported fossil energy is preferred over endogenous renewable energy resources.

The SUSCLIME model that we used is a huge simplification of the real world. The dynamics that are included in the model are highly stylized and many important details are ignored. The model excludes several processes that might be important for the results. A key assumption, for instance, in this model is that economic growth is possible through increased labour productivity due to rising capital-labour ratios (mechanization, infrastructure, automation-computerization etc.). Classical economic growth models use the 'black-box' multiplier of total factor productivity to explain past statistical records. Such a multiplier would not (or later) lead to stabilization in (monetary) output. It is unclear how this would affect our results, if only because the nature and determinants of economic growth are a crucial but ill-understood element in growth dynamics (de Vries et al., 2000; Helpman, 2004). We expect that the differences in the results between high-income and low-income regions would remain similar, though.

The model includes a limited set of energy options: fossil energy, non-carbon energy, efficiency and import. Thus, we do not consider the possibility that fossil energy (e.g. oil), upon depletion, is replaced by a more carbon intensive alternative: coal (or coal-derived energy carriers). The option of (cheap) imports mimics such substitution but without accounting for the higher carbon intensity. The feedbacks from climate change are also highly stylized, although our model formulation includes the, according to some optimistic, view that the economic system can adapt to altered climate conditions. The agents are also kept simple: they have full information about the future impacts of their decisions, for instance. A final remark is that we only assessed single-region situations for climate change. This narrows the focus to intertemporal trade-offs, whereas the social and political dilemma's and strategies (who is the first to take action, build coalitions, etc) are equally important.

What real-world conclusions can we draw about the position of developing regions, on the basis of these experiments with a simplified economy-energy-climate model?

- First, low-income regions seem more vulnerable to both depletion of endogenous resources and climate change, due to their lower economic productivity and associated higher energy-intensity. Therefore both the potential impacts and the costs of avoidance-strategies put a larger burden on developing economies. High-income regions are also confronted with these issues, but seem less impacted as a result of higher incomes and higher economic productivity and with associated lower energy-intensity.
- If little endogenous energy fossil resources are available (for instance in India and several African countries), cheaply imported energy is the preferred option to avoid endogenous resource depletion. This might be economically attractive, but also puts the importing region in a financially and geo-politically dependent situation. Stimulation of alternative energy sources might absorb economic resources in the short term, but ultimately leads to a more independent situation.
- With respect to climate change, developing regions balance between short term emission mitigation and long-term impacts. It is attractive to postpone climate policy until a certain income level is reached. However, the economic 'take off' phase of surging income growth, capital accumulation and productivity increase (e.g. China's current situation) should be combined with climate policy if such policy is to be effective. Once capital is accumulated and major amounts of carbon have been emitted into the atmosphere, deployment of climate policy might be too late and ineffective. Mitigation in the form of emission reduction in high-income counties seems not to have a major impact on their economic development. Therefore, an alternative approach might be the use of investments from high-income regions to mitigate emissions in developing regions, like in the current Clean Development Mechanism (CDM) or other emission trading schemes.

Chapter 4: Uncertainty from model calibration: applying a new method to calibrate energy demand for transport[1]

Abstract:
Uncertainties in energy demand modelling originate from both limited understanding of the real-world system and a lack of data for model development, calibration and validation. These uncertainties allow for the development of different models (from different scientific paradigms), but also leave room for different calibrations of a single model. Here, an automated model calibration procedure was developed and tested for transport sector energy use modelling in the TIMER 2.0 global energy model. This model describes energy use on the basis of activity levels, structural change and autonomous and price induced energy efficiency improvements. We found that the model could reasonably reproduce historic data under different sets of parameter values, which project different future energy demand levels. Two different model interpretations of the past can generally be distinguished: 1) high useful energy intensity and major energy efficiency improvements or 2) low useful energy intensity and little efficiency improvement. Generally, the first lead to higher future energy demand levels than the second, but model and insights do not provide decisive arguments to attribute a higher likelihood to one of the alternatives.

[1] Submitted to Environmental Modelling and Assessment. Co-authors: Jeroen van der Sluijs, Detlef van Vuuren, Bert de Vries, Peter Janssen, Peter Heuberger

1 Introduction

Uncertainties play a key role in projecting future developments of the energy system. At least two factors contribute to this: the energy system is complex and there is a lack of empirical data. Starting with the first factor, energy demand and production patterns result from the interplay of many complex and uncertain societal trends, such as changes in economic activity, developments in economic structure, lifestyle changes and technology trends. These trends may go in very different directions, resulting for instance in high energy-intensive futures (e.g. larger cars; more mobility; further penetration of air conditioning; rapid growth in developing countries) but also in futures with much less energy use (e.g. higher share of services; less mobility growth; strong focus on energy efficiency). The lack of empirical data complicates the development and calibration of models, especially for developing regions.

Despite limitations in both theory and data availability, a wide range of models has been developed to explore trends at global, regional and national scales. These models are partly developed from different scientific paradigms, which may lead to different interpretations of the past and different expectations of the future (Löschel, 2002; Rotmans and de Vries, 1997). A clear-cut example is the difference between models that stem from a macro-economic tradition (top-down) and those from a technological tradition (bottom-up). These two traditions (which either take historic behaviour as starting point or assessments of current technology performance) lead to different interpretations of the present situation with respect to energy efficiency ('improvement of energy efficiency always leads to higher costs' vis-à-vis 'major opportunities for improvement without substantial costs'). Even within one model, however, different options may exist on how to interpret the past and current situation. For instance, macro-economic demand functions often include both income-elasticity and price-elasticity. These factors interfere and are hard to identify unambiguously. A different interpretation of the past (a trade-off between income and price elasticity to describe historic improvements in energy intensity) may lead to different calibrations of the model and uncertainty in future projections. So far, different methods have been used to explore uncertainty in global energy models (da Costa, 2001; Kann and Weyant, 2000; Tschang and Dowlatabadi, 1995; van Vuuren et al., 2008), but relatively little attention has been given to the influence of model calibration on future projections.

The issue of multiple model calibration is closely related to the concept of equifinality, which focuses attention 'on the fact that there are many acceptable representations that cannot easily be rejected and should be considered in assessing the uncertainty associated with predictions' (Beven, 2006). These 'acceptable representations' are called *behavioural*, which can be defined strictly quantitative (e.g. above a threshold value of a likelihood measure) or more qualitative (e.g. trend simulation). At present, calibration of energy models is often done using the modeller's expert knowledge to identify a single set of plausible parameter values. However, if multiple sets of parameter values are tenable and model projections are sensitive to the parameter values chosen, this practice is questionable (see also Draper, 1995).

We developed a method to automatically calibrate models and obtain sets of parameter values that perform reasonably against historic data. These calibrated sets are obtained by varying the main model parameters within a limited range, choosing an initial estimate in this range, and searching consecutively for a (local) optimum to minimise the error between observations and model results. Repeating this procedure many times, initialised at different locations in the parameter space, generates a series of (different) calibrated sets of parameter values. This method is related to both nonlinear regression methods like PEST (Doherty, 2004) or UCODE (Poeter et al., 2005) and (sequential) Monte Carlo based methods like GLUE (Beven and Binley, 1992) or SimLab (Saltelli et al., 2004).

We apply this method to the global energy model TIMER 2.0, a system dynamics model that simulates developments in global energy supply and demand (de Vries et al., 2001; van Vuuren et al., 2006b). The TIMER 2.0 model is the energy sub-model of the Integrated Model to Assess the Global Environment, IMAGE 2.4, that describes the main aspects of global environmental change (Bouwman et al., 2006). In recent years, this model has been used in several global scenario studies like the IPCC Special Report on Emission Scenarios (IPCC, 2000a), the Millennium Ecosystem Assessment (MA, 2005), UNEP Global Environmental Outlook (UNEP, 2007) and the OECD Environmental Outlook (OECD, 2008).

Since the development of the TIMER model several uncertainty studies have been performed (van den Berg, 1994; van der Sluijs et al., 2001; van Vuuren, 2007). These analyses accepted the model's initial calibration and focused on the spread in model outcomes based on variation in central input values. Moreover, all TIMER uncertainty studies (and for that matter the same applied to other global energy models) focused on the global level, neglecting interesting underlying trends in different regions. Recent analysis of TIMER found that uncertainty in energy demand trends – and thus the factors underlying these trends – is a major source of model uncertainty (van Vuuren et al., 2008). Therefore, we focus this analysis on the TIMER energy demand sub-model. Within energy demand modelling a further choice was made to focus on the transport sector, which is the sector with the fastest growth in energy demand. For the regional focus, 6 regions were selected: the USA, Western Europe, Brazil, Russia, India and China. These regions are among the largest regions in terms of energy use and, moreover, represent a wide spectrum of development levels.

In this paper, Section 2 provides an introduction to uncertainty in energy modelling and Section 3 describes the methodology that we use for model calibration and forward calculations. In the second part of the article, we elaborate on the application of the method: Section 4 describes the structure of the TIMER 2.0 energy demand model and selects parameters that are useful for model calibration. Section 5 presents the results of the analysis, Section 6 evaluates the presented methodology and Section 7 discusses and concludes.

2 Uncertainty in energy modelling

Exploration of different futures on the basis of models is complicated by inherent uncertainties (Refsgaard et al., 2006; Refsgaard et al., 2007; Risbey et al., 2005; van der Sluijs, 2002, 2005, 2006, 2007). As Oreskes et al. (1994) highlighted, "fundamentally, the reason for modelling is a lack of full access, either in time or space, to the phenomena of interest. In areas where public policy and public safety are at stake, the burden is on the modeller to demonstrate the degree of correspondence between the model and the material world it seeks to represent and to delineate the limits of that correspondence." Beck (2002a) noted that almost all models suffer from a lack of identifiability, i.e. many combinations of values for the model's parameters may permit the model to fit the observed data more or less equally well.

Uncertainty and associated terms (such as error, risk and ignorance) are defined and interpreted differently by different authors (for reviews see Janssen et al., 2005; Refsgaard et al., 2007; van der Sluijs, 1997; Walker et al., 2003). These different definitions reflect the underlying traditions and their associated scientific philosophical way of thinking. Also the notion of ambiguity in model identification and calibration can be valued differently (see e.g. Edwards, 1999). In statistical modelling traditions, ambiguity in model calibration is typically interpreted as over-parameterisation of the model. Following Occam's razor, this could be solved with model reduction (e.g. Crout et al., 2009; Jakeman et al., 2006; Young, 1998; Young et al., 1996) or developing multiple specialised models (e.g. Beck et al., 1997) to strike a balance between model complexity and data-availability. In rule-based (system-dynamic) and engineering models[2] the model structure is based on (intuitive) causal relations and rules (either in physical or in monetary terms) that are calibrated to historic data (see for instance Dogan, 2004; Oliva, 2003). Such causal relations may be postulated, even in the absence of sufficient data for calibration.

Beven (2006) aims to extend traditional schemes with a more realistic account of uncertainty and rejects the idea that a single optimal model exists for any given case. Instead, models may not be unique in their accuracy of both reproduction of observations and prediction (i.e. unidentifiable or equifinal) and subject to only a conditional confirmation, due to e.g. errors in model structure, calibration of parameters and period of data used for evaluation.

In energy modelling literature, the most analysed sources of uncertainty are parameters, model structure and future projections of model drivers. As a typical example, Tschang and Dowlatabadi (1995) deal with input parameter uncertainty when performing an uncertainty analysis of the Edmonds-Reilly global energy model. They use Bayesian updating techniques to filter out model simulations that do not conform to outputs on energy consumption and carbon emissions and determine updated prior distributions for several

[2] Also, especially global energy models are highly policy relevant and are applied for multiple purposes (for instance looking into carbon emission, total energy use, structure of energy use or costs of mitigation measures). This implies that not all model-parameters influence the results of all outputs. Hence, these models are de-facto over-parameterised.

core parameters. Van Vuuren et al. (2008) use a slightly more complicated method, in which sampling of input parameters is made conditional upon different consistent descriptions of the future. With respect to model structure, a nice example is provided by Da Costa (2001) who compares the results of two different energy models for Brazil. He concludes that although the aggregate results of these models are comparable, considerable differences exist when the results are broken down. Therefore, he argues that various decision criteria (e.g. marginal production cost or marco-economic cost) should be applied in energy models, especially with respect to developing countries, to allow models to incorporate national priorities, experiences and expertise.

This study focuses on uncertainty that originates from parameter values. However, in contrast to earlier work, we explore the existence of different 'behavioural sets' of parameter values in model calibration for the TIMER energy demand model, inspired by Beven's work on equifinality. For this, it should be noted that when addressing the question how good a given model with given parameter values reproduces observed data, the mismatch between model prediction and observation can stem from at least six error terms (Beven, 2006): 1) measurement error in the observation, 2) commensurability error (i.e. if the variable that is predicted is not the same as the quantity measured, if they are modelled or measured at different levels of aggregation, or if natural variability is involved and accounted for differently in model and measurement), 3) model structure error, 4) parameter error, 5) input and boundary condition error, and 6) random residual error. In many model calibration practices, including ours, all these error terms are taken for granted and the difference between modelled and observed values is entirely attributed to parameter error. Techniques exist to overcome this simplification and better deconstruct the mismatch between observation and prediction into the six constituting error terms of Beven (2006), e.g. by explicitly incorporating an 'error model' accounting for the role of noise, uncertainties and mismatches involved. In principle, our approach can be extended with these techniques, but this is beyond the scope of the present paper. To keep our analysis manageable, here we assume that the parameter error is the dominant error component – and focus on the question whether our calibration procedure can indeed identify multiple, equally valid, calibrations of the energy demand model. In addition, we focus on what these different calibration imply for future projections.

3 Methodology to identify calibrated sets of parameter values

We developed an automated parameter estimation procedure in order to explore the impact of different sets of parameter values on model outcomes. This procedure closely follows the manual model calibration process that is normally applied to the TIMER model. In developing this method we followed several steps, described in this section: 1) quantify the fit between model predictions and observations, 2) select the relevant parameters for model calibration (see Section 4), 3) use an optimisation algorithm to minimise the deviation between model predictions and observations by varying the parameter values and 4), analyse the resulting calibrated sets of parameter values and their impact on model projections.

3.1 Quantifying the fit between model and observations

Several measures exist to evaluate the deviation between model results (predictions, P) and observed data (O), of which an overview can be found in Janssen and Heuberger (1995). We choose to use the normalised root mean square error (NRMSE), comparing individual time series of observations and predictions, and defined as:

$$NRMSE = \sqrt{\frac{\sum_{t=1}^{T}\left(\frac{P_t - O_t}{O_t}\right)^2}{T}} \qquad 1$$

In this, P_t and O_t indicate the predicted and observed value in year t and T is the number of years in the time series (in our case the time step in the time series is one year). This measure has values between zero (perfect fit) and infinite (random). Multiplied with 100, the NRMSE can be seen as the time averaged percentage deviation between the time series of model results and the time series of observations. A certain threshold level for the NRMSE can be defined, below which models are called *behavioural* with the data (e.g. a NRMSE<10%), but in Section 5 we show that it is hardly possible to find criteria for such generic threshold.

We use the NRMSE for several reasons. First, it expresses model error at the individual data level. The alternative, expressing model error on the average level, only provides a rough impression of the model-data-discrepancy and averages out the dynamic features (Janssen and Heuberger, 1995), whereas with calibration one wants to simulate both trends and patters in the data. Second, the NRMSE can easily be normalised in each year to observed energy use to prevent that years with higher energy demand dominate the estimated overall error.

3.2 Parameter estimation methodology

The aim of the developed parameter estimation methodology is two-fold. It is an automated model calibration procedure that minimises the error between model results and observations, generating a set of calibrated parameter values. In this sense it is related to nonlinear regression methods like PEST (Doherty, 2004) or UCODE (Poeter et al., 2005). By repeatedly applying the method it can be used to perform an uncertainty analysis on model calibration and generate and analyse a series of calibrated sets of parameter values. This aspect is more related to (sequential) Monte Carlo based methods like GLUE (Beven and Binley, 1992) or SimLab (Saltelli et al., 2004).

The automated parameter estimation procedure of TIMER involves three steps. First, we identify ranges for the calibration parameters, based on behaviour of the model formulations, the values used in former calibrations, literature and expert judgement (see Section 4 and appendix). These ranges are used as boundaries in the parameter estimation process. Second, a set of locations in the multi-dimensional parameter space is chosen as starting points for the parameter estimations. This is the initial dataset (SI) for P parameters

and N parameter estimation attempts: $SI_{P,N}$. We use a combination of design of experiments (central composite design, see NIST/SEMATECH (2006), to explore the extremes of the parameter space) accomplished with a series of random numbers. The third step involves the estimation of parameter values that perform well in simulating the data. We do this by minimizing the NRMSE, starting at the locations in the parameter space defined in the dataset $SI_{P,N}$. We look for optimal parameter estimations by using a Matlab build-in functionality for constrained nonlinear optimisation, using sequential quadratic programming (Mathworks, 2007). This algorithm varies the parameter values until the derivative of the objective function (i.e. the NRMSE) reaches values between zero and a pre-defined threshold level. This results in a dataset with calibrated parameter values that have a good (or best obtainable) fit with observations of energy use for the period 1970-2003: $SC_{P,N}$. This can be best imagined as the collection of local optima in the objective function landscape spanned up by the explored parameter space.

3.3 Analysis of calibrated parameter values

We analyse the series of calibrated sets of parameter values in $SC_{P,N}$ in several ways. First, the distribution of the calibrated parameter values over their range is analysed (see Appendix 2). Second, we plot the calibrated parameter values against the NRMSE (see Figure 4.2, upper graphs). Relations between parameters and the impact of parameters on the NRMSE can be numerically expressed by the (linear) Pearson correlation coefficient between parameters. This is used as the simplest indicator to express a relation between two parameters, but does not capture non-linearity or the existence of multimodal distributions.

Based on this, behavioural sets of parameter values can be selected. The most straightforward method is based on the NRMSE value, for instance, one can decide to call sets of parameter values with NRMSE < 10% behavioural. An alternative, but less reproducible criterion is based on visual inspection of the parameter values and the observed and simulated time series of energy demand. For instance, as can be seen in Appendix 2, all sets of parameter values for the Chinese transport sector have an NRMSE>17%, but can still be called behavioural in the sense that they simulate the trend of historic observations. In our analysis, we decided not to remove any sets of parameter values based on non-behavioural outcomes. However, we use the NRMSE (hence, behavioural/non-behavioural) to weight future projections that are derived from the different sets of parameter values.

3.4 Impact on model projections

To analyse the impact of different parameter values on future projections of the model, we use the series of calibrated sets of parameter values in $SC_{P,N}$ to run the model forward for the period 2003-2030 using a similar scenario on the model drivers (see Section 5.2). This leads to a range of projected future energy use, based on the different sets of parameter values. We analyse this in a frequency diagram of energy use in 2030 and weigh the frequencies in the diagram relative to the NRMSE of the parameter set that obtained the best fit to historic data in $SC_{P,N}$ (implicitly assuming that sets of parameter values with a better fit to historic data lead to more plausible future projections). The weight (W) that the

N'th calibrated parameter set gets in the prediction ensemble is defined as the normalisation of the relative weight (R) of the parameter set to the best performing parameter set[3]:

$$W_N = \frac{R_N}{\sum_N R_N} \text{ where } R_N = \frac{NRMSE_{best}}{NRMSE_N} \qquad 2$$

4 The TIMER 2.0 Energy Demand Model: parameters and ranges

In the TIMER model, demand for end-use energy is related to economic activity in five sectors: industry, transport, residential, services and other. The demand formulation includes autonomous and price-induced changes in energy-intensity. Energy supply is based on fossil fuels (coal, oil, natural gas), biomass, solar and wind power, hydropower and nuclear power. Fossil- and biofuels can be traded among 26 world regions. The production of each primary energy carrier includes the dynamics of depletion and learning-by-doing.

Energy use is first modelled as the annual demand for useful energy[4] (*UE*, in GJ/year), which is converted to secondary energy use, using specific efficiencies for different fuels. Useful energy demand is modelled as function of four dynamic factors: structural change, autonomous energy efficiency improvement (*AEEI*), price induced energy efficiency improvement (*PIEEI*) and price-based fuel substitution. Thus:

$$UE_{R,S,F} = POP_{R(t)} \cdot X_{R,S(t)} \cdot Y_{R,S,F(t)} \cdot AEEI_{R,S,F(t)} \cdot PIEEI_{R,S,F(t)} \text{ (GJ/yr)} \qquad 3$$

in which *POP* is the population (in persons), *X* is the per capita economic activity of a sector (in purchasing power parity (PPP), constant 1995 international $ /capita/yr), useful energy intensity (*Y,* in GJ/$/capita) captures intra-sectoral structural change and the *AEEI* and *PIEEI* (dimensionless) multipliers represent autonomous and price induced efficiency improvements. The indices *R*, *S* and *F* respectively indicate region, sector and energy form (heat or electricity).

Statistical time series are available for two variables: economic activity and secondary energy use. Between these observable variables, the model tells a story of useful energy intensity (structural change) and autonomous and price induced efficiency improvements, aggregates that can hardly be measured in the real world. The multiplicative structure of this model leaves room for different behavioural sets of parameter values: for different implementations of the UEI-curve, *AEEI* and *PIEEI*, a similar result can be obtained for the observable value of final energy use.

[3] This measure does not hold in the unlikely situation that the model exactly reproduces historic data and the best obtained fit becomes zero.

[4] With useful energy defined as the level of energy services or energy functions, for instance a heated room or cooled food; conversion efficiencies are taken from statistics (e.g. Eurostat)

The model distinguishes two forms of energy: electricity and fuels. In this analysis, we focus on the total demand for energy (i.e. the sum of all energy carriers); the fuel mix is assumed constant, calibrated to (historic) energy prices. We equate energy demand and energy use, as the statistical data are assumed to have satisfied demand in a state of economic equilibrium on an annual basis; hence, we do not consider the concept of latent (or unfulfilled) demand for energy (which is relevant for low-income regions).

4.1 Energy intensity curve

From energy analysis it is known that[5]:

- there is a tendency for energy use to increase with population and economic activity
- in many countries, energy intensity tends first to rise then decline; this takes place at the level of the whole economy but also at the sector level – this is usually explained from a mix of saturation and dematerialization (i.e. change to more value-added per unit of energy input)
- the level at which such a maximum is reached tends to decrease over time – interpreted as the collective dissemination of energy-innovations and of learning-by-doing.

Assuming that this also holds for useful energy, these stylized facts are represented in the model equation for useful energy intensity ($Y_{(t)}$) in the form of a (asymmetric) bell-shaped function of the sector-specific per capita economic activity. For each region (R), sector (S) and energy form (F) at time t, this can be expressed as[6]:

$$Y_{(t)R,S,F} = Y_0 + \frac{1}{\beta \cdot X_{(t)} + \gamma \cdot X_{(t)}^{\delta}} \qquad 4$$

with $X_{(t)}$ the sectoral economic activity per capita and β, γ and δ parameters (of which δ is negative to maintain a bell-shaped form, see Figure 4.1). All parameters in this equation are defined per region, sector and energy form.

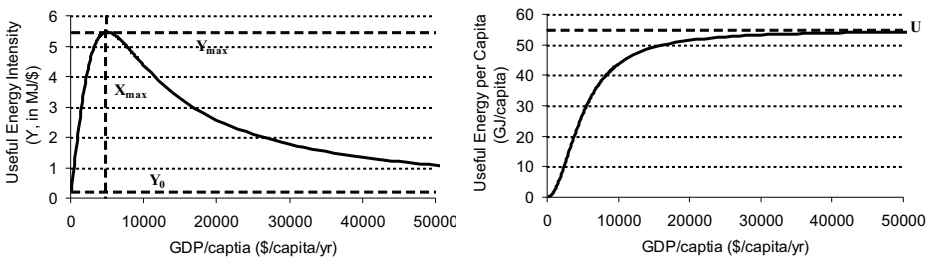

Figure 4.1: UEI curve (left) and useful energy use per capita (right) for hypothetical parameter values

[5] See for instance Focacci (2005), Medlock III and Soligo (2001) and Reddy and Goldemberg (1990)
[6] This bell-shaped curve can also be written in terms of elasticity with GDP/capita as is common for energy use, but for the transport sector it can also be done for vehicle ownership (Dargay et al., 2007).

The flexible formulation of this curve implies also a high sensitivity to parameter values. From an energy point-of-view, some reasonable constraints can be made to limit the potential parameter space to a relevant subspace and to shape the curve on the basis of understandable quantities:

1. the activity level at which the maximum occurs, X_{max}, can be estimated from regional energy use data. This has the risk of cyclical reasoning, because one draws conclusions from the observed data which are to be explained; one should do it only for datasets (regions, periods) where presumably end-use conversion efficiency has hardly changed[7].
2. The second term of the curve may be related to the saturation level of useful energy per capita per year at high income levels (U, see Figure 4.1, right graph). This saturation level can be based on sector and region specific features such as climate or population density.
3. Y_0 can be interpreted as the ultimately lowest energy-intensity of sectoral activity (in \$/GJ) in the both limits $X \to \infty$ and $X \to 0$.

Values and ranges for the parameters β, γ and δ can be derived from these constraints, in combination with the assumption that the curve should be forced through one observed reference point, defined as (X_{ref},Y_{ref}), which can be any year in the period 1971-2003[8] (see Appendix 3). Each implementation of the curve (as function of X_{max}, U and Y_0) can be characterised by its maximum energy intensity, i.e. the top of the curve (Y_{max}, see Figure 4.1), derived as:

$$Y_{max} = Y_0 + \frac{U}{X_{max}} \cdot \frac{\delta}{(\delta - 1)} \qquad 5$$

This allows a consistent set of parameter choices, for which these three key variables have to be investigated. We first establish suitable prior ranges for the variables X_{max}, U and Y_0 and translate these into values for the curve parameters β, γ and δ. The range for values of X_{max} and U in the parameter estimation process is defined as 10% broader than the maximum and minimum values applied in earlier (manual) calibrations of the TIMER model and is shown in the appendix (Table A 1). Conceptually, Y_0 is only limited by the value of Y_{ref}, because the ultimately lowest energy intensity cannot be higher than the observed historic energy intensity[9]. However, if Y_0 equals Y_{ref}, the second term of eqn. 13 (the 'curve' itself) would be irrelevant and the model would become linear. To force the model to explain the major part of energy intensity from the curve, we assume Y_0 to be lower than 20% of Y_{ref}.

[7] For instance, transport energy efficiency in the USA, where improved fuel efficiency is offset by vehicle mass (IEA, 2007d)
[8] In our model implementation this is the year 2003, the latest year of the calibration period
[9] Since energy intensity is defined in energy use per (monetary) unit of GDP, there is no theoretical or thermodynamic limit to the value of Y_0.

4.2 Autonomous Energy Efficiency Improvement (AEEI)

The continuous decline of energy intensity due to technology change is represented in the TIMER model by the autonomous energy efficiency improvement (*AEEI)* multiplier. Marginal *AEEI* is defined as fraction of economic activity growth (Manne et al., 2005):

$$AEEI_{marg\,(t)R,S} = F_S \cdot \left(\frac{GDPpc_{(t)R}}{GDPpc_{(t-1)R}} - 1\right) \cdot 100 \qquad (\%/\text{yr}) \qquad 6$$

with F_S a sectoral specific fraction of economic activity growth. The vintage structure modelling for energy using capital in TIMER determines that the current *AEEI* is the weighted average of the marginal *AEEI* over the capital life time (de Vries et al., 2001). This means that rapid economic growth leads to a faster decline in *AEEI*, due to both increased decline in the marginal *AEEI* and a larger share of the capital stock that is relatively new (van Vuuren, 2007). In case of economic decline, the marginal *AEEI* cannot become negative and is limited to zero.

The parameter that has to be estimated for *AEEI* is the fraction of GDP growth (F_S). For the percentage of annual *AEEI* a range of 0.2-1.5% per year is suggested by experts consulted by van der Sluijs et al (2001). This is used to establish a range for F_S by using the average annual regional GDP per capita growth over the period 1970 to 2003 (see Table A 1 and A2). In the above formulation, *AEEI* is related to the general economic growth in a region and not to a sector specific activity indicator, such as value added. During economic structural change, some sectors will grow faster or slower than the average economic growth, but this can be accounted for by using a sector specific value for F_S. In the presentation of the results, *AEEI* is expressed as the average percentage of annual sectoral efficiency improvement, based on the average historic regional GDP per capita growth for the period 1971-2003.

4.3 Price Induced Energy Efficiency Improvement (PIEEI)

The *PIEEI* reflects that with increasing energy prices end-users take measures to use energy more efficiently. The description of *PIEEI* in TIMER is based on an assumed energy conservation supply-cost-curve. This curve describes the increasing marginal cost of energy conservation. By comparing the gains of efficiency improvement (annual saved energy times payback time and energy prices) to the cost of investments, an optimum can be found. As such, there are three main factors that determine the level of energy efficiency: first, the form of the supply-cost-curve; second, the value of the pay-back time and third, learning-by-doing of energy efficiency technology. In the TIMER model, the energy conservation supply-cost-curve can be compared to bottom-up technology data (de Vries et al., 2001) but is modelled as an aggregated stylized function. The optimal level of energy efficiency (*E*, as fraction of total energy use) is defined as the point at which marginal energy conservation measures still yield net revenue:

$$E_{R,S,F} = M_{R,S,F} - \frac{1}{\sqrt{M_{R,S,F}^{-2} + \frac{C_{R,S,F} \cdot T_{R,S,F}}{S_{R,S,F} \cdot I_{R,S,F}}}} \qquad 7$$

in which M is the maximum potential price-induced efficiency improvement (as fraction of total frozen energy use), C the sectoral average costs of useful energy (*in $/GJ)*) and T the (apparent or desired) pay-back time (*in years*). I is the dimensionless factor with which the cost curve declines as a result of learning-by-doing. The scaling parameter S is used to scale the curve to the sector-specific costs of useful energy. The *PIEEI* on marginal capital investments, which is used in eqn 3, is a dimensionless multiplier defined as: $1\text{-}E_{R,S,F}$. Vintage modelling of energy demand capital delays the impact of the *PIEEI*, as the current *PIEEI* is the weighted average of the marginal *PIEEI* over the capital life time.

In the parameter estimation procedure we vary values of payback time (T) and the learning parameter (I)[10] using historic energy prices. From equation 7 it can be seen that both a higher payback time and a lower learning multiplier lead to more efficiency improvement. These two parameters are linearly interchangeable, but the overall *PIEEI* value provides more accessible information. Therefore we express these two *PIEEI* related parameters together as the cumulative efficiency improvement up to the year 2003. The ranges for the learning and payback time parameters in the experiment are shown in Table A 1**.**

5 Application to transport energy demand modelling

The above described model is used as generic formulation for the five economic sectors in the TIMER model: industry, transport, residential, services and other. In this analysis we look specifically into the transport sector implementation of the model. This model is calibrated to energy use data as provided and defined by the IEA; and involves all fuels that are used for transport regardless of other sectors they could be reported in (e.g. residential, industry; excluding marine bunkers, including pipelines). This means that energy use for passengers and freight is combined in one model, and one UEI-curve is applied for both fuels and electricity. Data for energy prices are derived from the IEA and data on economic activity is obtained from the World Bank WDI (World Bank, 2004). Compared to other models for transport energy use (Azar et al., 2003; Schafer and Victor, 2000; Wohlgemuth, 1997), the TIMER model is aggregated and stylized, because it does not take into account the intermediate variables of car ownership or person and freight kilometres or generic concepts like time and money budgets.

[10] Alternative parameters to vary would be the maximum improvement level (M) or the steepness (S). However, M is based on a theoretical maximum efficiency improvement expressed in energy intensity terms. This is a useful parameter to explore, but has more impact on future projections than on historic calibration. The steepness parameter (S) is used to scale the *PIEEI* curve to the useful energy costs per sector and is therefore not useful to vary.

5.1 Calibration to historic data

Energy consumption in the transport sector is rapidly increasing and might become the major final energy use in the near future. We tested our method to identify multiple behavioural sets of parameter values to the transport sector energy demand sub-model of TIMER. We performed 100 parameter estimation attempts per region (so N=100 in $SI_{P,N}$ and $SC_{P,N}$). If we only look at the NRMSE, an error of less than 10% between model results and observations is obtained for the regions USA, Europe and India; the results for Brazil, Russia and China are less good (Figure 4.9, Appendix 2).

Table 4.1: Linear correlation coefficient of calibrated parameter values

USA	UEI (Y_{max})	*AEEI*	*PIEEI*	**Europe**	UEI (Y_{max})	*AEEI*	*PIEEI*
AEEI	-0.17	-		*AEEI*	0.33	-	
PIEEI	0.77	-0.69	-	*PIEEI*	-0.54	-0.86	-
NRMSE	-0.71	-0.46	-0.26	NRMSE	-0.52	-0.57	0.85
India	UEI (Y_{max})	*AEEI*	*PIEEI*	**China**	UEI (Y_{max})	*AEEI*	*PIEEI*
AEEI	-0.52	-		*AEEI*	-0.35	-	
PIEEI	0.06	-0.23	-	*PIEEI*	0.69	-0.24	-
NRMSE	0.91	-0.75	0.17	NRMSE	0.91	-0.48	0.82
Brazil	UEI (Y_{max})	*AEEI*	*PIEEI*	**Russia**	UEI (Y_{max})	*AEEI*	*PIEEI*
AEEI	0.16	-		*AEEI*	0.54	-	
PIEEI	-0.15	-0.63	-	*PIEEI*	-0.26	-0.85	-
NRMSE	-0.04	0.37	-0.32	NRMSE	0.53	0.96	-0.76

5.1.1 Europe and USA: equifinal sets of parameter values

Final energy use of the transport sector in both the USA and Europe shows an increasing trend, with temporary slower growth after 1980 due to oil-price increases. Generally, the model simulates transport energy use in Europe quite well with a best NRMSE of 2.8% (Figure 4.9). Also, the fluctuations during the 1980s are well-captured (Figure 4.2, lower graphs). The calibrated parameter values vary over a wide range and only U, *AEEI* and *PIEEI* have relations with the NRMSE, although X_{max} is generally high and Y_0 is low (Figure 4.2, upper graphs). About 5% of the sets of parameter values have an NRMSE higher than 10% and can be identified as outliers on the basis of the parameter values. Generally, the parameter values follow two model stories: the best-fitting sets of parameter values have high values for *AEEI* (>1 %/yr) and no *PIEEI*; a second group has low values for *AEEI* and high *PIEEI*. The high correlations between *AEEI*/*PIEEI* and NRMSE (Table 4.1) also indicate these different options for parameter values.

The best NRMSE values for the USA is 3.5% (Figure 4.9), and also here the model simulates both long-term and short-term trends (Figure 4.3). The calibrated parameter values show hardly any relation with the NRMSE: the distributions of Y_0, U, *AEEI* and *PIEEI* involve a wide range are rather flat to the NRMSE (with the exception of about 10% outliers). In general, however, we can distinguish two different groups of behavioural sets of parameter values as well. The relation between *AEEI*/*PIEEI* and NRMSE is opposite to that of Europe (Table 4.1): the best fitting sets of parameter values have a low *AEEI* and high *PIEEI*, a second group has high *AEEI* and low *PIEEI*. This implies that the USA is more sensitive to energy price changes than Western Europe. All UEI-curve solutions for

the USA have a top at low income levels: useful energy intensity has been declining in the period 1971-2003. The negative correlation between Y_{max} and NRMSE (Table 4.1) shows that the more behavioural sets of parameter values have (historically) higher energy intensity.

These results indicate that the model performs quite well in simulating energy use in the USA and Western Europe, regions that have been important during the model development phase. However, they also indicate that distinguishing between the drivers of energy efficiency improvement, technology (*AEEI*) vs. prices (*PIEEI*), is difficult and maybe even questionable; especially since the reaction of *PIEEI* on energy prices is slow, due to delays from capital turnover.

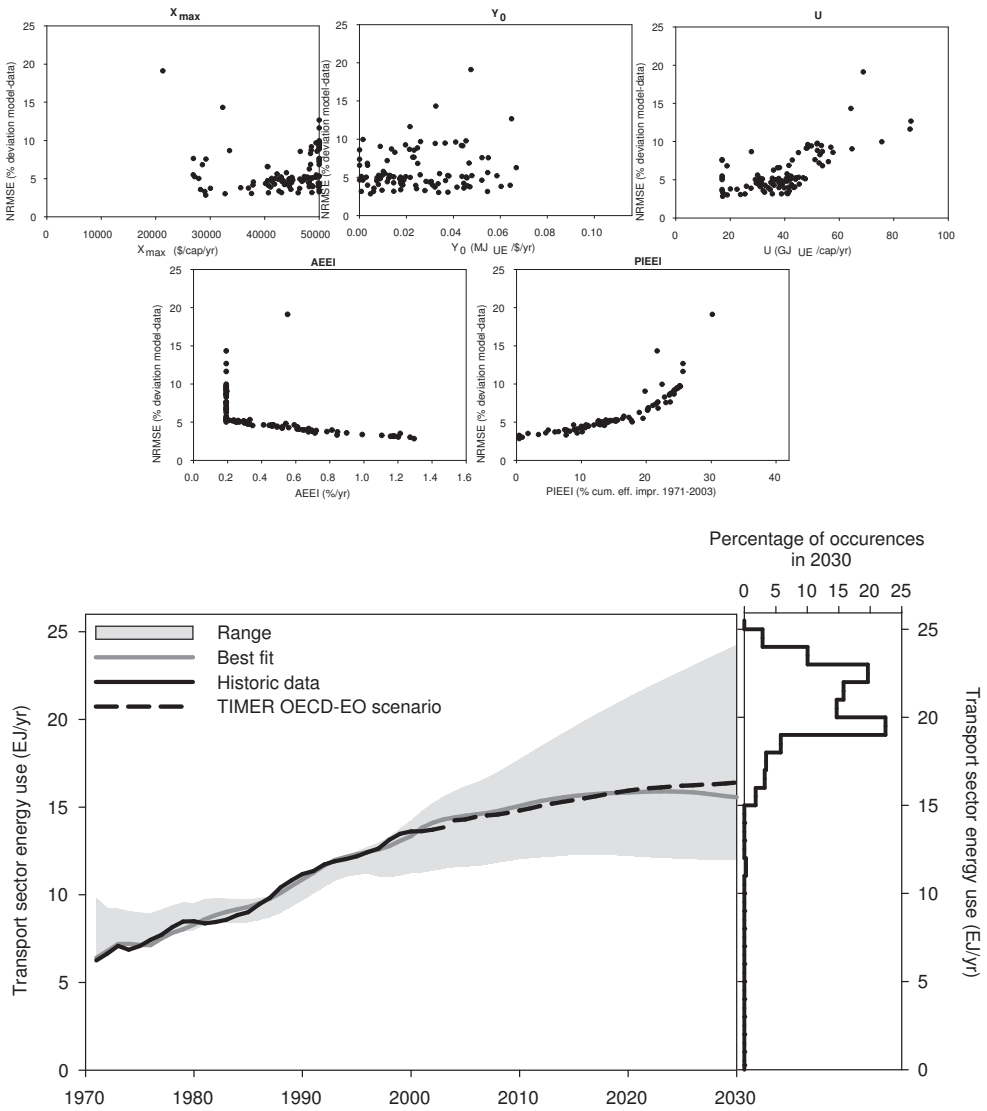

Figure 4.2: Upper graphs: plot of 100 calibrated sets of parameter values for transport sector energy use in Western Europe. Each dot represents a calibrated parameter value for the period 1971-2003. Lower graphs: historic and projected transport energy use for Western Europe up to 2030 (left graph) and histogram (right graph) of energy use in 2030 using the NRMSE as weighting factor. Projections based on OECD-EO scenario inputs and calibrated sets of parameter values

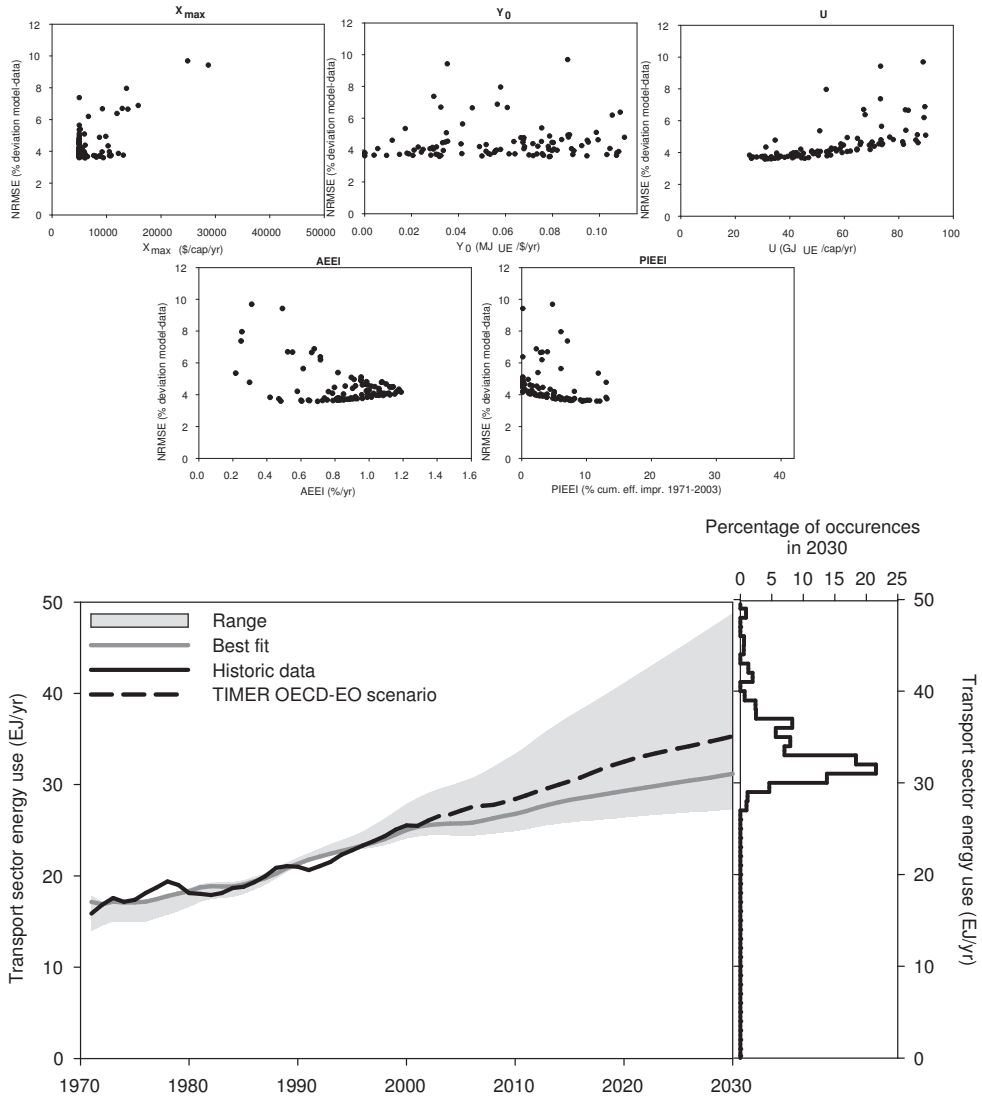

Figure 4.3: Upper graphs: plot of 100 calibrated sets of parameter values for transport sector energy use in the USA. Each dot represents a calibrated parameter value for the period 1971-2003. Lower graphs: historic and projected transport energy use for the USA up to 2030 (left graph) and histogram (right graph) of energy use in 2030 using the NRMSE as weighting factor. Projections based on OECD-EO scenario inputs and calibrated sets of parameter values

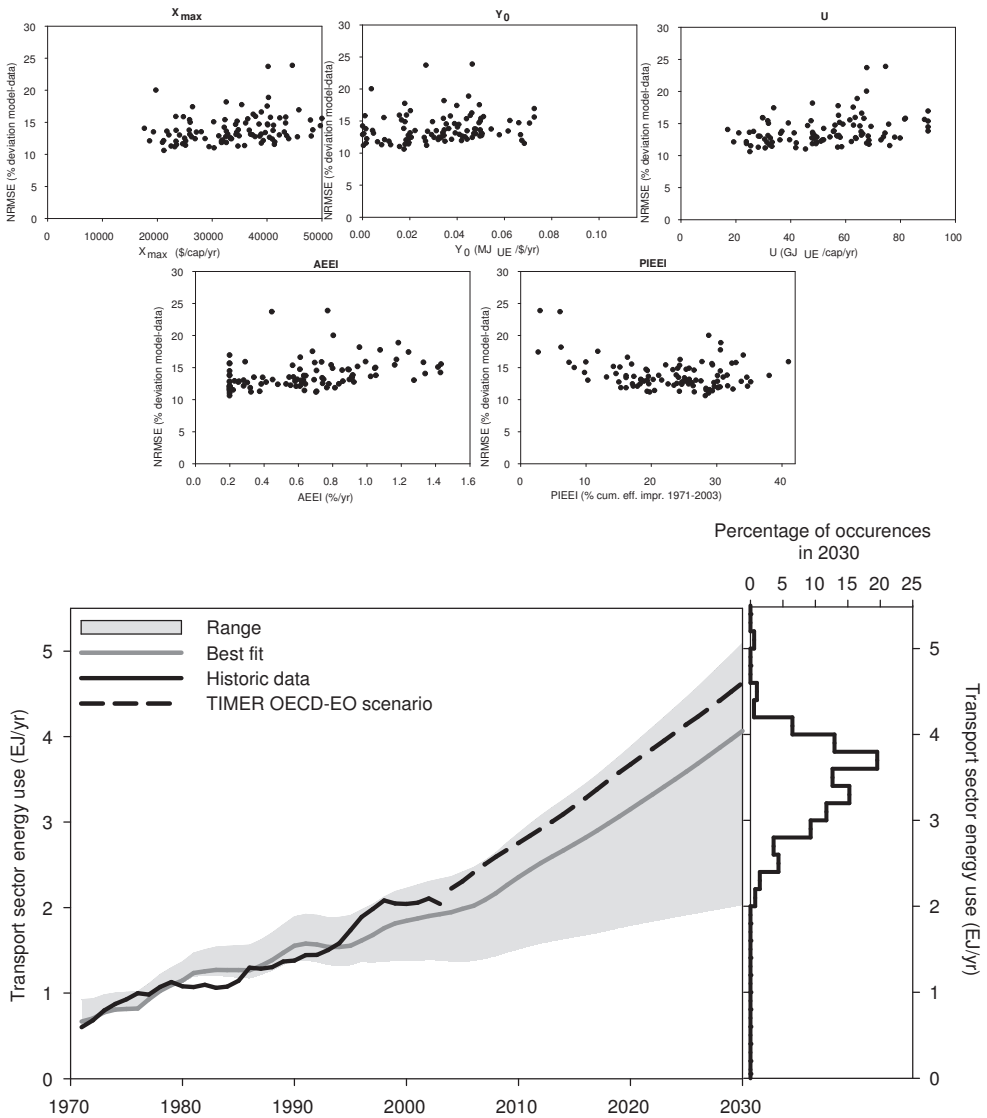

Figure 4.4: Upper graphs: plot of 100 calibrated sets of parameter values for transport sector energy use in Brazil. Each dot represents a calibrated parameter value for the period 1971-2003. Lower graphs: historic and projected transport energy use for Brazil up to 2030 (left graph) and histogram (right graph) of energy use in 2030 using the NRMSE as weighting factor. Projections based on OECD-EO scenario inputs and calibrated sets of parameter values

5.1.2 Brazil: fluctuation of economy and energy use

Brazilian GDP per capita and transport sector energy use have been fluctuating during the period 1971-2003. This complicates model calibration for this region, which can be seen in high NRMSE values: the best NRMSE is 10.6% (Figure 4.4). However, the simulation

might be called behavioural in following the long-term trends. The calibrated values of all parameters are distributed rather evenly over the range and show hardly relations with the NRMSE (see also Table 4.1). Analysis of the parameter values shows that *AEEI* and *PIEEI* are negatively correlated and rather interchangeable.

5.1.3 India and China: exponential growth

In the historic 1971-2003 period, energy use in the transport sectors of India and China has been growing exponentially. The Chinese data include some periods of decreasing energy use (1978-1980, 1990 and 1994), which makes the curve more difficult to simulate, especially before 1990. This shows up clearly in the NRMSE values: the best value for India is 4.3%, for China all calibrated parameter sets are between 17.18% (Figure 4.9). The main source of this high number is in mismatch in the period 1970-1990, but still, all sets of parameter values are generally behavioural in the sense that they simulate the exponentially increasing trend in the data. Both regions are simulated best with constant useful energy intensity (in the 1971-2003 GDP/capita range), *AEEI* of about 1 %/yr and no *PIEEI*. In relation to the NRMSE, both regions show a better fit with low values for X_{max}, high *U* and high *AEEI* (Figure 4.5 and Figure 4.6). There are no systematic relations between parameters (Table 4.1), except between maximum energy intensity (Y_{max}) and NRMSE (i.e. a lower Y_{max} leads to a better fit).

Several issues play a role in estimating the model parameters for the regions of India and China. With respect to the UEI-curve, these regions have rather narrow absolute GDP per capita ranges between 1971 and 2003 and they are forced to be below the top of the UEI-curve (the lower bound of X_{max} is 5000 $/capita/yr). Historically, useful energy intensity might have been constant, but it can be questioned whether such implementation of the model is representative outside the range of historically observed economic activity. Another source for the model error in India and China (but also Brazil) might be that the TIMER model does not capture some important concepts that are relevant for developing countries (e.g. urban/rural divide and unequal income distribution (see van Ruijven et al., 2008b)) and ignores the role of specific technologies (e.g. modal split).

5.1.4 Russia: dealing with (ir-)reversibility

The Russian combination of economic growth and decline within a range of 5000-9000 international $ per capita puts the model and its parameterisation to the test. Energy use in the Russian transport sector shows a sharp break of the increasing trend after the fall of the Soviet Union, with energy use decreasing from 4.3 EJ/yr in 1990 to 2.8 EJ/yr in 1997 (Figure 4.7). The model appears to be rather able to simulate historic Russian transport energy use with best NRMSE values of 11.6% (Figure 4.9). There are relations of Y0 and U with the NRMSE, and the values of these parameter are scattered over the range (Figure 4.9). However, lower Xmax, low *AEEI* and high *PIEEI* lead clearly to a better fit.

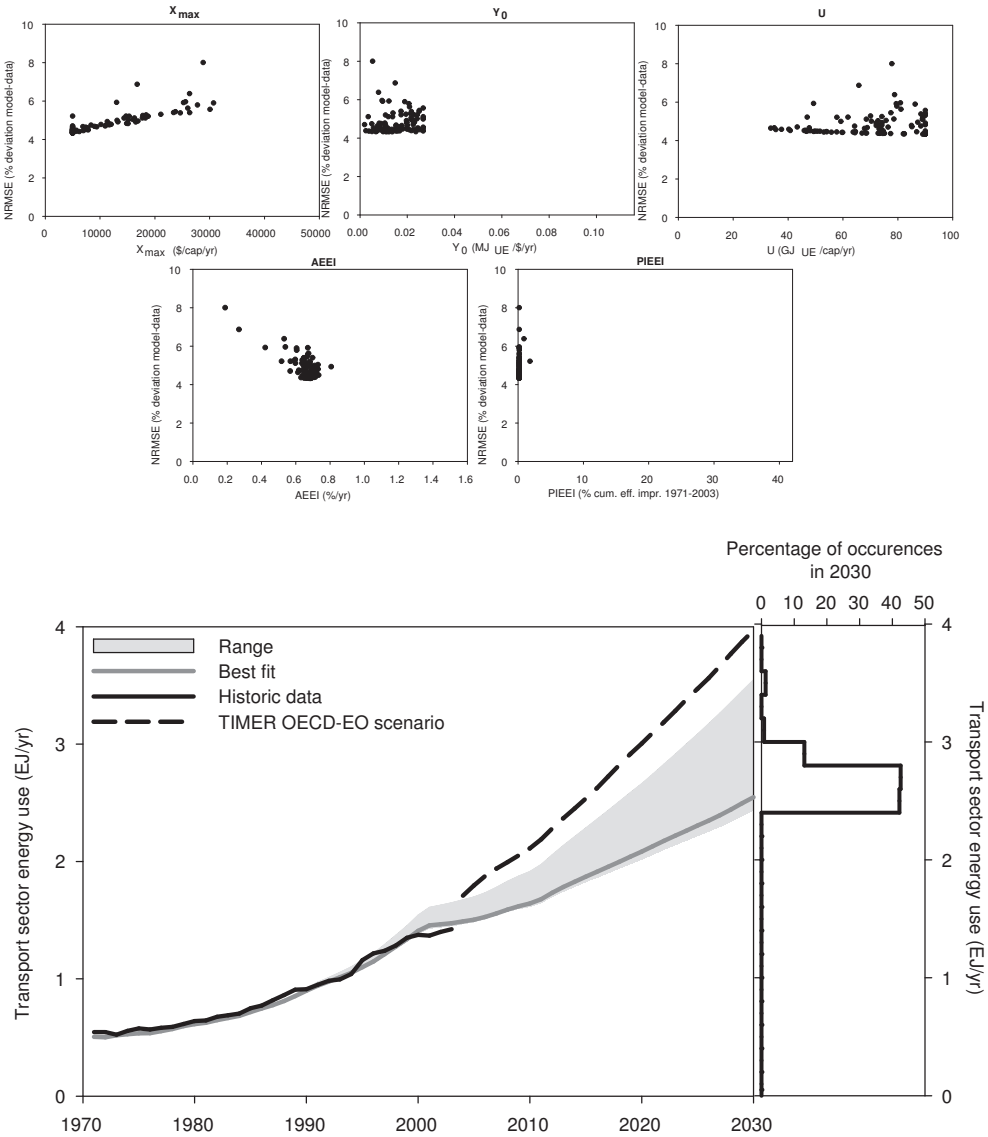

Figure 4.5: Upper graphs: plot of 100 calibrated sets of parameter values for transport sector energy use in India. Each dot represents a calibrated parameter value for the period 1971-2003. Lower graphs: historic and projected transport energy use for India up to 2030 (left graph) and histogram (right graph) of energy use in 2030 using the NRMSE as weighting factor. Projections based on OECD-EO scenario inputs and calibrated sets of parameter values

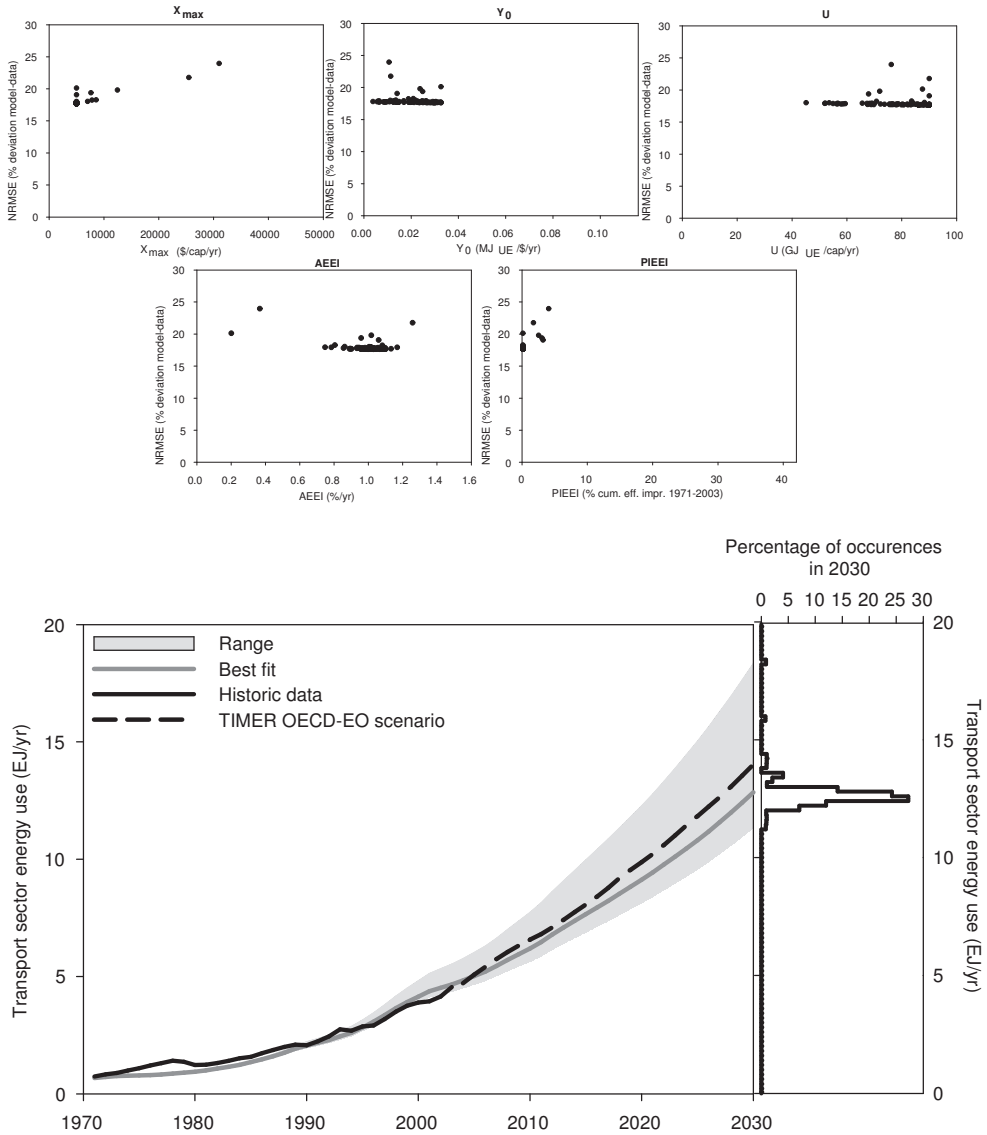

Figure 4.6: Upper graphs: plot of 100 calibrated sets of parameter values for transport sector energy use in China. Each dot represents a calibrated parameter value for the period 1971-2003. Lower graphs: historic and projected transport energy use for China up to 2030 (left graph) and histogram (right graph) of energy use in 2030 using the NRMSE as weighting factor. Projections based on OECD-EO scenario inputs and calibrated sets of parameter values

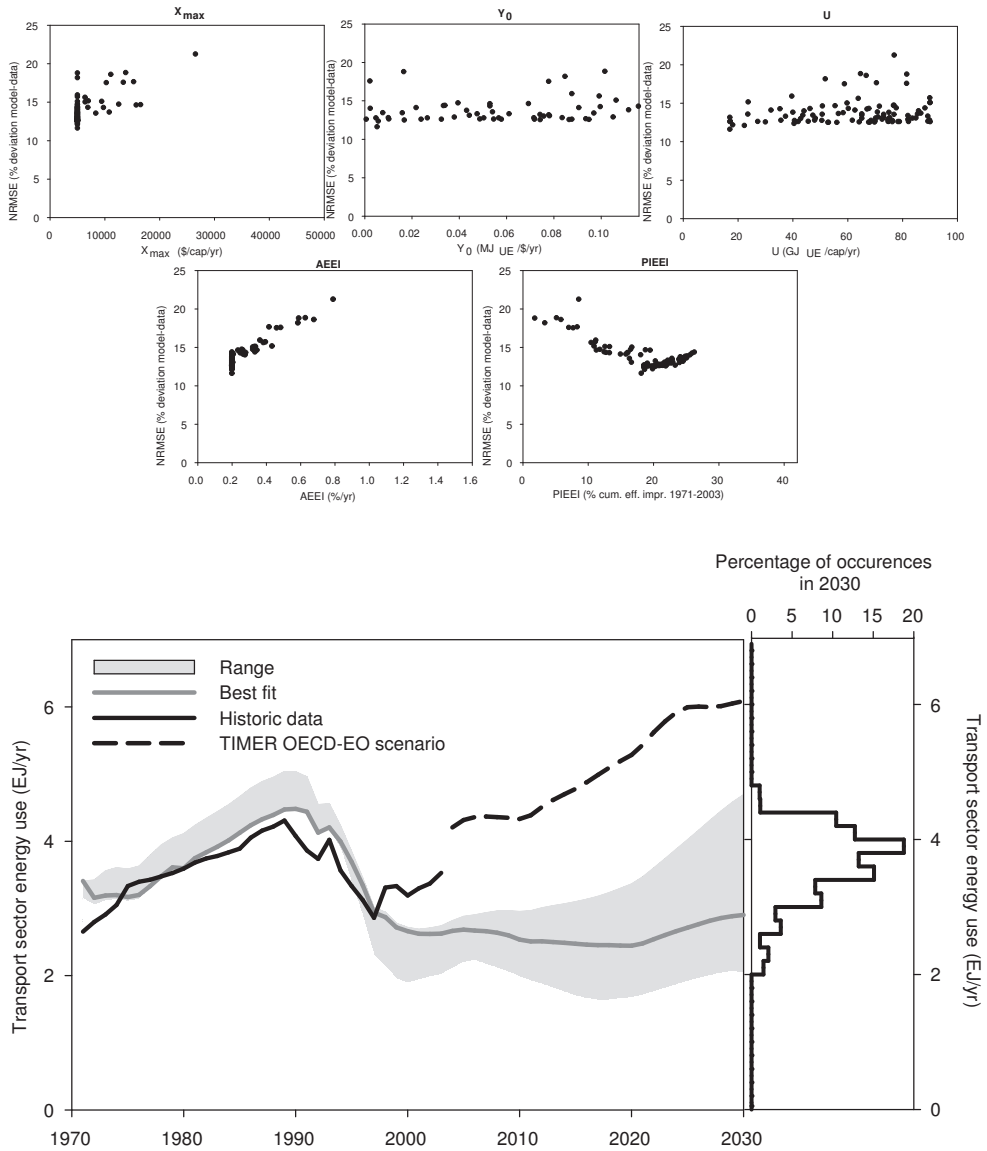

Figure 4.7: Upper graphs: plot of 100 calibrated sets of parameter values for transport sector energy use in Russia. Each dot represents a calibrated parameter value for the period 1971-2003. Lower graphs: historic and projected transport energy use for Russia up to 2030 (left graph) and histogram (right graph) of energy use in 2030 using the NRMSE as weighting factor. Projections based on OECD-EO scenario inputs and calibrated sets of parameter values

5.2 Impact on future projections

To determine the influence of the different sets of parameter values on future projections of the model we calculate the projected energy demand in 2030, using scenario inputs of the OECD environmental outlook scenario (OECD-EO, described in detail in Bakkes et al., 2008; OECD, 2008).These scenario inputs include projections for GDP, sectoral value added and population. The OECD-EO is a baseline scenario without new policies on economy and environment, in which energy use is based on moderate projections of population and economy. In this analysis we use the same energy prices for all forward calculations; these prices correspond with the default implementation of this scenario[11].

The TIMER model was used in its original setting within the OECD-EO study to project development of the future energy system, including energy transport demand. These projections can be very different from the current as 1) TIMER modellers have focused in model calibration not only on the performance of a single region but aimed to have similar parameter settings for different regions and 2) have calibrated to the model projections also against the IEA World Energy Outlook.

The projections of future transport sector energy use in Western Europe in 2030, based on the calibrated sets of parameter values, show a slowly increasing energy use toward 15-25 EJ/yr. In 2030, these projections vary over a wide range (Figure 4.2); expressed as percentage around the 'best fit' in 2030, this range amounts 79% (Table 4.2). However, from the distribution of projections (weighted to the NRMSE-value, see Section 3.4) it can be seen that the lower bound is heavily influenced by a singly outlier. The most behavioural sets of parameter values and the OECD-EO scenario are on the lower bound of this range. However, most sets of parameter values (weighted to the NRMSE) project an energy use of 19-23 EJ/yr in 2030, higher than the best fitted parameter set and the OECD-EO scenario.

Table 4.2: Correlation coefficient between calibrated parameter values (for both branches of δ) and projected energy use in 2030 for the transport sector

	UEI (Y_{max})	*AEEI*	*PIEEI*	*Range in 2030*
USA	-0.68	-0.50	-0.27	69%
Europe	0.65	-0.32	-0.15	79%
India	0.65	-0.78	0.41	44%
China	0.26	-0.97	0.06	55%
Brazil	0.11	-0.49	-0.34	75%
Russia	-0.22	-0.67	0.41	91%

A second issue of interest is which parameters mainly influence the projected energy use. This is explored in Table 4.2, showing the correlation between the calibrated parameter values and projected energy use in 2030. However, for Europe (and most other regions) there are no strong correlations, but we can analyse the direction. Generally, it can be stated that higher energy intensity and lower *AEEI* lead to higher projections for European energy demand for transport.

[11] Normally energy prices for future projections are calculated endogenously in the model based on depletion and learning. In this way, different energy demand projections lead to different energy prices, causing different market shares of fuels and other values for end-use-efficiency and *PIEEI*

For the USA, model-projections based on the calibrated sets of parameter values lead to a wide range of energy use in 2030: 30-50 EJ/yr, or 69% around the 'best fit' (Figure 4.3). However, this upper limit of this range is mainly determined by outliers that have little weight in the histogram. The best fitting sets of parameter values, which account for more than 50% of the weighted occurrences, project energy use in the range of 30-35 EJ/yr. The OECD-EO scenario is slightly above this range. Also for the USA, there is hardly any correlation between parameter values and projected energy use in 2030. The correlation with Y_{max} is negative, because the top of the UEI-curve is calibrated at low income levels. Correlation with the NRMSE is strong, indicating that a better fit leads to lower energy use projections.

For Brazil, which currently has a transport sector energy use of 2 EJ/yr, the projections vary in the range of 2-5 EJ/yr, with a peak of occurrences at 3.5-4 EJ/yr (Figure 4.4). The 'best fit' and the OECD-EO scenario project a somewhat higher energy use. Correlations between calibrated parameter values and projected energy use are weak; the negative correlations with efficiency improvements are the strongest.

Forward calculations for India indicate an increasing transport sector energy use from 1.5 EJ/yr in 2003 to 2.5-3 EJ/yr in 2030 (Figure 4.5). Relative to the 'best fit', the range for India is narrow: only 44%. The OECD-EO scenario is clearly above the range of projections, leading to 4 EJ/yr in 2030. Projected energy use correlates strongest with *AEEI* and Y_{max}: higher *AEEI* (and thus, better fit) leads to lower projected energy use (Table 4.2).

Projections for energy use in the Chinese transport sector in 2030 vary over a range of 11-19 EJ/yr, but a clear peak exists at 12.5 EJ/yr (Figure 4.6). The upper limit of the range is (>14 EJ/yr) is determined by two outliers. The 'best fit' is located in the peak and the OECD-EO scenario projects a slightly higher energy use of 14 EJ/yr. *AEEI* is the most decisive parameter for future energy use, with negative correlation of 0.97 (Table 4.2).

Future projections for Russia show that, although the historic calibrations are reasonable, the deviation between model results and data after 1997 has a crucial impact on future projections (Figure 4.7). The OECD-EO scenario projections are more in line with the historically increasing trend, but it seems that historic calibration can hardly be used as a ground for future projections for this regions. A solution might be to manually calibrate the model, specifically looking for sets of parameter values with a better fit in later years. Another option is to redefine how the model structure copes with the process of historic economic decline.

In general, the variation in parameter values accounts for quite some uncertainty in future projections (see the ranges of 44-90% around the 'best fit'). However, it is hard to attribute this uncertainty to single parameters. In most cases the *AEEI* is the most important model parameter for future projections, followed by the intensity curve. *PIEEI* seems less influential, although this is also related to slowly increasing projected energy prices.

5.3 General results and trends

The general results that emerge from this analysis are summarised in Figure 4.8, showing transport sector final energy intensity (i.e. transport sector final energy use per unit of GDP) and annual transport sector energy use per capita. With respect to energy intensity, major differences exist between countries, both on absolute levels and direction of trends. It is complicated to distinguish a general pattern in the results: China and India show maxima at low income levels, and historically declining energy intensities. Brazilian energy intensity is higher and historically rather stable. European energy intensity shows a maximum at GDP levels of about 20000 $/capita/year; final energy intensity of the USA is significantly higher than all other regions, but rapidly decreasing. Russia is an exceptional case: historically high energy intensity and low future projection (though these seem not very likely, see Figure 4.7).

Differences in per capita use of energy for transport are also outspoken. The USA shows a rather stable pattern at 80-90 GJ/capita per year both historically and in future projections. Europe increased historically from 20 to 40 GJ/capita, but is projected to stabilise. India has the current and projected lowest energy use per capita of the three low-income regions, whereas Chinese per capita energy use for transport is projected to increase from 4 to 8-12 GJ/yr. Also here, Russia is an exceptional case with a rapid decline in energy use. For the developing regions, the European level of energy use seems more likely than the high level of the USA.

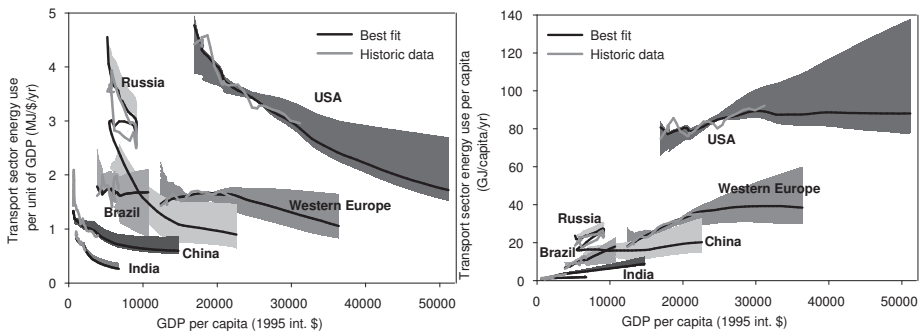

Figure 4.8: overview of transport sector final energy intensity (left graph, transport energy use per unit of GDP in PPP) and final energy use per capita (right graph) for all regions (except Russia) versus GDP/capita

The method applied in this paper calibrates the behaviour of each region individually to observed data. However, regions do not develop totally independently (e.g technology to improve efficiency is likely to be coupled between different regions) and especially the intensity curve (as described in Section 4.1) does originate from comparing different regions (cross regional data). For instance, transport energy use in India and China is calibrated against a period in which car ownership was low and (motorised) two-wheelers were the major transport mode; a possible future rise in car ownership and air-transport cannot be foreseen in these data. Therefore, a further step in the analysis would be to restrict the allowed parameter space in different regions, as a function of the values chosen

in other regions. The current method leads to somewhat low energy demand trends in Russia, India and China compared to other projections (represented here by the trends for the OECD-EO).

6 Method evaluation

Several remarks can be made about the presented method to identify variation in model calibration parameters. Because the method applies an optimisation-algorithm to minimise the error between model results and data, it does not guarantee the identification of the total fit-landscape. Hence, it is uncertain whether all behavioural sets of parameter values were found and all relations between parameters were identified correctly. However, by initialising the parameter estimation process from many different locations in the parameter space (including design of experiments initialisation from the extreme values ('corners') of the parameter space) we assume to have sufficiently lowered the chance of underestimating the range of behavioural parameter settings. For this model we chose 100 initialisations, balancing between calculation time and size of the database. Analysis of the results shows that for this model the shape of the distribution of the parameters and the NRMSE did not change significantly after 60 to 80 parameter estimation attempts. We expect this to be specific for each model, when this automated calibration procedure would be applied to another model, convergence of the NRMSE and the shape of the parameter distributions should be monitored to see whether enough initialisations have been chosen. It is clear that the method also identifies outliers if the optimisation-algorithm is terminated at relatively high NRMSE values. In the analysis that we performed, about 5-10% of the calibrated sets of parameter values could be identified as outliers. Hence, we conclude that the estimation technique performs well and most of the identified variation can be attributed to the model at hand.

In the error model that we use, we oversimplified by attributing the difference between modelled and observed values completely to the parameter error. One could extent the method towards more focus on measurement error in the observation, for instance by adding white noise to the calibration variable, or input and boundary condition error. In the specific case of TIMER, an error distribution on the reference energy intensity for the UEI-curve might deal with data-error and allow a broader range of sets of parameter values to be behavioural with the data. Another issue in the TIMER case is that parameter error and model structure error can hardly be separated, because the parameters related to the UEI-curve, can change the functional form of the model dramatically (e.g. from bell-shaped to linear).

The development of the described method is inspired by the concept of equifinality, developed by Beven based on his experiences with the GLUE methodology. The GLUE methodology has recently been subject of a scientific debate on its consistency with Bayesian statistics. A major criticism on GLUE was its application of 'less formal likelihood' measures; this may imply that it looses the learning properties of the Bayesian approach, leading to 'flat' parameter posterior densities and thus equifinality is build in the methodology (Mantovan and Todini, 2006; Mantovan et al., 2007). In response, it has been

argued that if strong assumptions about the error model cannot be justified, GLUE provides a reasonable alternative (Beven et al., 2007). The method applied here differs from both Bayesian updating and GLUE, because it does not apply sequential Monte Carlo analysis. Moreover, it also has elements of nonlinear regression methods like PEST and UCODE, in that its purpose is to identify 'peaks' in the fit-landscape. Therefore, we conclude that this discussion does not apply to this method.

7 Discussion, conclusion and implications

Energy use modelling knows many scientific paradigms and traditions, which lead to different interpretations of past and present and to different expectations of the future. Even within one model, several options may exist on how to interpret the past and current situation. We developed a method to identify the range of sets of parameter values that perform reasonably against historic data and analyse the impact of these different calibrations on future projections. The essence of this method is that by varying several essential parameter values, we search to minimise the error between model results and observations. By repeating this parameter estimation procedure, starting from different locations in the parameter space, we were able to identify a range of local optima in the error-landscape within the parameter space. These co-existing different interpretations (i.e. values of essential parameters) that explain historic energy use comparably well are incorporated in the prediction ensemble.

From the application of this method to the TIMER 2.0 energy demand model for the transport sector, we found that its model formulation, in combination with the aggregated character of energy statistics available for calibration, leaves room for multiple behavioural sets of parameter values. In the given model formulation, the different options for calibrated parameter values are related to the balance between useful energy intensity and energy efficiency improvement. Generally, high useful energy intensity combined with major efficiency improvements leads to similar results as low energy intensity and stagnant efficiency improvement. For some regions the transport energy demand model renders a more unique parameterisation: Chinese and Indian exponential growth of economic activity and energy use can only be simulated with historically constant energy intensity. With respect to future projections, we found that different (behavioural) sets of parameter values can lead to a wide range of future projections. *AEEI* and useful energy intensity are the most decisive model aspects with respect to future energy levels.

What does this analysis imply for the application and development of the TIMER model? Given the aggregate nature of both model and data some parameter ambiguity is inevitable and does not a priori disqualify the model. For the existing model, a workable situation can be created by using the 'best-fit' calibrated parameter values and communicating the calibration uncertainty range with the model results. More fundamentally, two options exist for model improvement. First, the data-based solution would be model reduction. However, because the model only involves three well-established concepts (energy intensity and autonomous and price induced efficiency improvement) model reduction implies econometric curve-fitting. A second option is to convert the model to a more bottom-up

nature and use the increasingly available data and insights from the underlying physical activity (in this specific case: data on person or freight kilometres, or ownership of cars, trucks, planes etc.; and the concepts of time and money budgets). Such development would lead to two major improvements: first, it provides an extra model layer (of physical activity) that can be calibrated to data and second, such model enhances insight in the actual activity that is simulated and projected.

Appendix 1: Values and ranges for parameter estimation

Table A 1: Ranges for the estimated parameter values

Variable	Minimum	Maximum
UEI-curve		
X_{max}	5000	50000
Y_0	0	0.116 (USA) 0.066 (EU) 0.072 (Brazil) 0.17 (Russia) 0.026 (India) 0.03 (China)
U	17	90
AEEI		
F_S	0.09 (USA) 0.09 (EU) 0.09 (Brazil) 0.28 (Russia) 0.07 (India) 0.03 (China)	0.68 (USA) 0.70 (EU) 0.68 (Brazil) 2.11 (Russia) 1.0 (India) 1.0 (China)[12]
PIEEI		
Payback time	0.007	6.760
P-value learning curve	0.70	1.00

Table A 2: Average annual GDP per capita growth for the analysed regions

	USA	WEU	Brazil	Russia	India	China
Average annual GDP/cap growth 1971-2003	2.19%	2.13%	2.21%	0.71%	2.69%	6.69%

[12] Because of the high economic growth in India and China, it might be that historic *AEEI* has been higher as well; therefore we increases the upped bound of the range to the total economic growth: F_S=1

Appendix 2: Analysis of calibrated parameter values and future projections

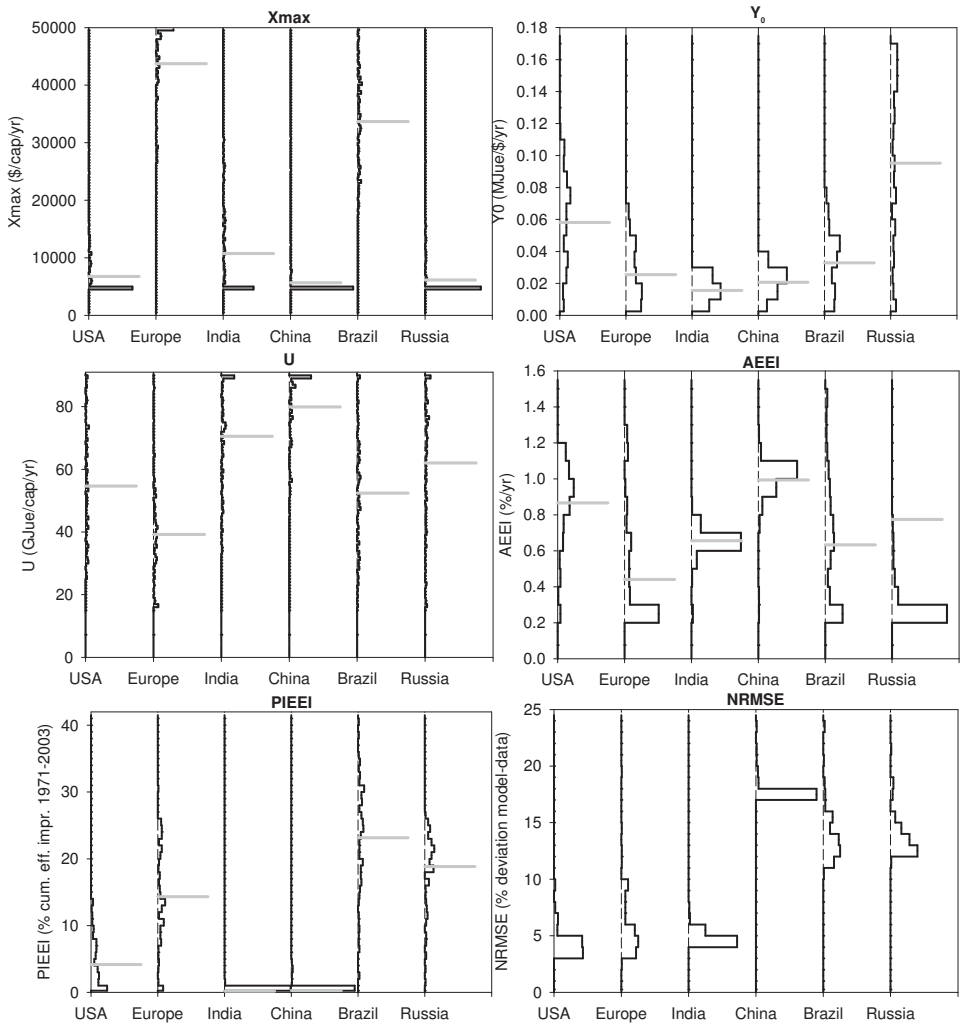

Figure 4.9: Calibrated parameter values for transport sector energy use in all regions. Distribution (black lines) and mean value (grey)

Appendix 3: Mathematical derivation of parameters for UEI-curve

The form of the UEI curve (Y) is given by:

$$Y = Y_0 + \frac{1}{\beta \cdot X + \gamma \cdot X^{\delta}} \qquad 8$$

where X denotes the per capita sectoral activity level. The condition for the maximum value of this curve is:

$$\beta + \gamma \cdot \delta \cdot X_{\max}{}^{\delta - 1} = 0 \qquad 9$$

which renders an explicit expression for γ (or likewise for β).

Relating the curve to the saturation level of useful energy per capita per year at high income levels (U), given that δ is negative and assuming that Y_0=0 in eqn. 8 (hence, focussing at the second term), means that:

$$U = X \cdot Y = \frac{X}{\beta \cdot X + \gamma \cdot X^{\delta}} \Rightarrow \lim_{X \to \infty} \frac{X}{\beta \cdot X + \gamma \cdot X^{\delta}} = \frac{1}{\beta} \text{ and thus } \beta = \frac{1}{U} \qquad 10$$

If the curve is forced through one observed reference point (X_{ref},Y_{ref}), the combination of eqn. 9 and using $\tilde{X}_{ref} = \frac{X_{ref}}{X_{\max}}$, renders the following expression for δ:

$$\delta = -\frac{ProductLog\left[\frac{\ln(\tilde{X}_{ref}) \cdot X_{\max} \cdot (Y_{ref} - Y_0)}{U + X_{\max} \cdot \tilde{X}_{ref} \cdot (-Y_{ref} + Y_0)}\right]}{\ln(\tilde{X}_{ref})} \qquad 11$$

where ProductLog[z] gives the solution for w in $z = w \cdot e^{w}$; depending on the value of z, this function has multiple branches of solutions involving complex numbers. If $z > -e^{-1}$ the principle branch solution is a real number; if $-e^{-1} < z < 0$ the secondary branch solution is a real number as well. This means that, depending on the values of X_{max}, Y_0 and U, multiple values for δ might exist. In model terms, the primary branch solutions of δ are closest to zero and generally lead to a lower maximum in the curve (more linear) than the secondary branch solutions (more bell shapd). Based on these derivations, the UEI curve can be determined as function of the quantities X_{max}, Y_0 and U.

Chapter 5: A meta-model for residential energy use: uncertainty in calibration to regional data[1]

Abstract:
Uncertainties in energy demand modelling allow for the development of different models, but also leave room for different calibrations of a single model. Here, we use an automated model calibration procedure to analyse calibration uncertainty in residential sector energy use modelling in the TIMER 2.0 global energy model. We found that the model simulates historic trends in energy use better for developed regions than for developing regions. This is explained from model deficiencies and energy policies. Model calibration uncertainty is identified as influential source for variation in future projections. Energy modellers should systematically account for this and communicate calibration-uncertainty ranges.

[1] Submitted to Global Environmental Change. Co-authors: Bert de Vries, Jeroen P. van der Sluijs, Detlef P. van Vuuren. The authors are grateful to Peter Janssen and Peter Heuberger for their contribution to the mathematical analysis and development of the Matlab tool.

1 Introduction

Developments of the energy system play a key role in both economic development and environmental problems at different scales. First of all, energy is needed to support economic activities; improving access to modern energy is therefore a key development priority for many low income countries. In addition, securing energy supply has become an important issue for both high- and low income countries, in response to increasing (apparent) oil scarcity. Finally, environmental problems at different scales (local, such as urban air pollution; regional, such as transboundary air pollution and global, such as climate change) are associated with the combustion of fuels.

In this context, it is important to assess different potential development paths of the energy system. Unfortunately, however, projecting future developments of the energy system is plagued by uncertainties. At least two factors contribute to this: first, the energy system is complex, and second, there is a lack of empirical information. With respect to the first factor, energy demand and production results from the interplay of many complex and uncertain societal trends, such as economic activity, developments in economic and population structure, changes in lifestyles, infrastructure and technology. The lack of information, including the limited availability of reliable data, complicates the development and calibration of models, especially for developing regions – and allows for multiple interpretations of the same phenomena.

Despite these difficulties, a wide range of models has been developed to explore trends in the energy system at global, regional and national scales. These models are partly developed from different scientific paradigms and modelling traditions. Such paradigms may lead to different interpretations of the past and different expectations of the future. The most clear-cut example is the difference between models that stem from a macro-economic tradition (top-down) and those from a engineering-economic tradition (bottom-up) that lead to different interpretations of the present situation with respect to energy efficiency (optimal vis-à-vis major opportunities for improvement). Even within one model, however, several options may exist on how to interpret the past and current situation. This may lead to different model calibrations, causing uncertainty in future projections.

In the past, different methods have been used to explore uncertainty in global energy models, but relatively little attention has been given to the influence of model calibration on future projections. Recently, we developed a method to analyse uncertainty in model calibration, described, discussed and tested in van Ruijven et al. (2008c). This method is inspired by the concept of equifinality, drawing attention to the phenomenon that there are many acceptable model calibrations that cannot easily be rejected and should be considered in assessing the uncertainty associated with predictions (Beven, 2006).

In this paper, we apply our calibration-uncertainty method to the global energy model TIMER 2.0, a system dynamics model that simulates developments in global energy supply and demand (de Vries et al., 2001; van Vuuren et al., 2006b). While our previous publication focused on the development and proofing of the method and testing it for the

transport sector, here our main interest is on the effect of model calibration for future scenarios for residential energy use at the regional scale. We focus on the residential sector because this sector is currently the main energy consuming sector in many developing regions and involves the transition from traditional to modern fuels.

So-far, uncertainty studies of global energy models focus mainly on the global level. Our choice here to focus on the regional scale is motivated by the fact that most trends actually occur at this level of scale (and not at the global scale). Finally, the analysis focuses on energy demand – as recent uncertainty analysis of this model found that the most important factor in total model uncertainty is the trend in energy demand (van Vuuren, 2007). The regional analysis provides a much tougher test on model calibration. Still, it is important, because such analysis might also improve insights in differences between regions and provide information for model improvements. We selected five regions that are among the largest regions in terms of energy use and represent a wide spectrum of development levels: USA, Western Europe, India, China and Brazil.

Thus, the central question in this paper is *what is the impact of uncertainty in model calibration on future projections of residential energy use in the TIMER model*? Section 2 provides an introduction to uncertainty and equifinality in the context of model calibration and Section 3 describes our methodology to identify uncertainty in model calibration and forward calculations. Section 4 describes the structure of the TIMER 2.0 energy demand model and discusses parameters for model calibration. In Sections 5, we analyse the performance of the model for residential energy use and the uncertainty in calibrated parameter values. Section 6 focuses on the impact of calibration uncertainty on projections for 2030 and finally, Section 7 discusses and concludes.

2 Uncertainty in model calibration

Exploration of different futures on the basis of models is complicated by many different sources of uncertainty (Refsgaard et al., 2006; Refsgaard et al., 2007; Risbey et al., 2005; van der Sluijs, 2002, 2005, 2006, 2007). Beven (2006) outlined a philosophy for modelling of environmental systems, in which he focuses on the challenges in model calibration. The basic aim of his approach is to extend traditional schemes with a more realistic account of uncertainty, rejecting the idea that a single optimally calibrated model exists for any given case. Instead, environmental models may be non-unique in their accuracy of both reproduction of observations and prediction (i.e. unidentifiable or equifinal), and subject to only a conditional confirmation, due to e.g. errors in model structure, calibration of parameters and period of data used for evaluation. The ‘acceptable representations’ are called *behavioural*, which can be defined strictly quantitative (e.g. above a threshold value of a likelihood measure) or more qualitative (e.g. trend simulation). Beck's (2002a) notion that almost all models suffer from a lack of identifiability (many combinations of values for the model’s parameters may permit the model to fit the observed data more or less equally well) is closely related to Beven’s equifinality concept.

In this study, we focus on the uncertainty that originates from model parameter values. Inspired by Beven's work on equifinality, we explore the existence of different behavioural parameter sets for the TIMER energy demand model. At present, calibration of energy models is often done by hand, using the modeller's expert knowledge and skills to identify plausible parameter values. If multiple parameter sets are tenable and model projections are sensitive to the parameter values chosen, this practice is questionable and may overlook relevant parameter sets. A more systematic exploration of the uncertainty space can help to overcome this limitation. For a more elaborate discussion on calibration uncertainty in energy modelling see van Ruijven et al. (2008c).

3 Methodology to identify calibrated parameter sets

We developed an automated parameter estimation procedure in order to explore the uncertainty space along with an assessment of the impact of different parameter sets on model outcomes (van Ruijven et al., 2008c). It minimises the error between model results and observations, generating a set of calibrated parameter values. By repeatedly applying this procedure, it can be used to perform an uncertainty analysis on model calibration and generate and analyse a series of calibrated parameter sets. This procedure involves several steps. First, we identify ranges for the calibration parameters, based on behaviour of the model formulations, the values used in former calibrations, literature and expert judgement (see Section 4 and appendix). The total set of these ranges of all parameters involved in the calibration spans up the uncertainty space that is explored and used as boundary in the parameter estimation process. Second, a series of locations in the multi-dimensional parameter space is chosen as starting points for the parameter estimations. This means that before doing the actual analysis, we have an initial dataset (SI) for P parameters and N parameter estimation attempts: $SI_{P,N}$. The third step involves the estimation of parameter values that perform well in simulating the observations (dataset). We do this by minimizing the Normalised Root Mean Square Error (NRMSE) between model results and observed data, starting at the locations in the parameter space defined in the dataset $SI_{P,N}$. We search for optimal parameter estimations by using a Matlab built-in functionality for constrained nonlinear optimisation, using sequential quadratic programming (Mathworks, 2007). This algorithm varies the parameter values until the derivative of the objective function (in our case the NRMSE) reaches values between zero and a pre-defined threshold level. This results in a dataset with calibrated parameter sets ($SC_{P,N}$) that have a best obtainable fit with a set of observations in the form of measurements and/or constructed datasets, in this case energy use for the period 1971-2003. This can be imagined as the collection of local minima in the objective function landscape, spanned up by the explored parameter space. Not all parameter sets in $SC_{P,N}$ describe the same global optimum, it involves a range of parameter values and accompanying model results. An insightful example of the parameter values in $SC_{P,N}$ can be found in the appendix (Figure 5.10), showing the landscape of NRMSE-values against calibrated parameter values. For a more elaborate description and discussion of this method we refer to van Ruijven et al. (2008c).

To analyse the role of different parameter values in future projections of the model, we use the series of calibrated parameter sets in $SC_{P,N}$ to run the model forward for the period

2003-2030 using the OECD Environmental Outlook scenario on the model drivers (see Section 6 and OECD, 2008). We then analyse the range of projected future energy use by a frequency diagram of energy use in 2030. We weight the frequencies in the diagram relative to the NRMSE of the parameter set that obtained the best fit to historic data in $SC_{P,N}$. Hence, the weight (W) that the N'th calibrated parameter set gets in the prediction ensemble is defined as the normalisation of the relative weight (R) of the N'th parameter set to the best performing parameter set[2]:

$$W_N = \frac{R_N}{\sum_N R_N} \text{ where } R_N = \frac{NRMSE_{best}}{NRMSE_N} \qquad 1$$

4 The TIMER 2.0 Energy Demand Model: parameters and ranges

The TIMER model is a system dynamics energy system simulation model[3]. Energy use is modelled at a high level of aggregation; the model structure is similar for 26 world regions and five economic sectors and specific circumstances are captured by region- and sector specific parameter values. The energy demand model has a top-down macro-economic character: energy use is associated with economic activity via changes in energy intensity and efficiency (see below). Contrary to bottom-up models, sector-specific physical indicators are not taken into account. For residential energy use, this means that intermediate variables like floor area or appliance ownership are not explicitly considered.

In a first step, energy use is modelled as the annual demand for useful energy (*UE*, in GJ/year), this is the level of energy services or energy functions, for instance a heated room or cooled food. Useful energy demand is a function of changes in population and economic activity and three dynamic factors: structural change, autonomous energy efficiency improvement (*AEEI*), price induced energy efficiency improvement (*PIEEI*). The demand for useful energy is converted to secondary (or final) energy use (*SE*), using specific efficiencies (η) for different fuels, capturing price-based fuel substitution. Thus:

$$SE_{R,S,F} = \frac{POP_{R(t)} * X_{R,S(t)} * UEI_{R,S,F(t)} * AEEI_{R,S,F(t)} * PIEEI_{R,S,F(t)}}{\sum_{EC} \eta_{R,S,C(t)} * MS_{R,S,C(t)}} \text{(GJ/yr)} \qquad 2$$

in which *POP* is the population (in persons), *X* is the per capita economic activity of a sector (for the household sector, the activity level used in TIMER is private consumption in purchasing power parity (PPP), constant 1995 international $ /capita/yr). The useful energy

[2] This measure does not hold in the unlikely situation that the model exactly reproduces historic data and the best obtained NRMSE becomes zero.

[3] The TIMER energy model has been described elsewhere in detail (de Vries et al., 2001; van Vuuren et al., 2006b) and has been applied in a variety of contexts, for instance the IPCC/SRES (IPCC, 2000a), GEO (UNEP, 2007) and MA (MA, 2005). The derivation of the energy demand model formulas is described more elaborately in van Ruijven et al. (2008).

intensity (*UEI*) multiplier captures intra-sectoral structural change (in GJ/$/capita) and the *AEEI* and *PIEEI* (dimensionless) multipliers represent autonomous and price induced efficiency improvements. *UEI*, *AEEI* and *PIEEI* are functions of other state variable in the model, as we will elaborate further on. The market shares of the secondary fuels (*MS*) are derived from the fuel prices via a multinomial logit allocation formula. The indices indicate region (*R*), sector (*S*), energy form (*F*, heat or electricity) and energy carrier (*C*, coal, oil, natural gas, modern biofuel, hydogen, secondary heat and traditional biofuel). The multiplicative structure of this model leaves room for different behavioural parameter sets.

The residential model distinguishes two forms of energy (motivated by their different functions): electricity and fuels, which we treat separately. For fuels, we focus on the total final demand i.e. the sum of all energy carriers. Secondary fuel substitution is not considered in the analysis; we use exogenous historical fuel prices to determine market shares. It should also be noted that we assume no supply constraints by equating energy demand and energy use. The statistical data are assumed to have satisfied demand in a state of economic equilibrium on an annual basis; hence, we do not consider the concept of latent (or unfulfilled) demand for energy. This might not be valid for developing regions, where electricity use is more limited by supply than by a lack of demand.

4.1 Energy intensity curve

From energy analysis (e.g. Focacci, 2005; Medlock III and Soligo, 2001; Reddy and Goldemberg, 1990) some generic trends in energy use are known:

1. there is a tendency for total energy use to increase with population and economic activity;
2. in many countries, energy intensity tends first to rise then decline; this takes place at the level of the whole economy but also at sector level – this is usually explained from a mix of saturation and dematerialization (i.e. change to more value-added per unit of energy input)[4];
3. the level at which such a maximum is reached tends to decrease over time – interpreted as the collective dissemination of energy-innovations and of learning-by-doing.

Assuming that these observations also hold for useful energy, this stylized fact is represented in the model equation for useful energy intensity ($UEI_{(t)}$) in the form of a (asymmetric) bell-shaped function of sector-specific per capita economic activity. This is expressed as[5]:

$$UEI_{(t)R,S,F} = Y_0 + \frac{1}{\alpha + \beta X_{(t)} + \gamma X_{(t)}^{\delta}} \qquad 3$$

[4] For instance, for the long-term (1870-2000, such decline has been found for Sweden by Kander and Schon (2007)

[5] This bell-shaped curve can also be written in terms of income-elasticity as is common for energy use. It implies first rising, than declining income elasticity.

with $X_{(t)}$ the sectoral economic activity per capita and α, β, γ and δ parameters. The assumed economic driver for residential energy use is household private consumption expenditure per capita (PCO/capita). All parameters in this equation are defined per region, sector and energy form, α is assumed to be zero and δ is negative to maintain a bell-shaped form.

This equation has as its main features that for very high activity levels ($X \to \infty$), *UEI* tends to reach asymptotically constant GJ/$ values, equal to Y_0 GJ/$[6]. For very low activity levels (X~0) the *UEI*-value approaches Y_0 if δ is negative and in combination with β and γ significant enough to create a maximum in the curve. The flexible formulation of this curve implies also a high sensitivity to parameter values. From an energy use point-of-view, some reasonable constraints can be made to limit the potential parameter space to a relevant subspace. If we assess the two terms of eqn. 3 independently, i.e. the asymptote (Y_0) and the bell-shaped curve, these are[7]:

- The Y_0 value can be interpreted as the ultimately lowest energy-intensity of sectoral activity (in $/GJ) in the both $X \to \infty$ and X~0[8].
- The second term of the curve may, at high income levels, be related to saturation of useful energy per capita per year (U), based on sector specific features such as climate or population density. Since we assume that δ is negative and α=0, assuming Y_0=0 in eqn. 13 (hence, focussing at the second term), means that:

$$U = X * UEI = \frac{X}{\beta X + \gamma X^{\delta}} \Rightarrow \lim_{X \to \infty} \frac{X}{\beta X + \gamma X^{\delta}} = \frac{1}{\beta} \text{ and thus } \beta = \frac{1}{U} \quad 4$$

- The activity level at which the maximum occurs, X_{max}, can be estimated from regional energy use data, although this has the risk of cyclical reasoning, because one then draws conclusions from the observed data which are to be explained[9].
- The curve can be further constrained by forcing it through one reference observed point, defined as (X_{ref}, UEI_{ref}), which can be any year in the period 1971-2003 [10].

This allows a consistent set of parameter choices, for which these three key variables have to be investigated: the activity level at which the maximum occurs (X_{max}), the saturation level of useful energy per capita (*U*) and the asymptote or ultimate GJ/$ value (Y_0). The range for values of X_{max} and *U* in the parameter estimation process is defined as 10% broader than the maximum and minimum values applied in earlier (manual) calibrations of the TIMER model and is shown in the appendix (Table A3). Although Y_0 is conceptually

[6] This asymptote coincides with a hyperbole of constant per capita energy use. The product of X in $/cap/yr and Y (*UEI*) in GJ/$/yr is the per capita use of energy (U) in GJ/cap/yr
[7] For a more elaborate discussion of these assumptions see (van Ruijven et al., 2008c)
[8] α could be used to distinguish energy intensity between extremely high and low income levels.
[9] One should do this only for datasets (regions, periods) where presumably end-use conversion efficiency has hardly changed. This is probably valid for electricity use, but not for fuel use, especially in developing regions. The transition from traditional biomass to modern fuels leads to major efficiency improvements, see η in eqn. (2).
[10] In our model implementation this is the year 2003, the latest year of the calibration period

only limited by the value of UEI_{ref}, the model becomes linear if Y_0 approaches UEI_{ref}[11]. To ensure that the bell-shape of the function (that we know as stylized fact from energy data) is maintained, we assume Y_0 to be lower than 20% of UEI_{ref}.

4.2 Autonomous Energy Efficiency Improvement (AEEI)

The continuous decline of energy intensity due to technology change is represented in the TIMER model by the autonomous energy efficiency improvement (*AEEI)* multiplier. The marginal *AEEI* is formulated as a fraction of economic activity growth (Manne et al., 2005):

$$AEEI_{marg\,(t)R,S} = F_S * (\frac{GDPpc_{(t)R}}{GDPpc_{(t-1)R}} - 1) * 100 \qquad (\%/yr) \qquad 5$$

with F_S a sectoral specific fraction of economic activity growth. The vintage structure[12] modelling for energy using capital in TIMER determines that the current *AEEI* is the weighted average of the marginal *AEEI* over the capital life time (de Vries et al., 2001). This means that rapid economic growth leads to a faster decline in *AEEI*, due to both increased decline in the marginal *AEEI* and a larger share of the capital stock that is relatively new. In case of economic decline, the marginal *AEEI* cannot become negative, and is de facto set to zero, because negative values are considered implausible.

The parameter value that has to be estimated for *AEEI* is the fraction of GDP growth (F_S). For the percentage of annual *AEEI* a range of 0.2-1.5% per year is suggested by experts consulted by van der Sluijs et al. (2001). Based on this, we established a range for F_S based on the average annual regional GDP per capita growth over the period 1971-2003 (see Table A4 and A5). Below, *AEEI* is expressed as the average percentage of annual sectoral efficiency improvement.

4.3 Price Induced Energy Efficiency Improvement (PIEEI)

The *PIEEI* reflects that with increasing energy prices end-users take measures to use energy more efficiently. The description of *PIEEI* in TIMER is based on an energy conservation supply-cost-curve, describing the increasing marginal cost of one unit of energy saved. The investments are annuitized by assuming a (apparent or desired) payback time PBT. By comparing the annual gains of efficiency improvement (saved energy times payback time and energy prices) to the annual cost of investments, an optimum investment cq. efficiency level can be found. Three factors determine the level of energy efficiency: the form of the supply-cost-curve, the pay-back time and the learning rate of energy efficiency technology.

In the TIMER model, the energy conservation supply-cost-curve can be compared to bottom-up technology data (de Vries et al., 2001) but is modelled as an aggregated stylized

[11] Since energy intensity is defined in energy use per (monetary) unit of GDP, there is no theoretical or thermodynamic limit to the value of Y_0.

[12] Vintage modelling is an essential element of system inertia in the model. It describes investments and depreciation of capital stocks on the basis of assumed lifetimes. Changes in the characteristics of capital (*AEEI*, *PIEEI*, end-use efficiency) are only adopted at the rate of new investments. For a more elaborate description see (van Vuuren, 2007).

function. The optimal level of energy efficiency (*E*, as fraction of total energy use) is defined as the point at which marginal energy conservation measures still yield net revenue:

$$E_{R,S,F(t)} = M_{R,S,F} - \frac{1}{\sqrt{M_{R,S,F}^{-2} + \frac{C_{R,S,F(t)} * T_{R,S,F(t)}}{S_{R,S,F} * I_{R,S,F(t)}}}} \qquad 6$$

in which *M* is the maximum potential price-induced efficiency improvement (as fraction of total frozen energy use), *C* the sectoral average costs of useful energy (*in $/GJ)*) and *T* the pay-back time (*in years*). *I* is a dimensionless factor with which the cost curve declines as a result of learning-by-doing. The scaling parameter S is used to scale the curve to the sector-specific costs of useful energy. The *PIEEI* on marginal capital investments, which is used in eqn 3, is a dimensionless multiplier defined as: $1\text{-}E_{R,S,F}$. Vintage modelling of energy demand capital delays the impact of the *PIEEI*, as the current *PIEEI* is the weighted average of the marginal *PIEEI* over the capital life time.

In the parameter estimation procedure we vary values of payback time (*T*) and learning (*I*)[13]. However, in the presentation of the results we express these two parameters together as the cumulative efficiency improvement up to the year 2003. The ranges for the learning and payback time parameters in the experiment are shown in the appendix.

4.4 Price-based fuel substitution

Market shares for fuels are assumed to be allocated on the basis of mutual cost differences, using the multinomial logit model:

$$MS_C = \frac{e^{-\lambda C_C}}{\sum e^{-\lambda C_C}} \qquad 7$$

in this, MS_C is the indicated share of each energy carrier, λ is the logit parameter that determines the sensitivity of markets to price changes and C_C is the market price for the end-user[14]. Including the secondary fuel substitution process in this model calibration exercise would add significantly to the potential set of parameter values. Therefore, we

[13] Alternative parameters to vary would be the maximum improvement level (*M*) or the steepness (*S*). However, *M* is based on a theoretical maximum efficiency improvement expressed in energy intensity terms. This is a useful parameter to explore, but has more impact on future projections than on historic calibration. The steepness parameter (*S*) is used to scale the *PIEEI* curve to the useful energy costs per sector and is therefore not useful to vary.

[14] We use historical prices adjusted for non-market effects such transaction and infrastructural cost. This is done by the use of premium factors, adjusted in such a way that market shares are adequately simulated. This procedure to construct what is usually called 'perceived costs' (or prices) does not affect the present outcome as neither market prices nor premium factors are part of the uncertainty analysis. It does, however, point to another deficiency in most energy demand/use models.

decided in this analysis to fix market shares to historic data and use a scenario of market share development, based on the prices of the OECD-EO scenario for future projections (see Section 5). Effectively, this keeps the denominator in eqn. 2 similar for all model runs.

During the last decades, the average final end-use conversion efficiency improved (Table 5.1). In TIMER, there is a set of pre-described efficiencies as function of fuel and time (η in eqn. 2[15]). Within this context, the improvement of overall efficiency (across all fuels) is driven by two processes: fuel switching towards more efficient energy carriers and improvement of end-use technology. The first process mainly takes place in developing countries (see 'share traditional fuels' and 'fuel switch' in Table 5.1), with a transition from traditional biofuels to commercial fuels. Generally, traditional fuels are applied in inefficient stoves, whereas commercial ('modern') fuels are applied more efficiently. Data on traditional fuels are highly unreliable, which makes it difficult to understand and model this transition. As stated above, in this analysis we directly determine the market shares of secondary fuels from historic data, without any modelling[16]. The second process represents improvements in the use of a particular fuel; for instance, the use of more efficient fuel wood stoves or the shift from normal to highly efficient boilers.

Table 5.1: Decomposition of assumptions on conversion efficiency improvement

		% traditional fuel in residential TFC	Average end-use conversion eff.	Index 2003 (1971=100):		
				Fuel switch	Technology	Total
W. Europe	1971	8%	58%			
	2003	9%	72%	104	120	125
USA	1971	4%	60%			
	2003	9%	72%	96	123	119
India	1971	94%	17%			
	2003	87%	25%	115	124	142
China	1971	82%	21%			
	2003	69%	33%	125	125	154
Brazil	1971	96%	17%			
	2003	78%	29%	144	124	177

5 Simulation of historic energy use in five world regions

We applied our method to identify multiple behavioural parameter sets, as described in Section 3, to the residential sector energy use model of TIMER. We performed 100 parameter estimation attempts per region, so N=100 in $SI_{P,N}$ and $SC_{P,N}$. This section describes the results per region and discusses differences and patterns in the parameter

[15] An interesting experiment could be to analyse the model behaviour if efficiencies were implemented in terms of exergy instead of energy, as proposed by (Warr and Ayres, 2006)
[16] Normally, the use of tradition fuels is described in TIMER as a function of income, urbanisation and commercial fuel price, based on (Birol and Lambert D'Apote, 1999)

values. We use Pearson's correlation coefficient[17] between the calibrated parameter values to indicate equifinality in the model. Correlation between two parameters indicates that (behavioural) solutions exist with different values for both parameters. The behaviour of the UEI-curve parameters is summarised by the value of Y_{max}: maximum useful energy intensity.

5.1 Residential energy use in the USA

Total residential sector fuel use in the USA declined in the 1971-2003 period from about 9 to 7 EJ/year (Figure 5.1, middle left graph). In the same time, the assumed drivers private consumption (Figure 5.1, upper left graph) and population increased as did floor space per capita, an important bottom-up driver of space heating (IEA, 2007c; Schipper et al., 1996). One factor in the decline has been the improvement in conversion efficiencies, largely due to the gradual switch from coal to oil and then, partly, to natural gas (Table 5.1). The use of traditional fuels has been minor, with temporarily an increase during the oil crisis. The data show many year-to-year fluctuations, which correlate strongly with warmer and colder years, expressed in heating-degree-days. Correcting fuel use for temperature fluctuations[18] smoothes the historic data, but does not change the decreasing trend (Figure 5.1, middle right graph).

The model is capable to simulate the declining trend, with a best obtained NRMSE value of 6.7% (Figure 5.1, middle left graph) and a rather broad spread around it with some parameter sets even leading to an increasing trend (with an NRMSE of 18%). Calibrating the model against temperature corrected data leads to a slightly better fit (5.7%) but the increasing outliers remain. The parameter settings indicate a declining useful energy intensity in the 1971-2003 period (UEI-curve) and the few non-behavioural parameter sets with an increasing UEI have low values for *AEEI* and *PIEEI* (see also the negative correlation coefficient for *AEEI*/*PIEEI* and NRMSE in Table 5.2). In energy terms, these results suggest that a rather wide range of technological (*AEEI*) and price-related (*PIEEI*) factors can explain the historic data (see Appendix 2, Figure 5.8).

Residential electricity use in the USA has been increasing rapidly from 2 to 4.5 EJ/yr in the 1971-2003 period (Figure 5.1, lower right graph). The most important underlying drivers are appliances and lighting (IEA, 2007c), and no clear fluctuations as a result of climate factors are visible. The trend can be simulated with a best fit of 3.6% and all calibrated parameter sets have NRMSE values below 6.5%. Although there is little correlation between the aggregated parameter values (Table 5.3), two options for the UEI-curve are found. The best fitting parameter sets are characterised by a combination of high *Xmax* and low Y_0 (i.e. historically increasing UEI), moderate technology improvement (*AEEI* around 0.6 %/yr) and low values for price-induced efficiency improvement. This implies a significant income-elasticity and a small price-elasticity, whereas technology is of moderate

[17] This is the common correlation coefficient, defined as $corr(X,Y) = \frac{\mathrm{cov}(X,Y)}{(\sigma_Y)(\sigma_X)} and \ \mathrm{cov}(X,Y) = \frac{1}{n}\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y})$

[18] The correction factor for each year *t* is defined as $\frac{AvgHDD_{(1971-2003)}}{HDD_{(t)}}$ and applied to the fraction of space heating in residential fuel use. This fraction is assumed constant at 70%, based on data from (DOE-EIA, 2006)

importance. Another behavioural implementation involves low values of *Xmax* (i.e. historically decreasing UEI), no technology development and moderate reactions to price changes. The average income-elasticity over the period 1971-2003 can be determined from the annual change in the use of useful energy. The range of calibrations suggests an income elasticity of 0.85-1.04, with values above 1 for the better-fit parameter sets. This is higher than the 0.52 found by Silk and Joutz (1997) and 0.65-0.68 found by Kamerschen and Porter (2004)[19].

[19] It is questionable whether these numbers can be directly compared, because all models are based on different data, follow a different methodology (e.g. different functional forms) and take different factors into account.

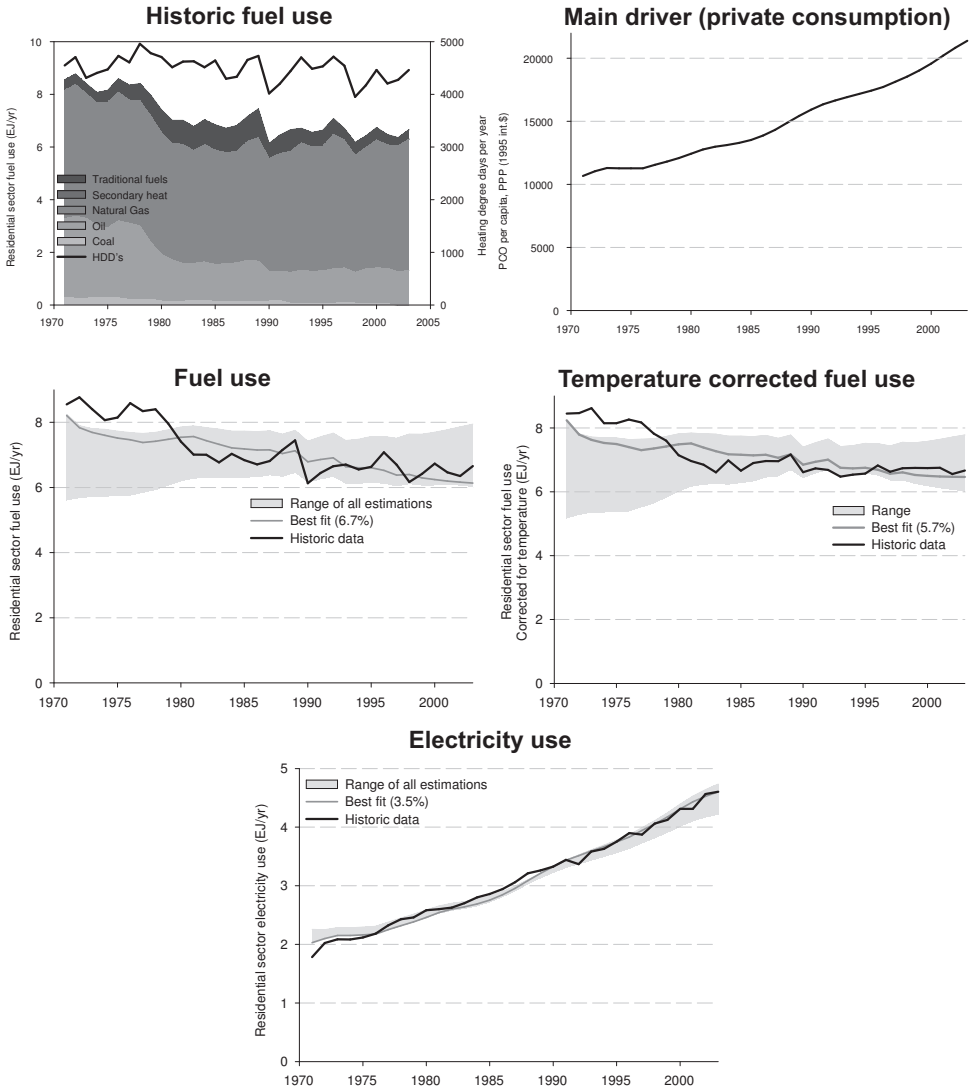

Figure 5.1: Historic data on household expenditures, fuel use and heating degree-days and results of parameter estimation for residential fuel and electricity use in the USA. Data on energy use from IEA (2005), data on degree-days from DOE-IEA (2006)

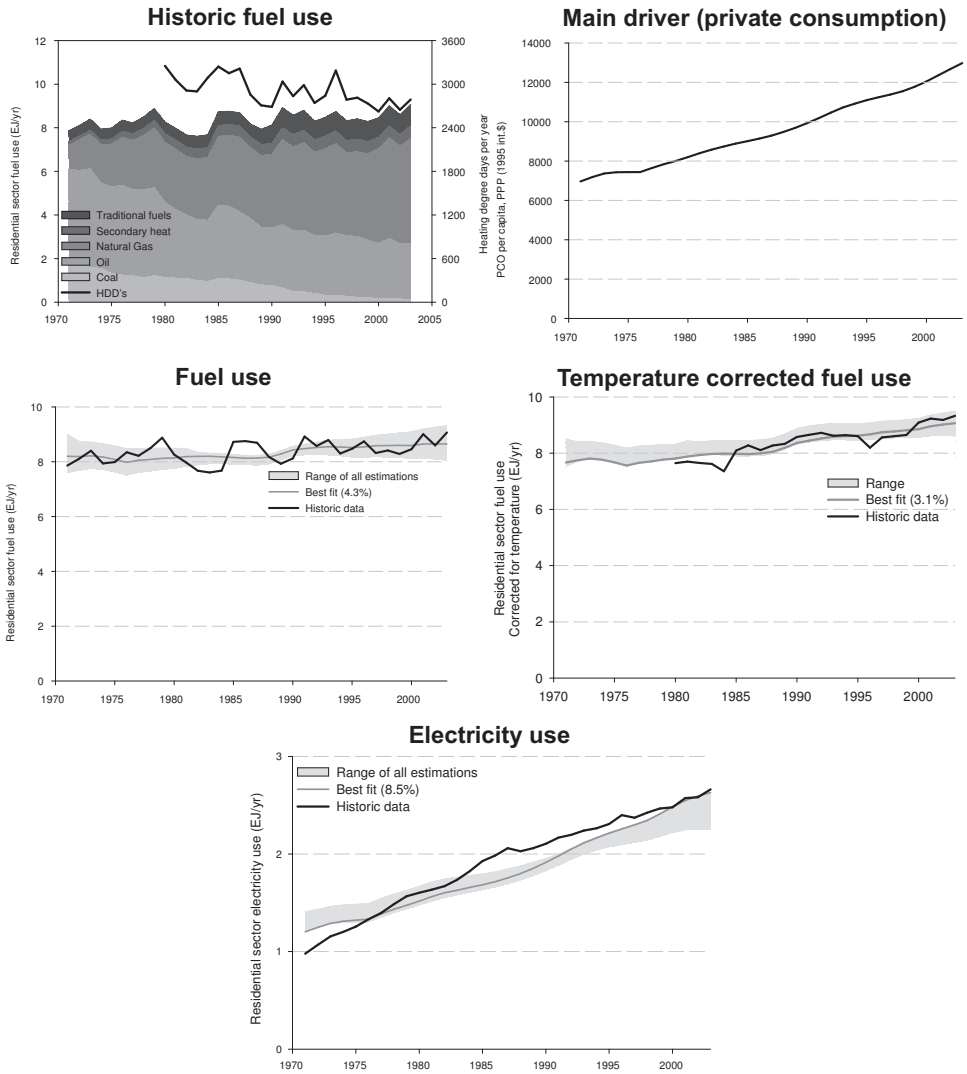

Figure 5.2: Historic data on household expenditures, fuel use and heating degree-days and results of parameter estimation for residential fuel and electricity use in Western Europe. Energy data from IEA (2005) and data on degree-days from Eurostat and Joint Research Center (2007)

5.2 Residential energy use in Western Europe

Western European[20] residential fuel use has been stable for the last 30 years at about 8 EJ/yr, with a gradual replacement of coal by oil and then natural gas. This has coincided with an (assumed) improvement in conversion efficiency even larger than in the USA (cf.

[20] The region of OECD Europe in the TIMER model is comparable to EU15 plus Norway and Switzerland

Table 5.1). Here too, much of the short term variation can be explained from temperature fluctuations (Figure 5.2, upper left graph). If fuel use is corrected for temperature changes, the trend increases in later years[21]. The trend of the data can be simulated by the model with best NRMSE values of 4.3%. There is little correlation in parameter values (Table 5.2) indicating that there are no patterns between the different calibrated parameters. The most behavioural parameter sets are characterised by a UEI-curve that is rather similar to the USA, with low values for *Xmax* and Y_0, but a higher value for *U*. Also, a clear signal of technological importance (*AEEI* of 0.5-0.7%/yr) and a moderate if any role for price-induced savings (*PIEEI*≈0) explain the historic data.

Just as in the USA, electricity use has been increasing rapidly in Western Europe, though after 1985 with a lower growth rate. With NRMSE values between 8.5-14.1%, the model is capable to simulate the growth but not the decline in growth rate. Table 5.3 shows some equifinality in the values for *UEI* and *AEEI*, although both parameters strongly determine NRMSE. The best-fitting parameter sets have high *Xmax*, low Y_0 and low *AEEI* and *PIEEI* values, which indicate the importance of activity growth as a determinant of electricity use and the lack of price effects.

We now proceed with the results for three low-income regions: India, China and Brazil. It is important to realise that for both fuel and electricity use some caveats are in place here. First, the data in these developing regions, especially the pre-1990 data, are notoriously unreliable. Secondly, the large income disparities within urban areas and between urban and rural areas may make the average income an unsuitable driving force indicator (see also van Ruijven et al., 2008b). Thirdly, market and other institutions such as banks are often partly or sometimes hardly functioning and governing elites often interfere with political means and for political reasons. This effects for instance the dissemination of technologies and the role of prices.

5.3 Residential energy use in India

Indian residential fuel use has been linearly increasing between 1971 and 2003, although private consumption increased exponentially (Figure 5.3, upper graphs). Residential fuel use in India is mainly applied for cooking and lighting (kerosene lamps); space heating is not important due to India's (sub-) tropical climate (Pachauri, 2007); air conditioning is still a luxury, although ownership is increasing in recent years (NSSO, 2003). Residential fuel use is dominated by traditional fuel use; use of commercial fuels, especially oil (kerosene and LPG) and coal increased as well, but in absolute terms not much. Government policies such as social price subsidies on electricity, kerosene and LPG and electrification for rural households influence people's energy-using behaviour and hence energy use, though it is hard to say how in the absence of equivalents for comparison (Dzioubinski and Chipman, 1999).

[21] The methodology for temperature correction is similar as described for the USA. For Europe we assumed a decline in the share of space heating in total residential fuel use from 79% in 1973 to 74% in 2003, based on data from (IEA, 2004a)

The aggregate fuel demand trend can be reproduced well by the model, with a best NRMSE of 5.9%. The behavioural parameter sets are characterised by declining energy intensity, low *AEEI* and hardly any *PIEEI*. Variation in parameter values is only observed for *U*. This means that technology (*AEEI*) and price-impacts (*PIEEI*) play no role in the explanation of Indian residential fuel use and that it can fully be explained from income related changes (*UEI*). Because data on traditional fuels are unreliable and these fuels are applied with low efficiencies, it is interesting to see whether the trends can be better simulated if only commercial fuels are taken into account (see Figure 5.3, middle right graph). For India, this leads to less behavioural model behaviour with a best NRMSE of 20% - mostly because model tends to describe energy use growth in India in more exponential way in contrast to a rather linear historic growth.

Though at very low levels (residential India used 0.35 EJ electricity in 2003), historic electricity use follows the exponential pattern of private consumption data. It is much less reproducible by the model: the best NRMSE is 31%. In the parameter values, *AEEI* and *PIEEI* play no role and electricity use is determined by rapidly increasing useful energy intensity. A possible explanation (for India, but also for China and Brazil, discussed further on) is that the demand for electricity is only partly met, due to constraints in generation, transmission and distribution. It is well known that in many parts of India, electricity shortages happen with subsequent outages and allocation schemes. This means that the structure of our model simulates the development of latent demand, without supply-constraints. This also appears from the very high income-elasticity values (2.8-3.2), compared to income-elasticities in literature of 0.88 (Bose and Shukla, 1999) and 0.6-0.63 (Filippini and Pachauri, 2004).

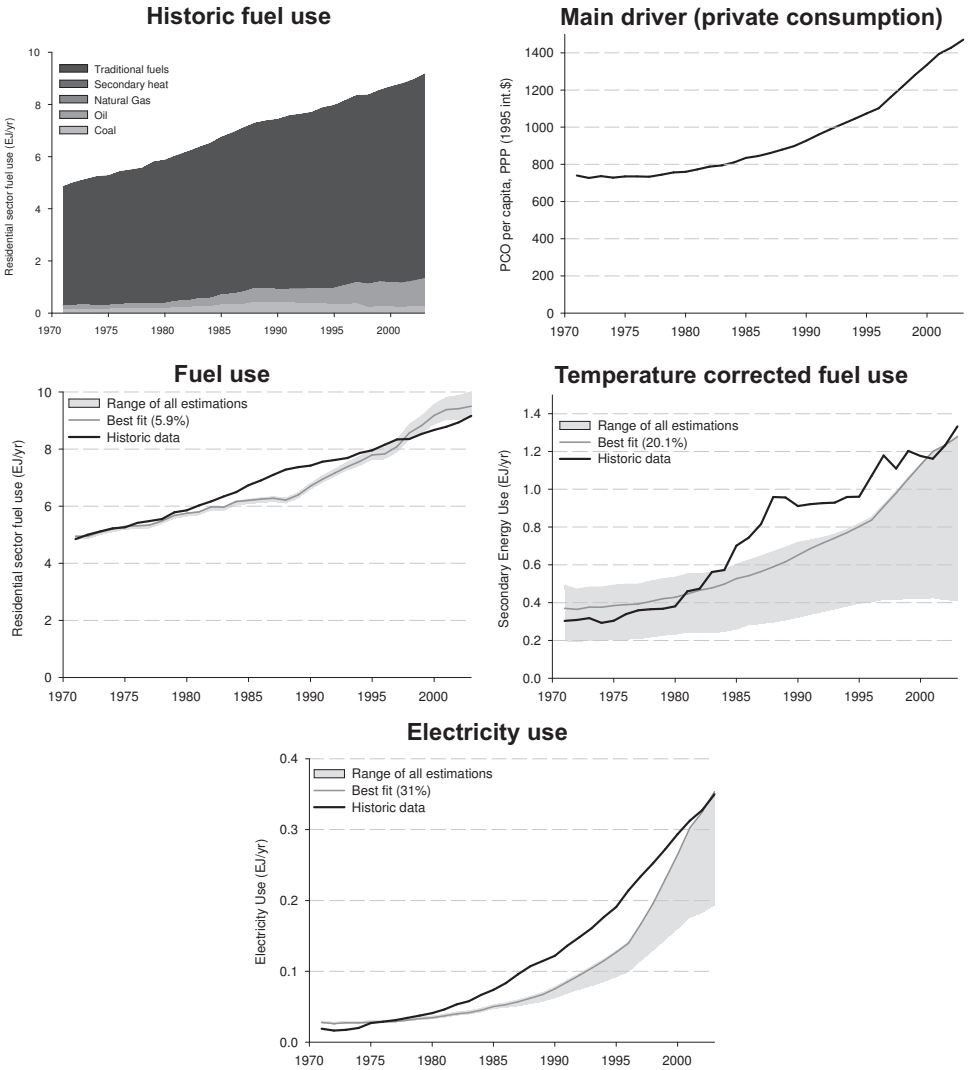

Figure 5.3: Historic data on household expenditures and energy use and results of parameter estimation for residential fuel and electricity use in India

5.4 Residential energy use in China

Chinese residential fuel use has been slowly increasing from about 10 to 12 EJ/yr. Rural household fuel use in China consists almost solely of traditional fuels and coal (Sinton et al., 2004) and Figure 5.4, upper left graph) while urban households use mainly electricity and gas, LPG and coal (Brockett et al., 2002). Residential coal use has been declining

rapidly during the 1990s, coinciding with a government campaign to close down small and unsafe mines (Sinton and Fridley, 2003).

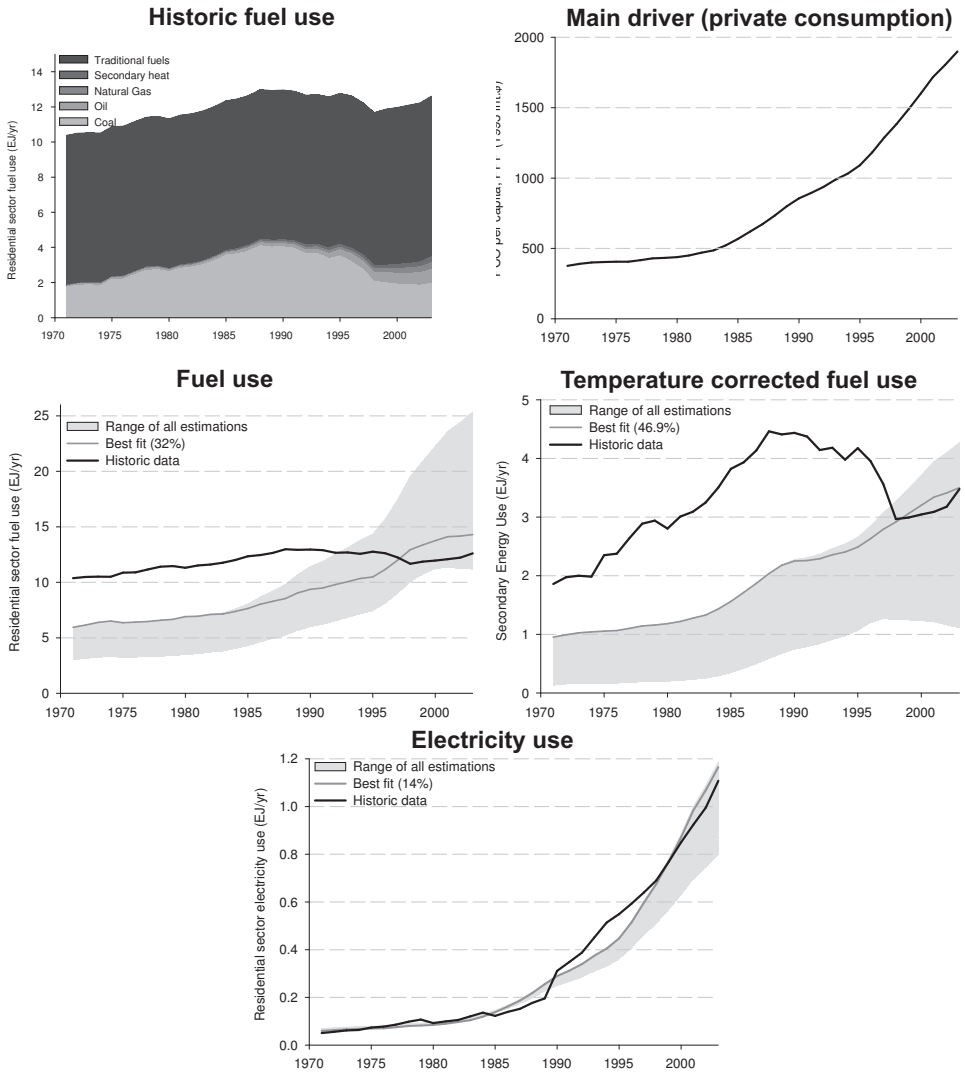

Figure 5.4: Historic data on household expenditures and energy use and results of parameter estimation for residential fuel and electricity use in China

The model has difficulties to combine the data series on the model driver (strongly increasing) with the historic data on energy use (nearly constant). The best fit shows an exponentially increasing trend with an NRMSE of only 32%. The *UEI*-formulation (eqn. 3) assumes at these low income levels a close relation between energy and income; *AEEI* or

PIEEI cannot offset this trend under the parameters that are allowed. Two alternative parameter sets lead to a better fit, but both are allegedly implausible. First, extremely low values for *Xmax* (10 $/cap/yr) and *U* (3 GJ_{UE}/cap/yr) combined with high *AEEI* values (6 %/yr) lead to a historically constant energy use, but also to rapidly declining future projections. A second option is to increase the value of the reference *UEI* in 2003 (see Section 4.1), but this implies higher end-use conversion efficiencies (η in eqn. 2), which is rather implausible (Sinton et al., 2004). Focusing only on commercial fuels hardly improves the quality of the simulations, since the model cannot explain the policy-driven coal phase-out of the 1990s (Figure 5.4, middle right graph). Further explanations may be related to data quality[22], and very high efficiency improvements resulting from large inefficiencies in 1971 that cannot be reproduced by the current model.

Residential electricity use does follow an exponential trend, as in India, and can therefore be reproduced quite well with the exponential rising private consumption. Because the data show some short-term deviations from the exponential trend (which are likely to be data errors or supply-shortages), the best fit has still a rather high NRMSE value of 14%. The parameter values for the best fitting parameter sets are characterised by relatively rapidly increasing useful energy intensity, with a peak a relatively high income levels (20-30000 int$/capita); technology (*AEEI*) and price (*PIEEI*) play hardly any role in explaining the historic trend (see Appendix 2, Figure 5.9). Although there is variation in parameter values (Figure 5.9), this is mostly between the UEI-parameters and no pattern between the values of *UEI*, *PIEEI* and NRMSE can be observed (Table 5.3).

5.5 Residential energy use in Brazil

Brazilian total final energy use is characterised by a rapid decline of traditional fuels, although the rate slows down in recent years (Brito, 1997). It also happened in the residential sector (Figure 5.5, left upper graph and (Goldemberg et al., 2002; Goldemberg and Mielnik, 1996). Especially during the 1980s the share of modern (renewable) energy sources in total energy use increased as a result of policies adopted in the 1970s (Schaeffer et al., 2005). These policies were mainly driven by energy import policy and were focused on the transport sector (i.e. the alcohol program). The major commercial fuel in the residential sector is LPG, mainly applied for cooking; space heating is almost nonexistent in Brazil (Poole et al., 1998). Explanations for the rapid decrease of fuelwood use are substitution by LPG and improved efficiency. The use of electricity in Brazil is rapidly increasing, mainly driven by the increased ownership of (energy-intensive) appliances (Poole et al., 1998). Compared to other developing countries, Brazil shows a high ownership of electric appliances (McNeil and Letschert, 2007). One peculiar – and disturbing – phenomenon in simulating Brazil's energy use are fluctuations in the major driver, private consumption, after 1983 and the sometimes extremely high inflation rate which makes the monetary time-series probably a bad indicator of activity (Figure 5.5, lower left graph).

[22] It should be note that pre-1990 levels of traditional fuel use in China are constant in this dataset

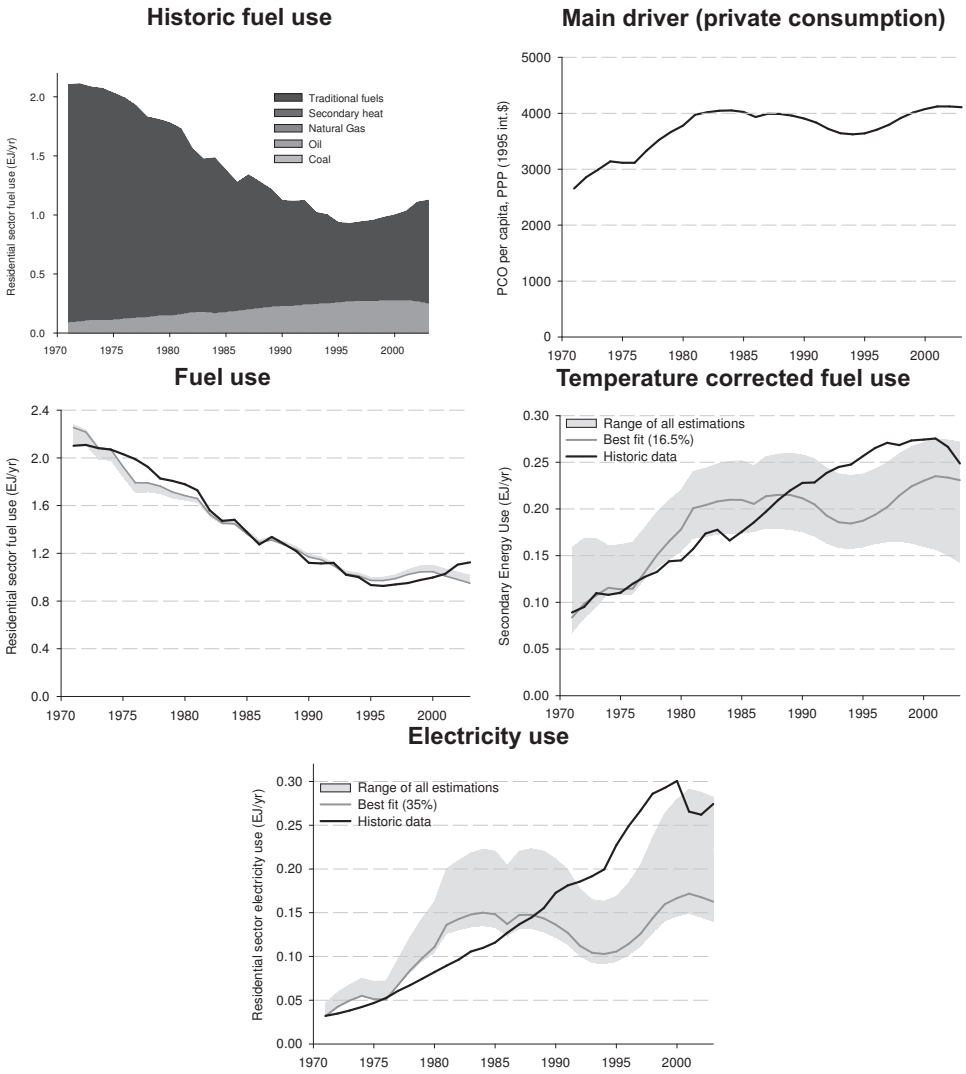

Figure 5.5: Historic data on household expenditures and energy use and results of parameter estimation for residential fuel and electricity use in Brazil

The model is able to simulate fuel use rather well, with NRMSE values of 5.4%. However, this is strongly influenced by changing the model assumption of constant efficiency for traditional fuels before 1985 towards a linear increase from 5% (1971) to 15% (1985), reflecting large scale implementation of improved stoves. The parameter values indicate various possible UEI-curves (*Xmax* has values both below and above the 2003 private consumption level and can thus historically be both decreasing and increasing) leading to different stabilisation level (wide variation in U). Also, technology improvement has been important with *AEEI* values between 0.5-0.8 %/yr. However, responses to prices (*PIEEI*)

are unimportant in explaining historic developments. The variation in values is mainly within the UEI-curve, and does not appear in Table 5.2. Ignoring the role of traditional fuels does not lead to a better fit with historic data, and seems much more sensitive to changes in economic activity.

Brazilian residential electricity use is more difficult to simulate. In periods of constant or declining private consumption levels, historic electricity use increased linearly. The most important cause is probably the uncoupling of real activity levels and monetary data due to high inflation rates, but in addition it might be that the growth of electricity use in Brazil might be more supply-driven by slowly expanding capacity.

Table 5.2: Pearson's linear correlation coefficient between calibrated parameter values for residential fuel use. Chinese fuel use is considered non-behavioural.

USA	UEI (Y_{max})	*AEEI*	*PIEEI*	**Europe**	UEI (Y_{max})	*AEEI*	*PIEEI*
AEEI	0.36	-		*AEEI*	-0.30	-	
PIEEI	0.23	-0.04	-	*PIEEI*	0.06	-0.25	-
NRMSE	-0.47	-0.53	-0.60	NRMSE	0.07	0.08	0.15
India	UEI (Y_{max})	*AEEI*	*PIEEI*	**China**	UEI (Y_{max})	*AEEI*	*PIEEI*
AEEI	0.31	-		*AEEI*	0.29	-	
PIEEI	-0.30	-0.33	-	*PIEEI*	-0.13	-0.29	-
NRMSE	-0.98	-0.36	0.14	NRMSE	-0.37	-0.84	0.07
Brazil	UEI (Y_{max})	*AEEI*	*PIEEI*				
AEEI	-0.03	-					
PIEEI	-0.02	-0.54	-				
NRMSE	0.07	-0.84	0.14				

Table 5.3: Pearson's linear correlation coefficient between calibrated parameter values for residential electricity use. Brazilian electricity use is considered non-behavioural.

USA	UEI (Y_{max})	*AEEI*	*PIEEI*	**Europe**	UEI (Y_{max})	*AEEI*	*PIEEI*
AEEI	0.04	-		*AEEI*	-0.54	-	
PIEEI	0.17	-0.30	-	*PIEEI*	-0.11	-0.14	-
NRMSE	0.75	0.37	0.48	NRMSE	-0.89	0.81	0.04
India	UEI (Y_{max})	*AEEI*	*PIEEI*	**China**	UEI (Y_{max})	*AEEI*	*PIEEI*
AEEI	-0.31	-		*AEEI*	0.10	-	
PIEEI	-0.12	0.65	-	*PIEEI*	0.01	-0.26	-
NRMSE	-0.32	0.75	0.07	NRMSE	-0.32	0.75	0.07
Brazil	UEI (Y_{max})	*AEEI*	*PIEEI*				
AEEI	0.02	-					
PIEEI	-0.03	-0.25	-				
NRMSE	-0.19	0.05	-0.61				

5.6 Differences and patterns in parameter values

While we have seen that the model can reproduce some trends in regional energy use very well, the model results on fuel use in China are not behavioural with historic data. With respect to electricity use, India and China can be regarded behavioural, despite their relatively high NRMSE values, but Brazil is clearly not behavioural. These non-behavioural parameter sets provide no useful information on the model parameter values and they

should not be used to analyse patterns or differences. Also forward calculations on the basis of these parameter sets are not useful.

What are the differences in parameter values between the regions? The parameter values for residential fuel use show that all UEI-curve implementations (except Brazil) are historically declining with hardly any base-intensity and comparable levels of saturation of approximately 30 GJ_{UE}/yr (except for the USA). Peculiarly, the USA and Europe have the lowest stabilisation levels of useful energy, despite differences in temperature and the demand for space heating. This uncovers a weakness of our method, in which each region is calibrated to its own historic data without any reference to other regions (this issue is discussed below in more detail). Here, it leads to extrapolation of the decreasing trends in Europe and the USA and the increasing trends in developing countries. Technology improvement is relatively important in explaining historic fuel use, with average values for *AEEI* between 0.5 and 1.2 %/yr (China has higher values, but is not considered behavioural). Price-induced changes are unimportant in all regions, except for the USA.

For electricity use, the calibrated energy intensity curves are historically increasing for all regions (X_{max} is higher than 2003 private consumption levels), except for the USA (see Appendix 2, Figure 5.9). Further, UEI is in most regions characterised by a low base level (Y_0=0-0.02 MJ/$/year, except for Brazil, which is not behavioural). Useful energy use per capita saturates at about 70 GJ_{UE}/capita/yr for all regions. Technology and price-impacts are unimportant in all regions, with all *AEEI* values below 0.5 %/yr and hardly any *PIEEI*.

6 Uncertainty in projections for 2030

To determine the influence of the different behavioural parameter sets on future projections of the model, we calculate the projected energy demand in 2030 using scenario inputs of the OECD environmental outlook scenario: OECD-EO (Kram and Bakkes, 2006; OECD, 2008). These scenario inputs include projections for private consumption (the residential model driver) and population. The OECD-EO is a baseline scenario without new policies on economy and environment, in which energy use is based on moderate projections of population and economy. In this analysis, the share of final energy carriers is the same in all forward calculations, corresponding to energy prices in the default implementation of this scenario[23]. The TIMER model has also been used within the OECD-EO study to project developments of the future energy system. The parameter settings for that study were globally calibrated against the IEA World Energy Outlook (IEA, 2004b) and are quite different from the ones we use here. These projections are shown for comparison in subsequent graphs, indicated as TIMER OECD-EO scenario.

For Western Europe, residential fuel use in the OECD-EO scenario is projected to remain stable until 2030 at about 8 EJ/yr, with a slight decrease after 2020 (Figure 5.6, upper

[23] Normally energy prices for future projections are calculated endogenously in the model based on depletion of resources and learning of exploitation technology. If this were included, different energy demand projections would lead to different energy prices, causing different market shares of fuels and diverging values for end-use-efficiency and *PIEEI*

graph). The range of projections that results from our calibrated parameter sets broadens after 2000, resulting in projections between 6-10 EJ/yr in 2030. Expressed as relative deviation from the best-fitting parameter set, this amounts to a range of 46% (Table 5.4). The projection of the best fitting parameter set is both in the middle of this range and in the peak of the weighted distribution of projections in 2030: slightly over 8 EJ/yr in 2030. The OECD-EO projection for electricity use in Europe (Figure 5.6, lower graph), follows the declined growth rate after 1990, increasing slowly towards 3.2 EJ/yr in 2030. The automated calibration procedure was not able to follow this decreasing growth rate (see Section 5.2), leading to higher electricity use projections of 4 EJ/yr in 2030. The range of future projections on the basis of calibrated parameter sets for 2030 are between 2-4 EJ/yr, or 43% relative to the best-fit projection (Table 5.4).

The ensemble projections for all other regions are shown in Appendix 3. For fuel use in the USA, the distribution in 2030 shows that the wide range of projections (100% of the best-fit) originates mostly from a few outliers: the majority of calibrated parameter sets follow the decreasing trend of historic data (Figure 5.11). The better-fit projections indicate a 2 EJ/yr lower energy use in 2030 than the OECD-EO scenario. Electricity use in the USA for both the best-fit parameter set and the OECD-EO scenario is projected at the level where most projections are clustered: 6-7 EJ/yr in 2030 (there is also a range of only 34% around the best-fit projection, Table 5.4). For India (Figure 5.12), in the OECD-EO scenario fuel use stabilises around 12 EJ/yr, but the range of parameter sets projects 13-18 EJ/yr in 2030 (or 38%). Projections for electricity use diverge far more: in the OECD-EO scenario it is 1.8 EJ/yr whereas the best-fit parameter set (and most other projections) indicate exponential growth towards 7 EJ/yr (with a range of 82% around the best-fit). For China, the calibration of fuel use is not behavioural and is therefore not discussed here. However, modelling of Chinese electricity use faces the same problem as India: the OECD-EO scenario projects 4 EJ/yr in 2030, whereas most automatically calibrated parameter sets project about 10 EJ/yr (Figure 5.13), though with a range of 58%). Projections for Brazilian fuel use show a relatively narrow range around the OECD-EO scenario (only 27% of the best-fit) and are stable at about 1 EJ/yr. Electricity use was considered non-behavioural is and is not further discussed.

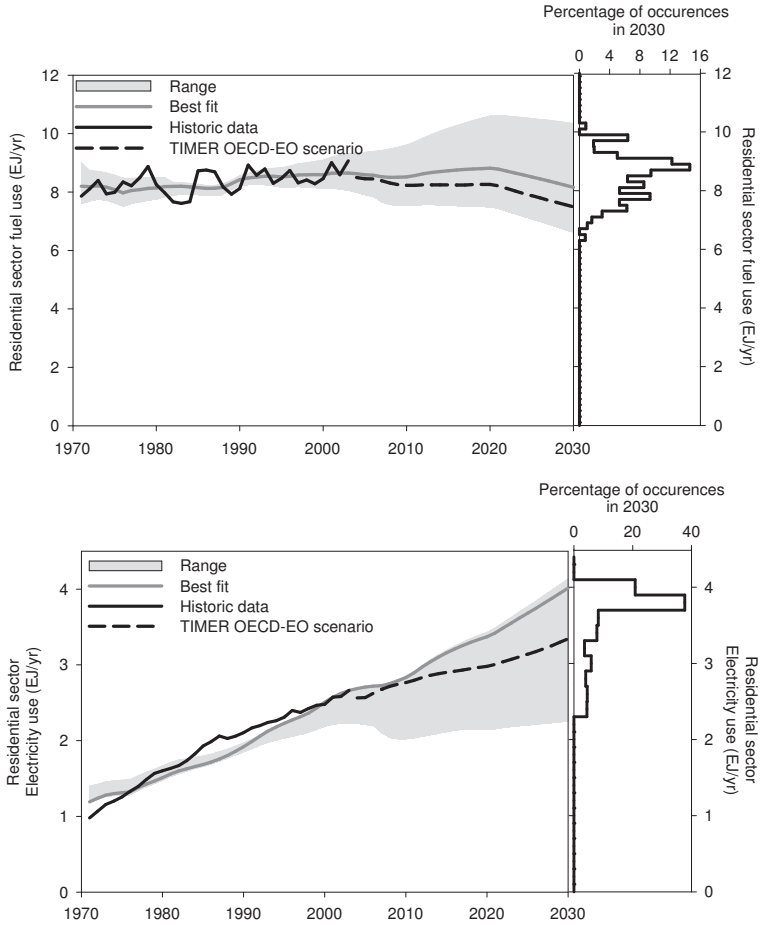

Figure 5.6: Projected residential fuel (upper graph) and electricity (lower graph) use for Western Europe up to 2030 and histogram of energy use in 2030 using the NRMSE as weighting factor. Projections based on OECD-EO scenario inputs and calibrated parameter sets

Now that we have seen that uncertainty in calibration leads to wide ranges of future projections already for 2030[24], it is interesting to see the influence of individual parameters on these projections. The non-linear nature of the model features complicates insights in the influence of an individual parameter; for instance, useful energy intensity might have been historically increasing, but can be decreasing towards 2030. The simplest method to identify these influences is the linear correlation between the calibrated parameter values and projected energy use in 2030 (Table 5.4 and 5.5). As can be expected, technology improvement (*AEEI*) correlates negatively with future energy use, though its influence varies between regions and is not necessarily related to regions with high *AEEI*-values. Usually price-induced improvement should also be negatively correlated with future energy

[24] These models are often used to make projections towards 2050 or 2100

use, since energy prices are projected to increase. However, in many regions the *PIEEI* plays no role and has values close to zero (and thus outliers can easily disturb the correlation coefficient). The role of energy intensity changes differs between fuel and electricity use. For fuel use, most regions have the peak of the UEI-curve at historic income levels, projecting declining energy intensity and thus a negative (though weak) correlation. For electricity use, the peak is mostly at future income levels, and energy intensity is increasing towards 2030, leading tot positive (but also weak) correlations. The role of the NRMSE is peculiar, because it correlates stronger with future projections than other parameters. For fuel use, a better fit with historic data leads to lower future projections; for electricity a better fit correlates with higher projections. This might be related to historic trends: fuel use is mostly stable or decreasing and electricity use increases in all regions. Better-fit parameter sets apparently project a stronger extrapolation of these trends.

Table 5.4: Pearson's linear correlation coefficient between parameter values and projected residential sector fuel use in 2030 (left). The right column contains the range of projected fuel use in 2030 as percentage of the best-fit projection. The calibration of Chinese fuel use is considered non-behavioural

	UEI (Y_{max})	*AEEI*	*PIEEI*	*NRMSE*	*Range in 2030*
USA	-0.46	-0.52	-0.56	0.91	100%
Europe	0.25	-0.09	0.05	0.22	46%
India	-0.79	-0.82	0.36	0.82	38%
China	-0.31	-0.87	0.03	0.79	324%
Brazil	-0.06	-0.87	0.20	0.93	27%

Table 5.5: Pearson's linear correlation coefficient between calibrated parameter values and projected residential electricity use in 2030 (left). The right column contains the range of projected electricity use in 2030 as percentage of the best-fit projection. The calibration of Brazilian electricity use is considered non-behavioural

	UEI (Y_{max})	*AEEI*	*PIEEI*	*NRMSE*	*Range in 2030*
USA	-0.48	-0.49	-0.21	-0.70	34%
Europe	0.86	-0.84	0.05	-0.99	43%
India	0.51	-0.86	-0.75	-0.96	82%
China	0.49	-0.55	-0.27	-0.88	58%
Brazil	0.11	-0.37	-0.76	0.69	160%

In this paper we calibrate the model for each region separately in order to obtain model behaviour that better matches historical data. Originally, however, the intensity-of-use curve has been proposed as a 'stylized fact' across all world regions, thus covering a large GDP-span over the 1971-2003 period. Also, regions do not develop totally independent (e.g technology to improve efficiency is likely to be coupled between different regions) and also the paths that other regions have taken previously might be an indicator for other regions (cross regional data). For instance, residential energy use in India is calibrated here towards data from a period in which lighting is the major electricity function; a possible future rise in space cooling or energy intensive appliances cannot be foreseen in these data – but can be obtained from a comparison with the USA. A plot of energy use per capita versus private consumption for the period 1971-2030 reproduces the general shape of rapidly increasing annual energy use per capita at low income levels and saturation at higher levels (Figure 5.7). The historical data and our results clearly indicate that Brazil and China with declining per capita energy consumption do not match this pattern, however. The historical and projected curves for Europe suggest constant per person energy use and for the USA a further decline, both to be interpreted as signs that saturation and ongoing energy efficiency

improvements continues. Because space heating accounts for 60-80 percent of residential fuel use (DOE Energy Information Agency, 2006; IEA, 2007c), it is not to be expected that the low-income regions India and Brazil will track the European and USA experiences; for China it remains to be seen. Obviously, this can be accounted for by correcting the data for heating-degree-days, but data on this are notoriously weak in developing countries. Explicit modelling of heating and cooling demand is another option to overcome this issue (Isaac and Van Vuuren, 2008).

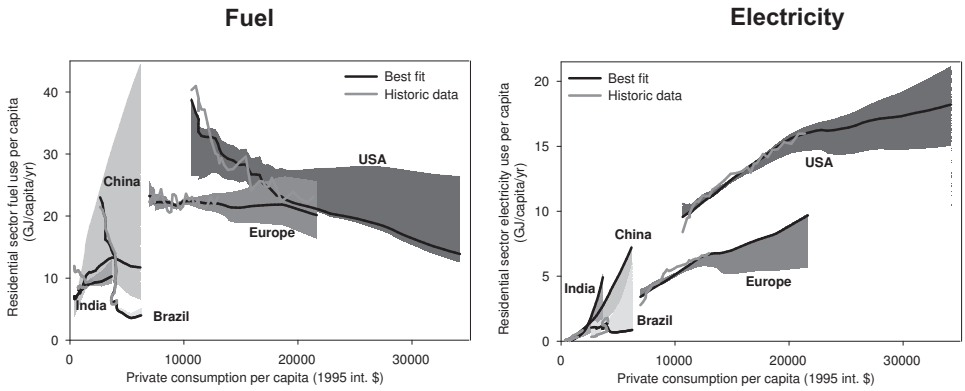

Figure 5.7: residential fuel and electricity use per capita for all regions versus private consumption ('income') for the period 1971-2030. Note that income generally increases (only Brazil had some periods of decrease) and regions do not reach similar income levels at the same time

Per capita residential electricity use is projected to increase with rising income for all regions, and shows no sign of saturation for the developed regions (Figure 5.7). The differences between Europe and the USA are rather outspoken and the best fitting projections for the developing regions indicate a growth to American levels of residential electricity use. However, the ranges for India and China show that an increase towards European levels is also possible.

7 Discussion and conclusion

In this paper we analysed impact of uncertainty in the calibration of the TIMER residential energy demand model on future projections for several world regions. First we identified the variety of parameter values that yield acceptable model calibrations. We found that the model generally performs better for developed regions than for developing regions, although there are some exceptions. For instance, residential fuel use in India and Brazil, and electricity use in China and India can be well simulated. Focussing on commercial fuels only does not improve the model's performance for developing regions. The TIMER model determines energy use on the basis of changes in useful energy intensity ('income elasticity'), technology development (*AEEI*) and price impacts (*PIEEI*); apparently this is insufficient for developing countries. For instance, energy prices in India are heavily subsidised and there is a lack electricity production capacity; China has similar problems, and also closed down small-scale coal mines. In Brazil, high inflation rates and periods of

decreasing income complicate the relation between economic activity and energy use. Also, understanding the transition from traditional to modern fuels is important for modelling residential energy demand.

Second, we analysed the impact of different parameter values on future projections. We found that the different parameter sets lead to a wide range of future projections. Already in 2030 there is a bandwidth of 27-100% around the 'best-fit' in most regions. This variation can be mostly understood from a different balance in settings of energy intensity and efficiency improvement. In most cases, the projected energy use for 2030 of the better fit parameter sets is comparably or higher than the OECD-EO scenario, which we used for reference.

This study shows that uncertainty in model calibration is has a relevant impact on future projections of energy models. Thus, modellers should systematically account for this source of uncertainty and communicated the bandwidth of possible projections with future scenarios. This makes clear that many of the dynamics that these models describe are barely understood and hard to represent by mathematical descriptions.

Options to improve this specific model, which might also decrease calibration uncertainty, are 1) to specify energy end-use functions, 2) to better account for hysteresis, and 3) explicitly account for policy. With respect to the first, more explicitly accounting for the heterogeneity in end-uses across world regions (in e.g. space heating, see Isaac and Van Vuuren, 2008) and adding intermediate variables like floor space and appliance ownership provides extra options for model calibration and explains much of the differences between regions. Second, the model's incapability to deal adequately with declining economic activity, leads to non-behavioural historic results and implicitly also unreliable future projections. The fact that future scenarios always assume increasing economic activity unveils another bias in energy use projections. Finally, specific policies, like protecting (poor) population from world energy prices, influence the use of energy in developing regions, an aspect that can be implemented in different scenarios (see also van Vuuren, 2007).

Given the wide ranges that evolve already in 2030, one can imagine the uncertainty levels associated with these models for 2050 or 2100. One option to keep this long-term uncertainty manageable is to use different models for different time horizons, an option suggested by Casman et al. (1999). For longer term projections, different (i.e. simpler) models can be used that better describe the rough dynamics that take place over longer time periods.

Appendix 1: Values and ranges for parameter estimation

Table A3: Ranges for the estimated parameters varied for residential fuel use

Variable	Minimum	Maximum
UEI-curve		
X_{max}	500	30000
Y_0	0	0.159 (USA) 0.235 (EU) 0.285 (Brazil) 0.284 (India) 0.285 (China)
U	15	45
AEEI		
F_S	0.09 (USA) 0.09 (EU) 0.09 (Brazil) 0.07 (India) 0.03 (China)	0.68 (USA) 0.70 (EU) 0.68 (Brazil) 1.0 (India) 1.0 (China)[25]
PIEEI		
Payback time	0.007	6.760
P-value learning curve	0.70	1.00

Table A4: Ranges for the estimated parameters varied for residential electricity use

Variable	Minimum	Maximum
UEI-curve		
X_{max}	5000	50000
Y_0	0	0.141 (USA) 0.097 (EU) 0.087 (Brazil) 0.039 (India) 0.068 (China)
U	50	80
AEEI		
F_S	0.09 (USA) 0.09 (EU) 0.09 (Brazil) 0.07 (India) 0.03 (China)	0.68 (USA) 0.70 (EU) 0.68 (Brazil) 1.0 (India) 1.0 (China)[24]
PIEEI		
Payback time	0.007	6.760
P-value learning curve	0.70	1.00

Table A5: Average annual GDP per capita growth for the analysed regions

	USA	WEU	Brazil	India	China
Average annual GDP/cap growth 1971-2003	2.19%	2.13%	2.21%	2.69%	6.69%

[25] Because of the high economic growth in India and China, it might be that historic *AEEI* has been higher as well; therefore we increases the upped bound of the range to the total economic growth: F_S=1.

Appendix 2: Calibrated parameter values

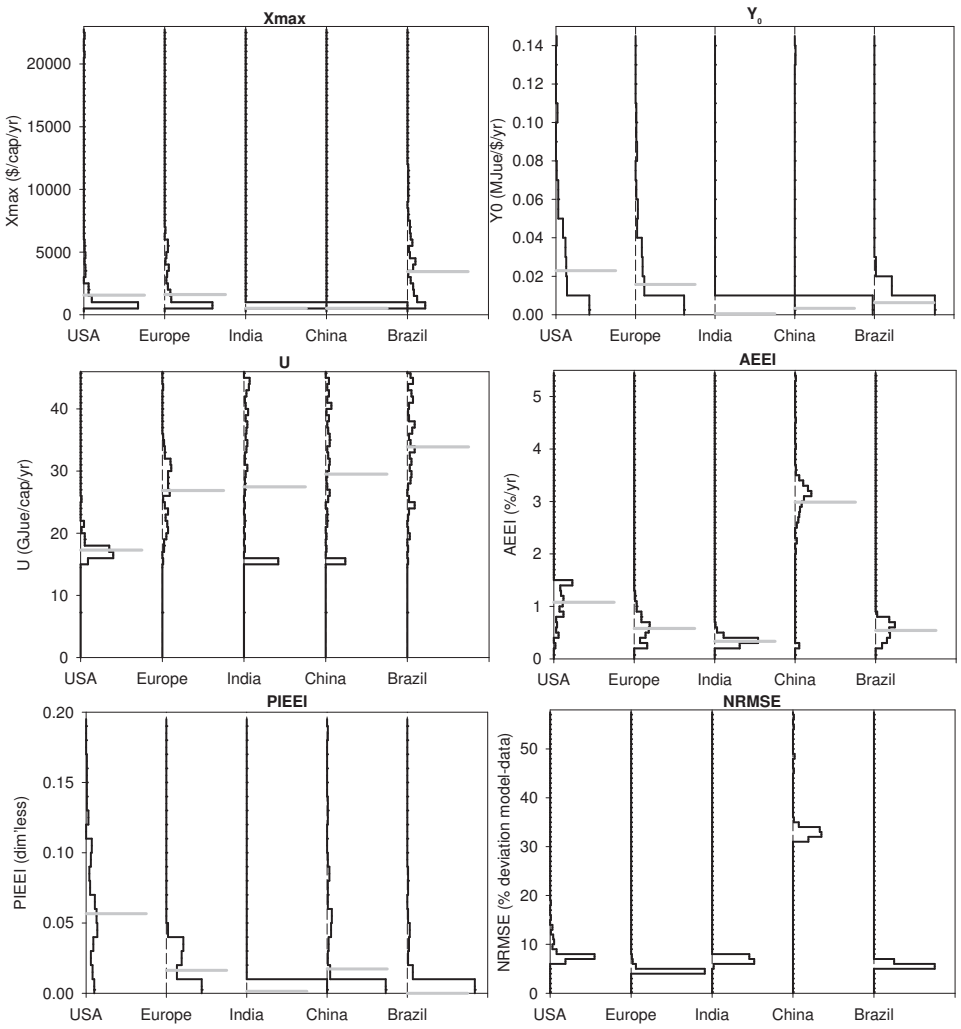

Figure 5.8: Calibrated parameter values (distribution, black lines, and mean value, grey) for residential fuel use

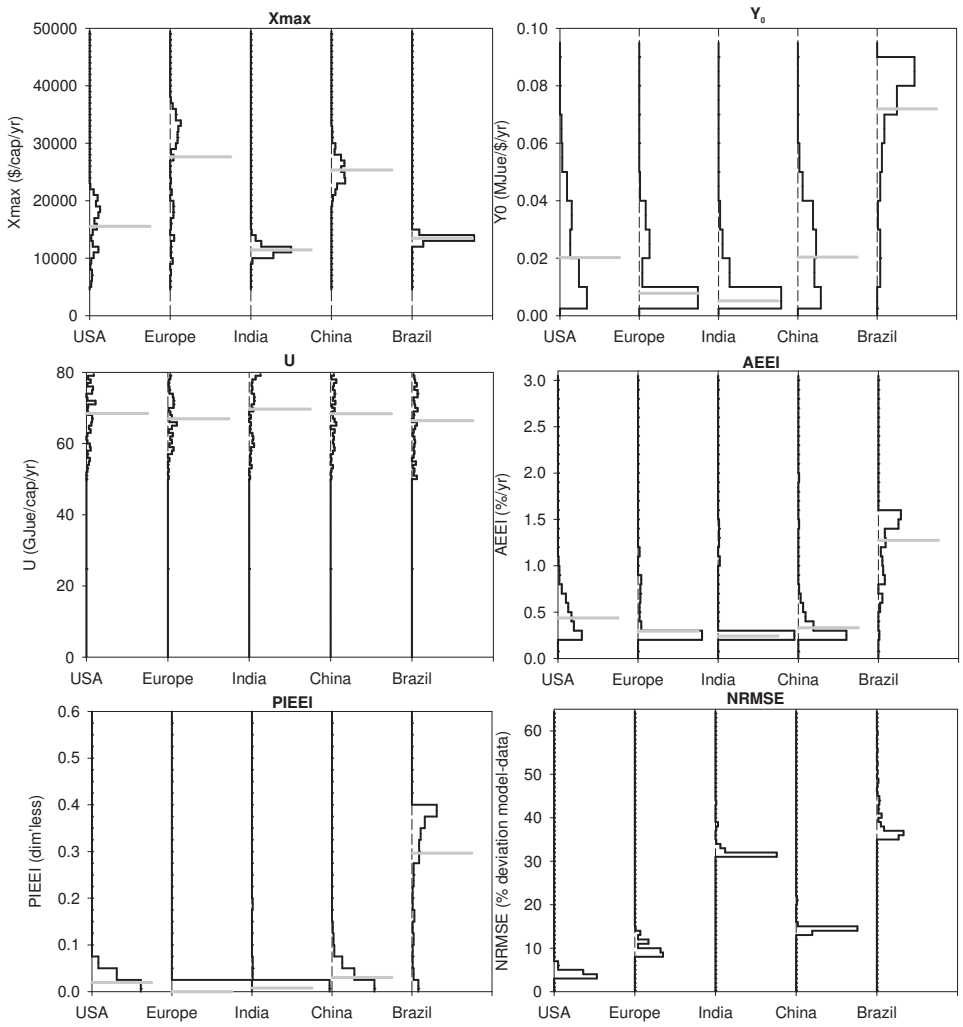

Figure 5.9: Calibrated parameter values (distribution, black lines, and mean value, grey) for residential electricity use

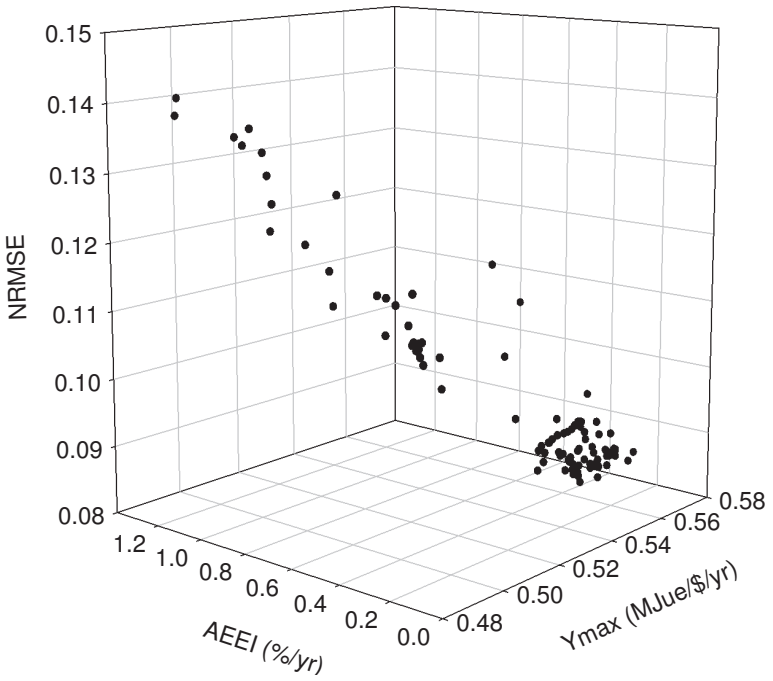

Figure 5.10: Insight in the parameter space: calibrated parameter values for *AEEI* and Useful Energy Intensity against NRMSE for residential electricity use in Europe

Appendix 3: Forward calculations

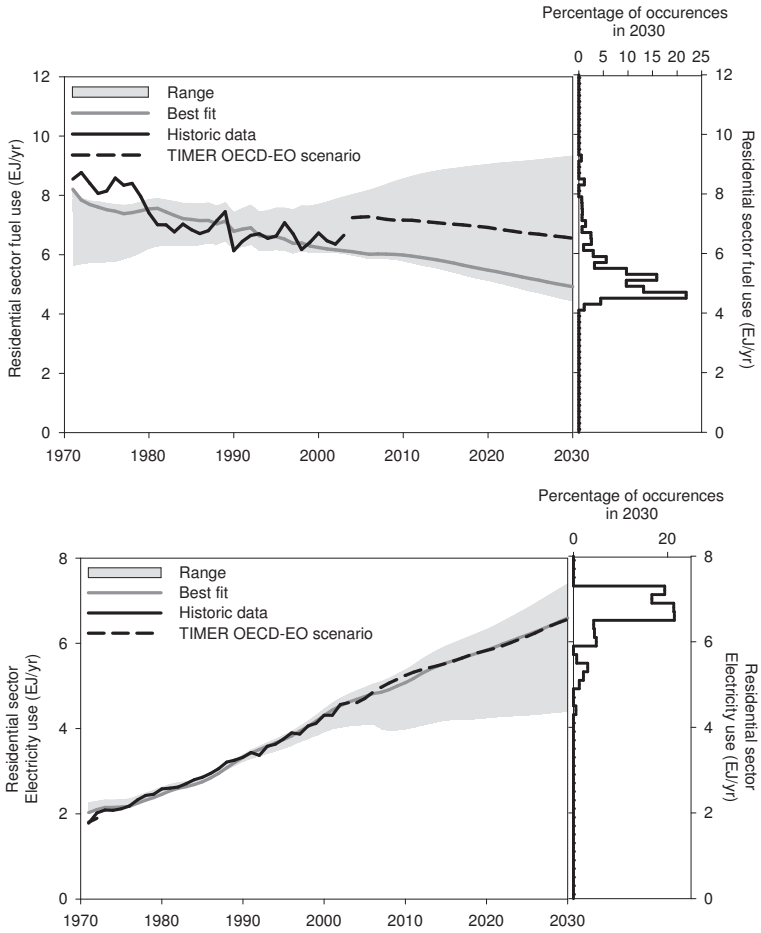

Figure 5.11: Forward calculations for residential fuel and electricity use in the USA, based on calibrated parameter sets

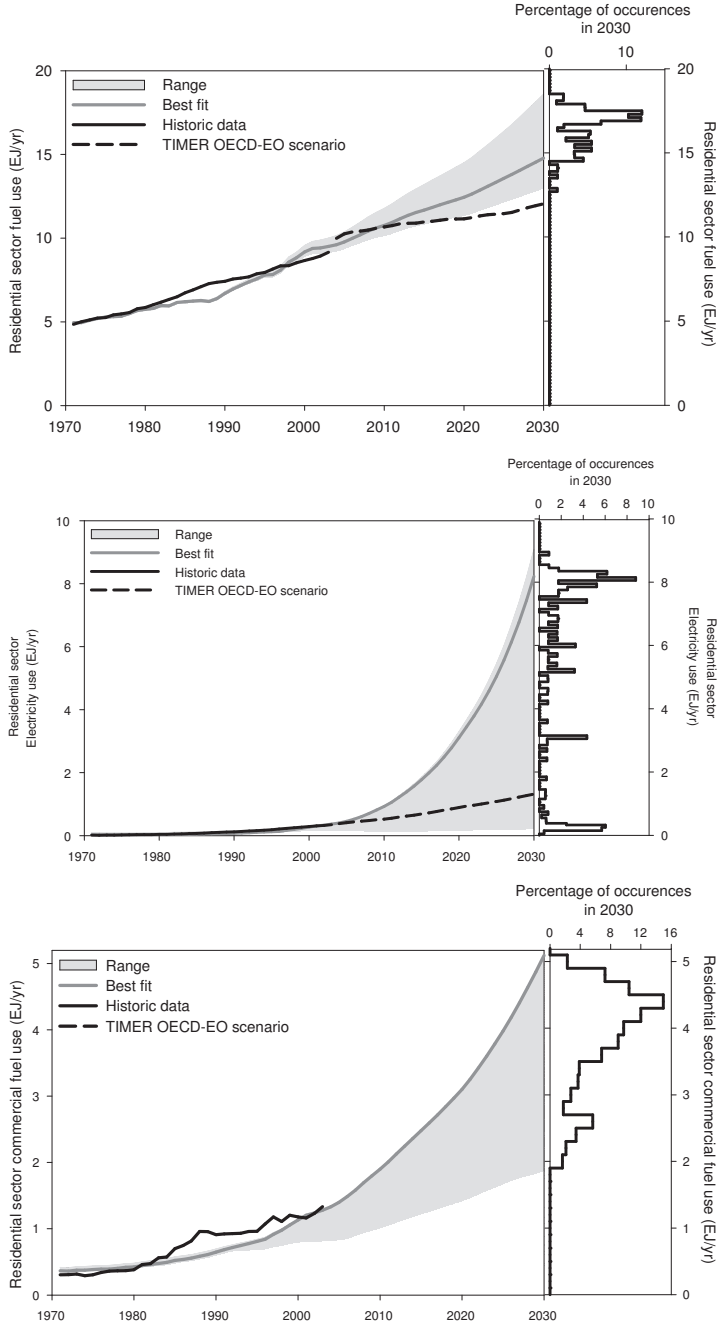

Figure 5.12: Forward calculations for residential fuel (with and without traditional fuels) and electricity use in India, based on calibrated parameter sets

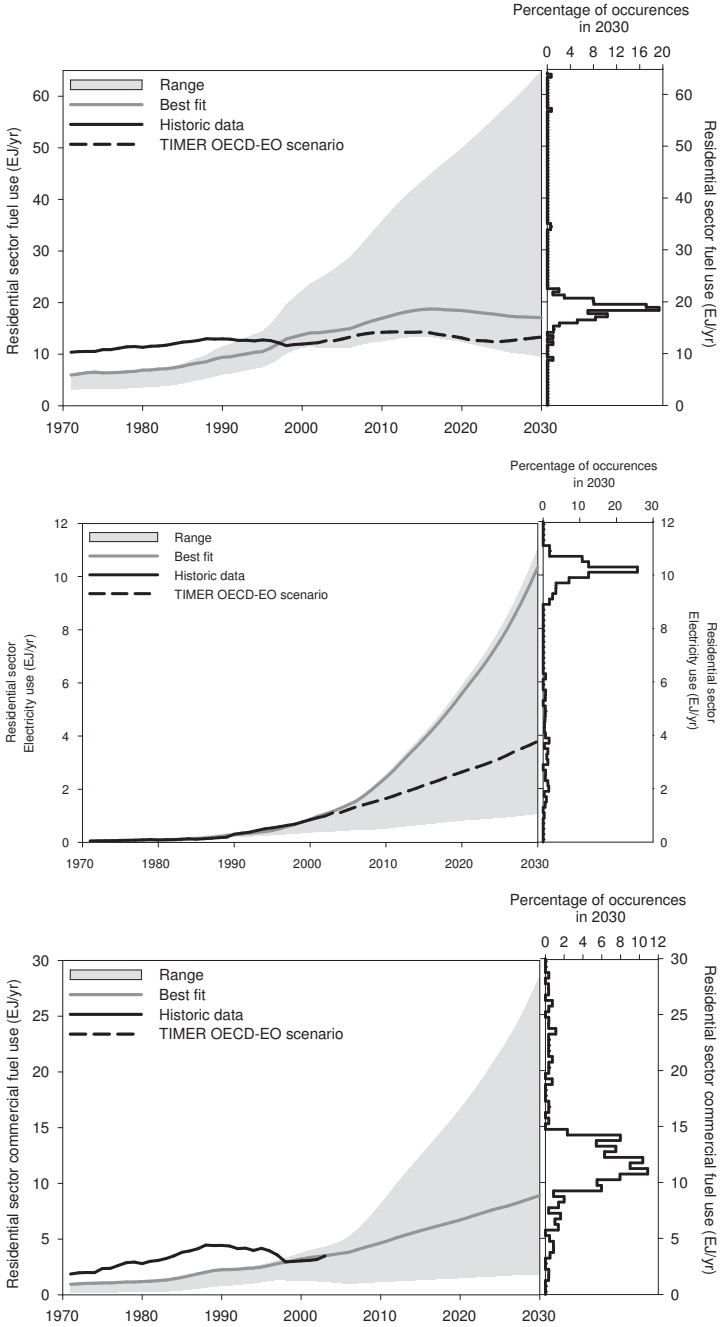

Figure 5.13: Forward calculations for residential fuel (with and without traditional fuels) and electricity use in China, based on calibrated parameter sets

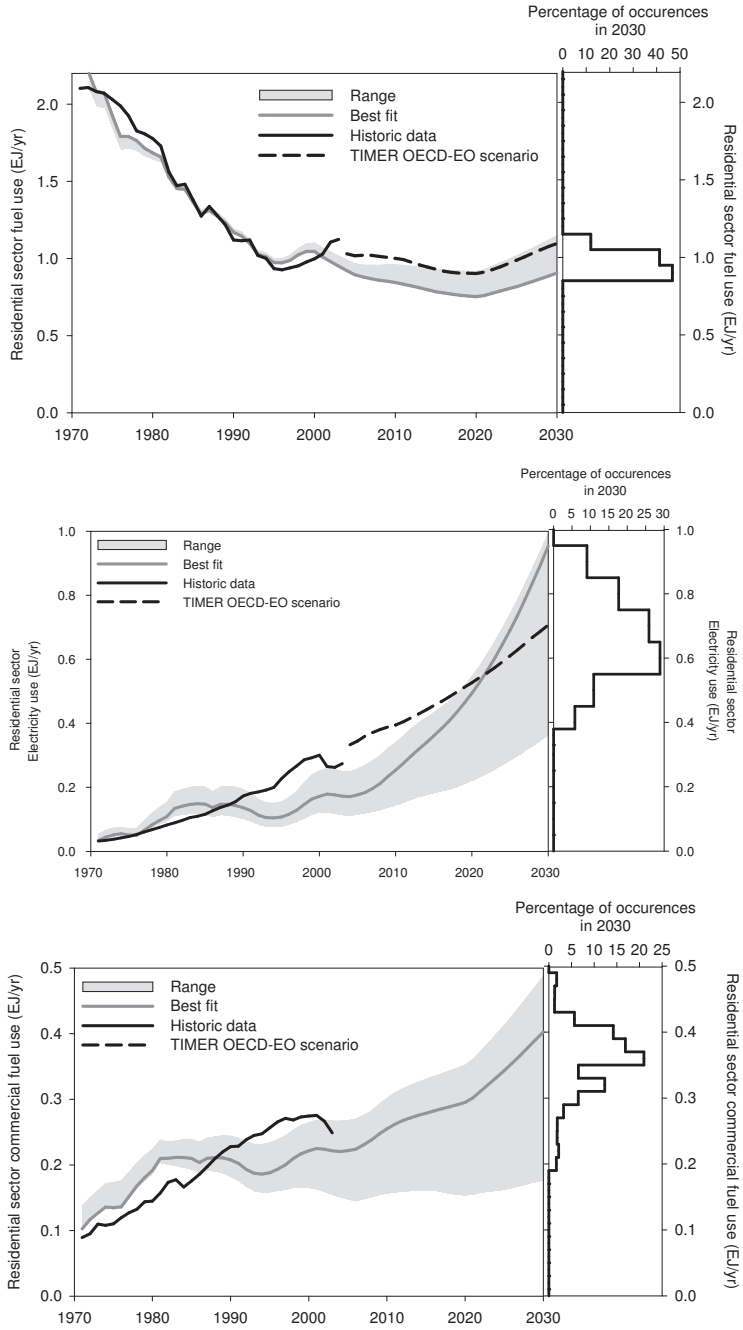

Figure 5.14: Forward calculations for residential fuel (with and without traditional fuels) and electricity use in Brazil, based on calibrated parameter set

Chapter 6: A new model for residential energy use in developing countries: the case of India[1]

Abstract

Energy use in developing countries is highly heterogeneous. Present day global energy models are mostly too aggregated to account properly for this heterogeneity. To remedy this omission, we developed a bottom-up, system-dynamics model for residential energy use in India, starting from the dynamics of development and energy use. In the model, energy use is determined for five end-use functions: cooking, water heating, space heating, lighting and appliances, for five different income groups and for rural and urban population. Fuel use is assumed to follow the pattern of succession of the energy ladder: cleaner, more convenient, but also more expensive energy options are preferred at higher income levels. Ownership of appliances follows the observed Indian preference ladder: fan, TV, refrigerator, and heavier appliances. We explored the consequences of two variables that are usually not considered in global energy models and that might be very important for developing countries: income distribution and electrification rate. We found in that total Indian residential energy use might increase 65-75% compared to 2005, whereas total residential carbon emissions may increase to 9-10 times the 2005 level. We also found that future projections are rather sensitive to variation in income distribution and electrification. While equal income distribution and rural electrification are good for decreasing poverty, there is a trade-off in terms of higher CO_2 emissions via an increase in electricity use. However, higher income for the poor also enhances the transition to commercial fuels, which leads to much less indoor air pollution.

[1] Co-authors: Bert de Vries, Detlef van Vuuren, Morna Isaac and Jeroen van der Sluijs. We are grateful to Dr. Patil Balachandra (IISc, Bangalore) for fruitful cooperation and insightful discussions on energy use in India and Paul Lucas (PBL) for cooperation on modelling income distribution.

1 Introduction

Historically, energy consumption in industrialised countries has dominated global energy use. However, at present energy consumption in developing countries is rapidly increasing, which is expected to have significant effects on global sustainability issues such as climate change and depletion of low-costs energy resources. Understanding and modelling the influence of socio-economic development on the demand for different energy carriers, particularly in low-income regions, is currently a major challenge for global energy models. In developing countries, residential energy use plays a dominant role in sustainability issues and socio-economic development through indoor air pollution and the transition from traditional fuels to commercial energy sources and increased access to electricity and LPG. The socio-economic factors that are driving residential energy use, such as income and household size (Narasimha Rao and Reddy, 2007; Pachauri, 2004), are more heterogeneous in developing countries than in industrialised regions, but are rarely specifically included in global energy models (Shukla et al., 2007; Urban et al., 2007; van Ruijven et al., 2008b).

To remedy the omission sketched above, we developed an energy model for residential energy use that accounts for the heterogeneity that is so typical for energy use in developing regions. The model distinguishes different energy functions and specifically models the driving forces for each of these functions. Moreover, it addresses heterogeneity in households and living areas by distinguishing different income groups and rural and urban circumstances. By including this heterogeneity, and issues such as electrification and subsidy schemes, this new model goes beyond many existing global energy models. The premise is that the insights obtained from simulations with this model are therefore more relevant for developing regions and projections of residential energy use are of a higher quality. In this paper, we document the data, assumptions and structure of this model and analyse its future projections, focusing on the issues where this model deviates from existing models: income distribution and electrification. For the development of this model we have chosen the case of India, but the model is meant to be ultimately implemented and parameterised for other developing regions as well and applied in the TIMER global energy model (de Vries et al., 2001; van Vuuren et al., 2006b).

India is an 'awakening giant' with slightly lower economic growth rates than China but with rapidly increasing population. For India, many relatively reliable data are available, with which an increasing amount of analyses is carried out. This combination of statistics and analysis provides a convenient starting point for model development. Total residential energy use in India increased about linearly between 1971 and 2003. The main end-use function of residential fuel use in India are cooking and lighting (kerosene lamps). Space heating is not important due to India's (sub-) tropical climate[2] (Pachauri, 2007). Air conditioning is still a luxury, although ownership increased in recent years (NSSO, 2003). Residential fuel use is dominated by traditional fuels; the use of commercial fuels, especially oil (kerosene and LPG), increased but is still minor in absolute amounts (IEA, 2007e). Government policies such as social price subsidies on electricity, kerosene and

[2] We include the end-use function 'space-heating' in the model to allow application to other world regions.

LPG and electrification for rural households influence energy use, though it is hard to say how in the absence of equivalents for comparison (Dzioubinski and Chipman, 1999).

The outline of this chapter follows the structure of the model developed: Section 2 provides and overview of the conceptual model and Section 3 discusses the primary drivers of residential energy use distinguished in the model: population, household expenditure, household size, and temperature changes. Section 4 describes the modelling of intermediate physical indicators: floor space and electrification. The subsequent sections focus on modelling energy use: Section 5 describes fuel use for cooking, water-heating and space heating; Section 6 describes electricity use for lighting and appliances. Section 7 explores and discusses the performance of the whole model and Section 8 analyses the impact and relevance of including the dynamics of developing countries on future projections. Finally, Section 9 discusses and concludes.

2 Conceptual model and overview

Energy models can be classified in two different ways, i.e. 1) the bottom-up, engineering approach versus the top-down macro-economic approach and 2) optimisation versus simulation models. Classically, bottom-up models describe technologies in detail, but do not account for micro-economic decision-making and macro-economic system feedbacks. Top-down models, on the other hand, cope with macro-economic structures in a general equilibrium framework, but use aggregate factors for technology development (Shukla, 1995). Optimisation models aim to describe least-cost energy systems under a set of constraints, operated from a centralised perspective. Simulation models project the consequences of specific policies, using equations that represent the causal structure of the energy-economy system in which the policies intervene. Although simulation models may describe real world systems better, their structure is usually much more complex than that of optimization models, so it may be at the cost of reduced transparency (van Vuuren, 2007).

The TIMER global energy model is a system-dynamics simulation model with a top-down character on energy demand and bottom-up modelling of energy supply options. In the current TIMER energy demand model, energy use is associated with economic activity through changes in energy intensity and efficiency (de Vries et al., 2001). For residential energy use, this means that intermediate variables, such as electrification, floor space or ownership of appliances, are currently not explicitly considered and end-use energy functions are not distinguished (van Ruijven et al., 2008a). To include the specific dynamics of energy use in developing countries, we developed a generic bottom-up model: it follows the causal chain of bottom-up modelling (from primary drivers and intermediate physical indicators to end-use functions and energy use), but uses stylized correlations (instead of detailed process descriptions) that are derived from econometric studies and regression analysis. The system-dynamics aspects of this model include delays of investment decisions and dynamics of capital stock vintage modelling. In the larger context of the TIMER model, energy use is influenced by feedbacks from depletion and fuel prices. While most basic model relations and drivers are derived from direct regression analysis of

the data, some model parts (especially fuel use) had to be calibrated against historic data. In this process of parameter estimation, we seek the parameter values where the error between model and observations is minimal.

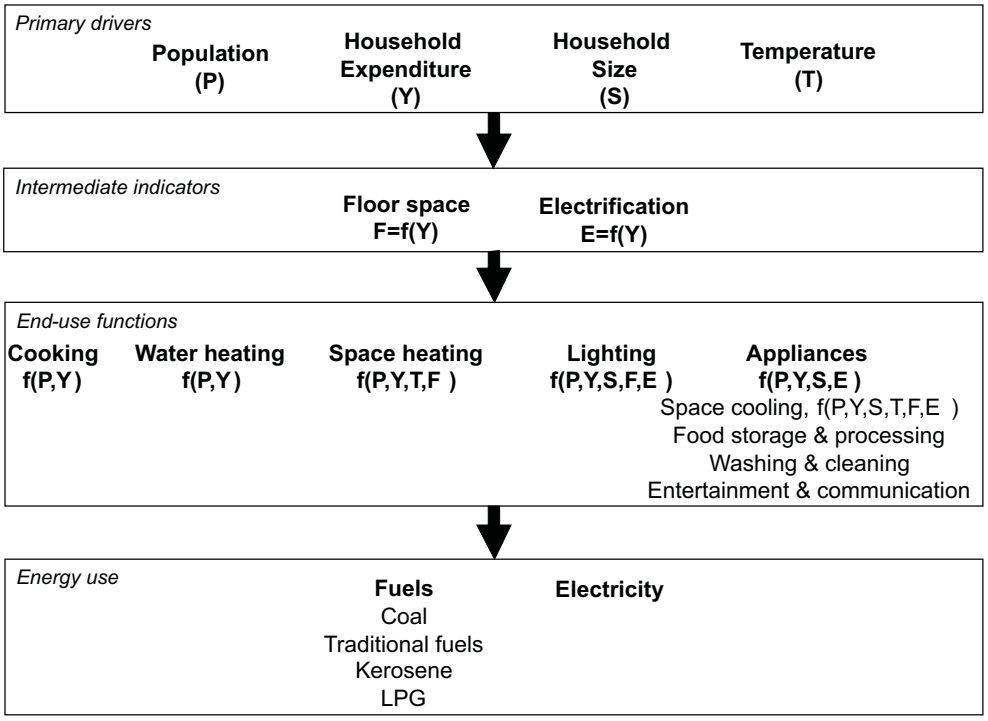

Figure 6.1: Outline of the residential energy use model; population and household expenditure have a direct influence on all end-use functions; all variables (except temperature) are distinguished for urban and rural areas and population quintiles.

Much more than in industrialised regions, residential energy use in developing countries differs between rural and urban areas and high and low income groups (van Ruijven et al., 2008b). Therefore, the main model drivers, income/expenditures and household size, are disaggregated to urban and rural population and different income levels. In a second step, the external model drivers are associated with intermediate physical indicators for energy use: residential floor space and electrification rate. Next, the demand for energy functions is determined as a function of the drivers. For instance, the demand for cooking energy is related to expenditures and population and demand for lighting is determined as a function of floor space, expenditures, households and electrification. Finally, the demand for energy functions is met by different end-use technologies, depending on the availability (electrification) and affordability of fuels. An important dynamic here is that, with increasing expenditures levels, cleaner, more efficient and more convenient energy sources are applied (i.e. the concept of the energy ladder). The outline of this model is graphically summarised in Figure 6.1. In the following sections we will discuss each of the components of the model.

3 Primary drivers of energy use

The demand for residential energy services is shaped by a variety of factors (Schipper and Meyers, 1992). Activity is indicated by population (or its structure: households) and the ability of a household to satisfy its desires it constrained by income. Climate is a relatively stable factor that explains differences between regions. Therefore, the primary drivers of energy use in this model are population and household size, household expenditure and temperature. The data used for model input and calibration are described in the next sections. For future projections, we focus on a single baseline scenario – and assess the influence of different assumptions for income distribution and electrification (see Section 8). A consistent set of future projections for each driver is derived from the OECD Environmental Outlook scenario (Bakkes et al., 2008; OECD, 2008).

3.1 Population and households

Data on household characteristics in India are collected regularly by the National Sample Survey Organisation (NSSO) of the Ministry of Statistics and have been obtained from a variety of sources (IndiaStat.com, 2007; NSSO, 2004; World Bank, 1996). Statistical analysis suggest that population is an important determinant of residential energy use (Schipper et al., 2001). During the last decades, total Indian population doubled from about 550 million people in 1970 to approximately 1.1 billion people in 2005, but the growth rate is decreasing (Figure 6.2). In the same period, the level of urbanisation increased, but the vast majority of Indian population still lives in rural areas (the share of urban population increased from 20% to 29%). The OECD Environmental Outlook scenario (Bakkes et al., 2008; OECD, 2008) assumes a further increase in the Indian population towards almost 1.6 billion in 2050, of which 47% lives in urban areas.

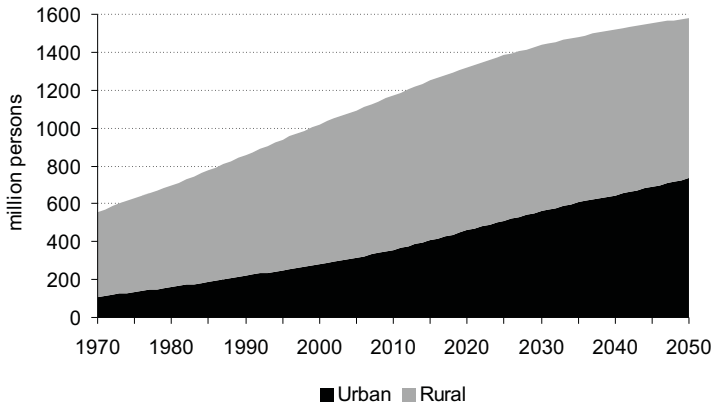

Figure 6.2: Historic data, up to 2004 (World Bank, 2007) and future projection (Bakkes et al., 2008) for urban and rural population in All India

3.2 Household consumption expenditure

Data on household income are hard to obtain in developing countries. Poor households do not pay income tax and many subsistence activities are not monetised. During surveys people often hide part of their income. Therefore, economic activity of households is often measured as expenditure or consumption rather than income[3]. Data are available from two different sources: household surveys (NSS) and National Account Statistics (NAS). Household survey data are obtained by canvassing a sample of households with standard questionnaires on their expenditures during a certain recall period. Non-monetary purchases, like home produced food, clothing or other services, are monetised by the National Sample Survey Organisation (NSSO) to the ex-farm or ex-factory rate. Private consumption expenditures in the NAS are residuals, derived from estimated domestic availability of commodities left after deducting non-private consumption uses (Srinivasan, 2001). Generally, household expenditure levels from surveys are lower than NAS data. In India, the ratio of 'NSS to NAS' decreased over the last decades to low values of about 0.5 (Deaton and Kozel, 2005). The differences in income-numbers led to a debate among poverty economists on which method is more reliable (Deaton, 2001; Deaton and Kozel, 2005; Ravallion, 2001; Srinivasan, 2001; Sundaram and Tendulkar, 2003). Adjustment of the data in both directions has been argued for by different authors, but the debate is rather inconclusive. Until 1990, the Indian Planning Commission adjusted the NSS data to the NAS, as do many economists that are not familiar with surveys. However, in recent years, the two measures are increasingly used in parallel (Sundaram and Tendulkar, 2003). In a modelling framework like TIMER this is not practical and macro-economic indices have to be applied in a consistent manner. As we use also information on income distribution, we chose to use NSS data because only these contained the full information on urban/rural differences and income classes. We have adjusted these data to the macro-economic expenditure levels of the NAS.

All monetary variables (e.g. household expenditures, investment costs, prices) were originally available in current Indian Rupees (Rs), which we converted to constant year 2000 values (Rs_{2000}) using consumer price indices[4] as provided by the Reserve Bank of India (RBI, 2007). Data on household expenditures are published in monthly per capita expenditure (MPCE). In the model we use annual values, mostly in market exchange rate (MER): USD_{2000} with a conversion rate of 44.9 Rs_{2000}/USD_{2000} (FXhistory, 2008). Purchasing power parity (PPP) is preferred in international comparison. In that case we use int.$\$_{2000}$ with a year 2000 PPP-factor of 5.2 for India (World Bank, 2007). We have focussed on MER conversion rates in the model, because our model distinguishes different income classes. The consumption pattern of rich households includes more internationally tradable goods (household appliances, flights, oil) than the pattern of poor households (fuelwood and food). Therefore, the relevant PPP-factor (both on incomes and prices) for

[3] Data on household income are rarely available in developing countries; therefore we use expenditure data as collected by the surveys of the NSSO. At low income levels, household expenditures can be assumed to roughly equal household income; however, at higher income levels households can use part of their income for savings. This is not directly reflected in the expenditure data, although one can argue that capital intensive purchased are the result of household savings.

[4] The Agricultural Labourers index was used for rural data; for urban data we used the average of the index for Industrial Workers and 'Urban Non-manual employees'.

high income classes is lower for rich households than for poor. In order to avoid income-dependent (and thus uncertain) conversion factors, we developed the model in MER values.

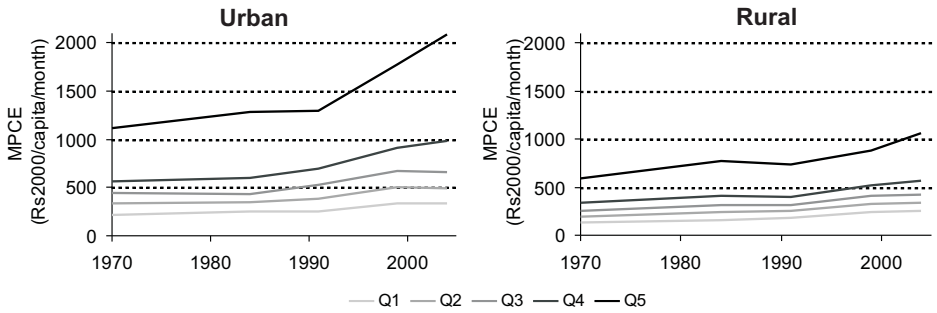

Figure 6.3: Historic data (IndiaStat.com, 2007; NSSO, 2004; World Bank, 1996) on household expenditure (not adjusted for NAS difference) in rural and urban areas allocated to population quintiles

The number of income classes and the class-limits changed regularly between survey rounds, complicating comparison over time. We clustered the expenditure classes to quintiles of the population (the poorest 20% and lower middle, middle, higher middle and high expenditure groups). We did not split expenditure classes, so this clustering led to population groups that range between 15-25% per quintile[5] (Figure 6.3). The survey data show that the growth rate of household expenditures per capita in India has been rather low until the economic reforms in 1991, followed by a rapid increase of urban expenditure levels during the nineties (Figure 6.3). On average, the urban expenditure level is about twice the rural expenditure per capita. This gap remained rather constant until 1991, but after the economic reforms, the gap between rural and urban expenditures increased rapidly.

Historically, the distribution of household expenditure within the rural and urban categories in India has been relatively stable. A commonly used measure to express inequality in income distribution is the GINI-coefficient (see Appendix 1 and Cypher and Dietz, 1997). India has GINI values about 30 for rural and 35 for urban areas, indicating a relatively equal income distribution. Future projections on the distribution of household expenditure levels are no regular output of macro-economic models, although some attempts are being made (Campano and Salvatore, 2006, 2007). Therefore, we apply an algorithm to disaggregate the average household expenditure levels to population quintiles, using the GINI-coefficient (Humberto Lopez and Servén, 2006; Rutherford, 1955). For details and performance of this disaggregation algorithm see Appendix 1 and van Ruijven et al. (2008d).

Future projections of household expenditure are derived in three steps:

[5] This means that the proportion of population and the number of expenditure classes varies for each quintile between different years.

1. Total all-Indian household expenditure; we use the OECD environmental outlook scenario (OECD, 2008) with average household expenditures increasing from about 300 USD_{2000}/capita/year in the year 2000 to 2300 USD_{2000}/capita/yr in 2050
2. Allocation of total expenditure to rural and urban areas, based on the ratio of the average rural and urban expenditure level to the all-Indian average expenditure level. Historically, the urban-to-average ratio decreased from 1.6 in 1970 to 1.45 in 2004. The rural-to-average ratio has been constant at about 0.82.
3. Finally, GINI coefficients are used to allocate expenditures over population quintiles within rural and urban areas.

For future scenarios, both the urban-rural ratio and the GINI coefficients should converge or diverge in line with the scenario storyline (see Section 8)

3.3 Household size

For several end-use functions, the number of persons per household (or household size) is another important determinant, because decisions are made at the household level or the energy function is used for the household as a whole. Historic data for household size at different income levels were derived from NSSO survey data (IndiaStat.com, 2007; NSSO, 2004; World Bank, 1996). In general, household size decreases at higher income levels (Figure 6.4), the richer quintiles have a clearly lower household size. However, the clustering of the data to population quintiles also indicates that historic trends within income quintiles are remarkably stable[6]. UN-Habitat (2005) provides future projections for the average household size in India until 2050; we assume that future household size in all population quintiles follows the trend of UN-Habitat (2005) projections towards 2050 (Figure 6.4).

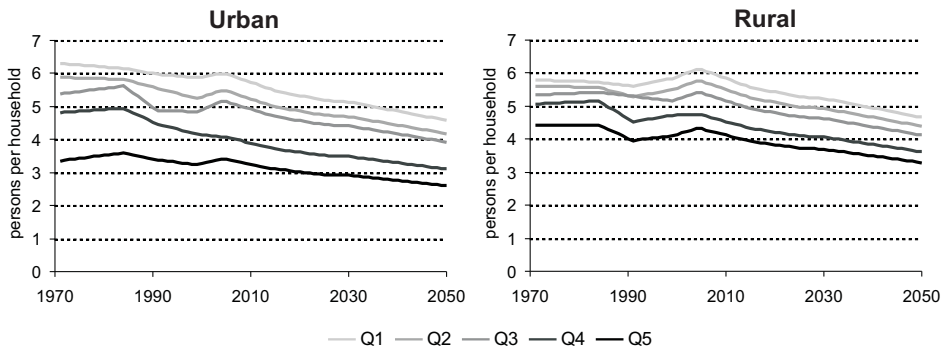

Figure 6.4: Historic data, up to 2004 (IndiaStat.com, 2007; NSSO, 2004; World Bank, 1996) and future projections (UN-Habitat, 2005) for household size per population quintile in urban and rural India

3.4 Temperature

Temperature is an important determinant of energy use for space heating and space cooling (Schipper et al., 2001). Isaac and Van Vuuren (2008) performed a global analysis on energy use for residential heating and air conditioning, at present and for a changing climate. Here,

[6] This might be partly due to variation in expenditure class definitions and aggregation problems (see Section 3.2).

we use their climate data, which include population weighted monthly temperature, historically calibrated against the CRU database (New et al., 2002) and the IMAGE model. To determine both heating and cooling degree days for world regions a base temperature of 18ºC was used. The base temperature varies between regions and is usually derived from the electricity load through the year. In both Europe and the USA, 18°C is commonly used, although individual studies use different values: e.g. 21°C for Florida (Sailor, 2001), 22°C for Athens, Greece (Giannakopoulos and Psiloglu, 2006) and 15ºC for natural gas use for heating in Turkey (Sarak and Satman, 2004). Electricity load curves in India are typically flat due to electricity supply constraints (IEA, 2002a) and cannot be used to determine such region-specific base temperature. The base temperature of 18ºC is, however, rather low and debated in India in the perspective of alternative consumption futures (de Vries et al., 2007a).

From these data and projections, it is clear that the need for space cooling in India is much larger than for space heating; especially because it is projected that climate change considerably decreases the number of heating degree days in the winter months and increases cooling degree days during summer (Figure 6.5).

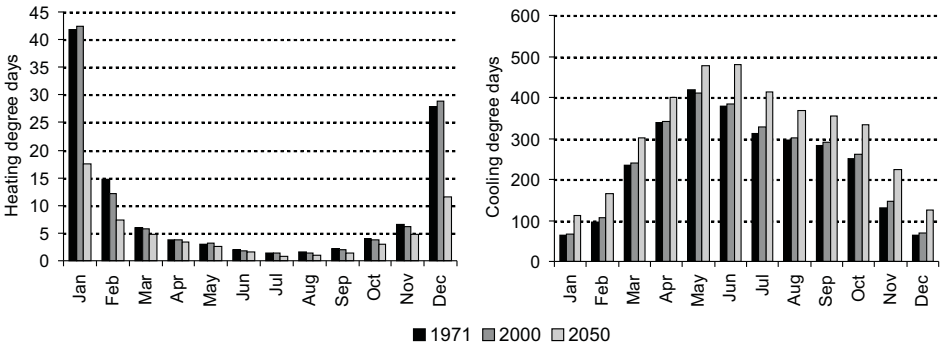

Figure 6.5: Population weighted heating and cooling degree days (in °C/yr) for India in 1971, 2000 and 2050, with a base temperature of 18 ºC

4 Physical indicators: residential floor space and electrification

On the basis of the primary drivers, two more direct drivers were derived, as intermediate indicators of residential energy use: residential floor space and the electrification rate.

4.1 Floor space

Floor space per capita is a useful indicator for energy use, because several end-use functions, like lighting and space heating and cooling, are closely related to living space (Schipper et al., 2001). Detailed and geographically explicit bottom-up models (e.g. Koomey et al., 1995; MacDonald and Livengood, 2000) include housing stocks with typical characteristics like floor space, but also insulation, retrofit-options and heating equipment.

More aggregate models (e.g. Isaac and Van Vuuren, 2008; Kainuma et al., 2003; Price et al., 2006) use data-regressions and assumptions on floor space trends.

Data on residential floor space are available from different sources, mostly for urban situations (Eurostat, 2006; IEA, 2004a; NSSO, 2003; Shen, 2006; UN-Habitat, 1998)[7]. Most available data are from single countries or cities and can be analyses against the average income in that city or country. This cloud of individual data-points is very scattered, and basically only indicates that industrialised countries have higher residential floor space levels, and that developing countries are rapidly catching up (Figure 6.6, left graph). IEA (2004a) time series for several OECD countries for the period 1973-1998 indicate a continuous growth of floor space per capita with increasing income levels (i.e. no signs of stabilisation) and a difference in floor space levels between densely populated countries (Japan), medium dense populated countries (Western Europe) and countries with low population density (USA, Canada, Australia). Data for India (NSSO, 2003) show a steep increase across rising household expenditure levels (Figure 6.6, right graph), driven also by a decreasing number of household members (Figure 6.4). At very low incomes, the data stabilise at a minimum floor space of approximately 4 m^2/capita.

The general trends in these data can be summarised as increasing floor space with higher income levels, but with a decreasing growth rate and lower floor space levels with higher population density. Using the observation of a minimum floor space value of 4 m^2/capita and the fact that India is a very densely populated country, we performed a regression analysis with a Gompertz curve through the available Indian data. This assumes logistic growth of residential floor space levels as function of household expenditure towards the present day levels for Japan (urban India) and Western Europe (rural India):

$$F_{p,q(t)} = \varphi 1_p \cdot EXP(-\varphi 2_p \cdot EXP(-\tfrac{-\varphi 3_p}{1000} \cdot Y_{p,q(t)})) \text{ (m}^2\text{/capita)} \qquad 1$$

with $F_{p,q(t)}$ per capita floor space for urban and rural areas (p=u,r) and population quintiles (q=1…5) as function of per capita household expenditures (Y, in USD_{2000}/cap/yr) and estimated parameters $\varphi 1_p$, $\varphi 2_p$ and $\varphi 3_p$. Regression to the available data for the year 2002 yields R^2 values of 0.98 for rural and 0.99 for urban areas (see van Ruijven et al., 2008d).

[7] Data from Shen (2006) include BMSB (1997-2004), CBS (2005), CNSB (2004), HKHA (2005), NRC (2005), Rector and Johnson (2004), SBJ (2002), Swedish Institute (2005) and Wolbers (1996).

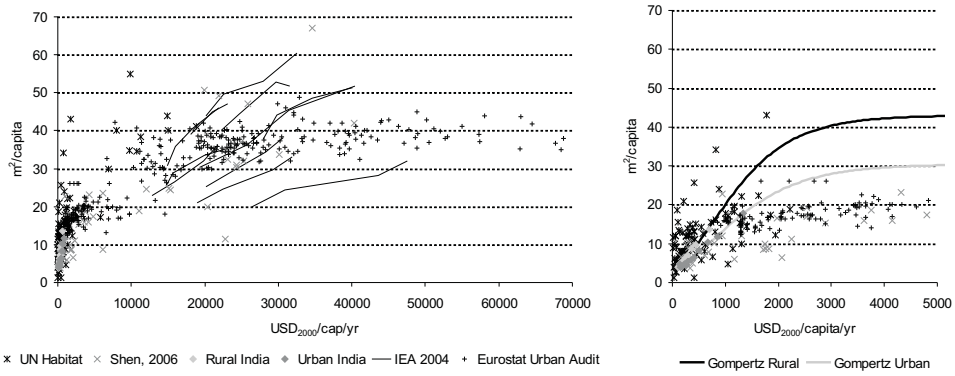

Figure 6.6: Data on residential floor space per capita, from several international databases (left) and for India (right, NSSO, 2003); we use a Gompertz curve that is fitted to the Indian data

Applying this function to Indian historic expenditure data yields a rather constant floor space per capita for urban and rural low expenditure quintiles (Figure 6.7). The highest expenditure quintile increased, in both urban and rural areas. Future projections show an increase for all quintiles, driven by rising expenditure levels.

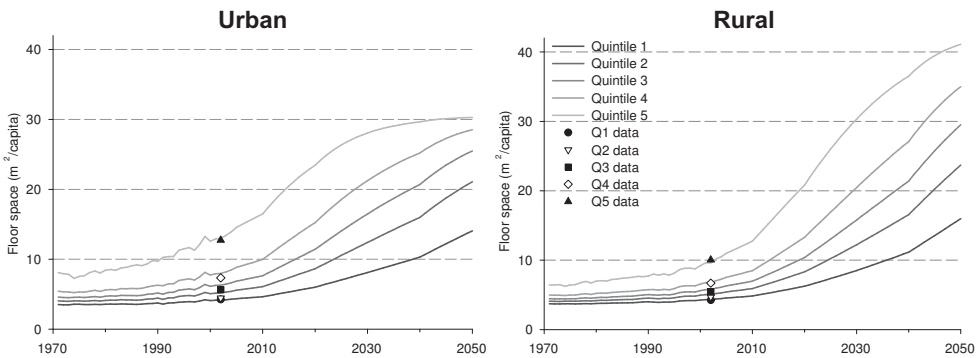

Figure 6.7: Historic simulation and future projections of residential floor space for urban and rural India, compared to the observed data in 2002 (NSSO, 2003)

4.2 Electrification

Access to electricity is an essential factor in household energy use. Without electricity, rooms have to be lighted by candles and kerosene lamps and the ownership of appliances like fans and TVs is useless. However, access to electricity is in most cases not a decision of the household itself but the result of policy-driven electrification schemes and State Electricity Boards (SEB). Moreover, data on household electrification are scarce; we use the application of electricity for lighting as a proxy for electrification rates of households at

different income levels. This assumes that once a household has access to electricity, it will be the preferred source of energy for lighting[8].

Electrification in this model is based on Kemmler (2007a; 2007b), who used a probit model (see Appendix 2) in an econometric analysis of the influence of different variables on residential electricity use in India (expenditure, household size, education, labour, electricity tariffs and geographical information). Kemmler (2007a; 2007b) found household expenditure as the main explanation for electricity use by households, and we fitted the following probit equation to the NSSO data on electricity use for lighting in population quintiles (Figure 6.11):

$$E_{p,q(t)} = N\left(POLICY \cdot (\varepsilon 1_p \cdot LN(Y_{p,q(t)}) + \varepsilon 2_p)\right) \qquad \text{(fraction)} \qquad 2$$

with $E_{u,q(t)}$ the electrification level for urban and rural areas *(p=u,r)* and population quintiles *(q=1…5)* in 1993 and 2002; *N* is the cumulative normal distribution and *Y* is household expenditure (in USD_{2000}/cap/yr). The values of parameters *ε1* and *ε2* are estimated for urban and rural areas, with R^2 values of resp. 0.94 and 0.98, based on data for 1993 and 2002.

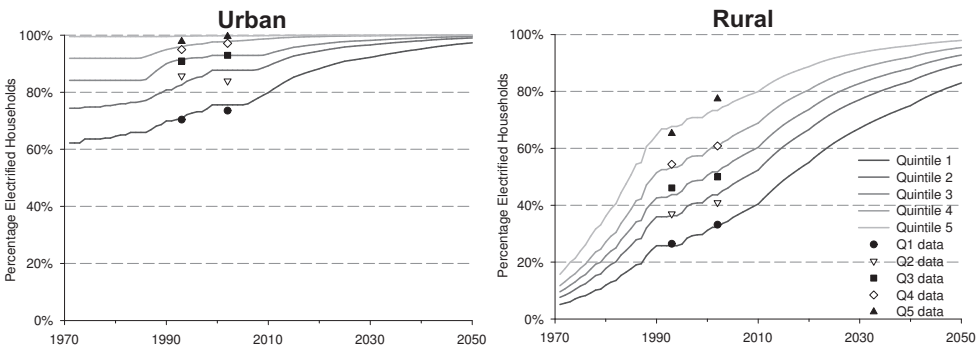

Figure 6.8: historic simulation and future projections for urban and rural household electrification, compared to data in 1993 and 2002 (NSSO, 1997, 2004)

Before 1990, rural electrification levels increased faster than household expenditures, the only explanatory factor in this model. Therefore, the rural model is adjusted for the trend of rural village electrification between 1971 and 1990 (see van Ruijven et al., 2008d). The factor *POLICY* is used to simulate increased or decreased electrification efforts in future scenarios and is historically (and in Figure 6.8) set to 1. Forward calculations with this model lead to rapid electrification in urban areas, towards almost full electrification in

[8] Comparing the aggregate data for lighting energy sources and electrification shows that less households are electrified (rural, 43% in 2002 and urban 82% in 1993) than use electricity for lighting (rural 52%in 2002 and urban 89% in 1993). This might be due to the use of centrally charged battery lamps, but also shows the weakness and inconsistency of the data and implies theft of electricity and the use of agricultural electricity (three-phase system) in households (two-phase system) (Kalra and Rastogi, 2007)

2050. Rural electrification projections proceed more slowly, towards levels above 80% in 2050 (Figure 6.8).

5 Fuel use for cooking, water-heating and space heating

5.1 Total energy use for cooking, water-heating and space heating.

In developed countries, space heating is usually the largest component of residential final energy use, followed by water-heating and cooking (Schipper et al., 1996). In many developing countries, however, cooking and water-heating are the largest energy consuming activities. Poor households primarily use fuelwood for these energy functions, causing sustainability problems like deforestation and health issues (Goldemberg et al., 2004).

The absolute amount of energy use for cooking, water heating and space heating varies widely throughout literature and between regions. Comparing available literature on energy use for cooking in India at the level of useful energy (that is: corrected for differences in end-use efficiency, indicated as *UE*) led to a range of 0.5-3.5 MJ_{UE}/capita/day, although most studies seem to cluster between 1.7-2.7 MJ_{UE}/capita/day (Ang, 1986; D'Sa and Murthy, 2004; ESMAP, 2003; Gupta and Ravindranath, 1997; Kumar Bose et al., 1991; Purohit et al., 2002; Reddy and Balachandra, 2006a; for details see: van Ruijven et al., 2008d). Broadening the perspective towards studies from China (Price et al., 2006; Xiaohua et al., 2002), Japan (Price et al., 2006), Turkey (Utlu and Hepbasli, 2005) and the Netherlands (EnergieNed, 2004; UCE et al., 2001) provides a similarly wide range for cooking energy use, though without any relation to income. This can be explained from several arguments: energy use for cooking is strongly dependent on cultural food habits and relations with income changes can be in multiple directions (unfortunately, most studies do not provide data for such analysis). On the one hand, people can afford more food, which might also be more energy intensive; on the other hand, people might choose convenient pre-processed food or eat more often in restaurants, thus shifting energy use from households to industry and services. Finally, family size tends to decrease with rising income levels, increasing the per capita use of energy per meal (decreasing scaling advantages). Based on these considerations and data analysis, we assume a constant value of 2 MJ_{UE}/capita/day for cooking in India.

Energy use for warm water is currently very low in India, about 0.5 MJ_{UE}/capita/day, but data from other countries indicate an increase with income or GDP per capita. Based on the scarce available data, we derived the following stylized curve for useful energy demand for warm water as function of household expenditure level (in PPP (int$\$_{2000}$/cap/yr), for population quintiles, q=1…5):

$$UEwater_{p,q(t)} = 8.5 \cdot (1\text{-EXP}(-\tfrac{0.1}{1000} \cdot \text{Yppp}_{\text{p,q(t)}}) \quad (\text{MJ}_{\text{UE}}\text{/capita/day}) \qquad 3$$

Energy use for space heating is derived from Isaac and Van Vuuren (2008) and elaborated for population quintiles and a different function for floor area (see Section 4.1) This model follows the decomposition approach of Schipper et al. (1996) and IEA (2004a) and

describes useful energy demand for residential space heating per capita as function of floor space (*F*) and heating intensity:

$$UEheating_{p,q(t)} = F_{p,q(t)} \cdot HDD_{(t)} \cdot Intensity_{(t)} \text{ (kJ}_{UE}\text{/capita/year)} \qquad 4$$

in which floor area (*F*) is in m^2/capita, *HDD* reflects heating degree days (in °C/yr, see Section 3.4) and *Intensity* is useful energy intensity per square meter per degree day (kJ_{UE}/m^2/°C/yr). Heating intensity is determined as a residual factor between energy use for cooking and lighting and historic total energy use (although this ignores the use of electricity for heating). We found a rather constant average value of 130 kJ_{UE}/m^2/°C/yr for the period 1971-2003 (with many short term fluctuations)[9].

The assumptions on the volume of energy use for cooking, water heating and space heating are directly derived from data (i.e. space heating) or from local studies and literature (i.e. cooking and water heating). In other words, these assumptions are based on data, but not calibrated against the data.

5.2 Fuel choice for cooking, water-heating and space heating.

In the general concept of the energy ladder, it is assumed that, with increasing income, households switch towards cleaner, more efficient and convenient fuels: from dung and fuelwood towards kerosene, LPG and electricity (Hosier and Dowd, 1987; Reddy and Reddy, 1994; van Ruijven et al., 2008b). This concept has been criticised for being an oversimplification, because household commonly use multiple fuels in parallel (Masera et al., 2000) and other factors than income influence fuel choice as well (Farsi et al., 2007). Nevertheless, for a first go it provides a consistent basis for long-term dynamics that is sufficiently adequate for the purpose of our model, since income is the main explanatory factor for fuel choices and households are observed to switch fuels on the long-term, even while there may be periods of simultaneous fuel use.

[9] For reference, useful heating intensity in Canada, USA and Western Europe decreased between 1971 and 2000 from about 150-180 to the range of 90-130 kJ_{UE}/m^2/°C/yr

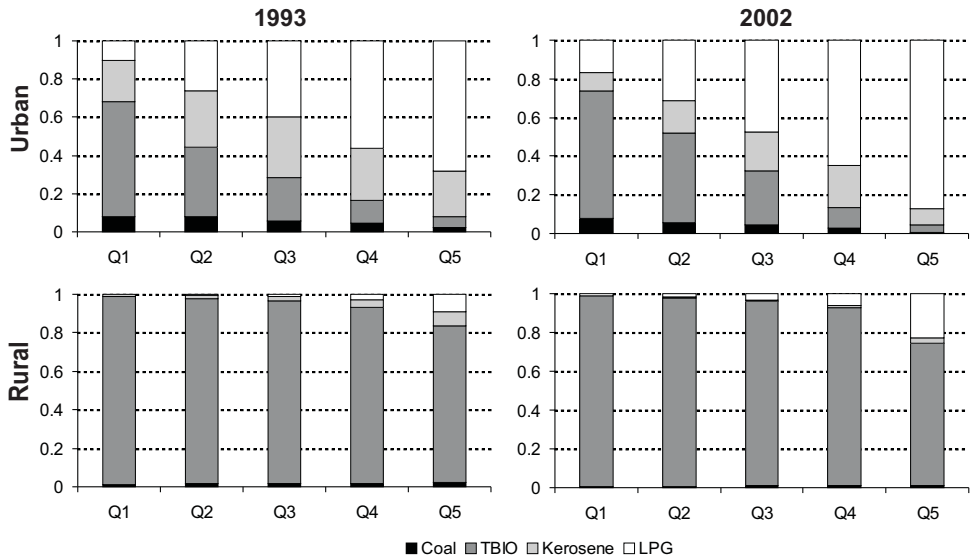

Figure 6.9: Historic shares of fuels for cooking and water heating in household expenditure quintiles; TBIO includes fuelwood and dung (NSSO, 1997, 2004)

Data on energy use for cooking and water heating of households in India are regularly collected during the major NSSO rounds. Figure 6.9 shows that energy for cooking and water heating in India indeed generally follows the energy ladder. Energy in rural areas is mainly provided by fuelwood, followed by kerosene and LPG; even the richest rural quintile relied for 70% on traditional fuels in 2002. For urban households, the use of fuelwood is still common at low-income levels, but LPG gained market share between 1993 and 2002 in all urban expenditure groups. Coal is almost solely used in low-income urban households and regionally bounded to the northern Indian states.

The dynamic pattern that emerges from the data is the change in market shares of energy options with increasing income: the energy ladder. We distinguish two forces that drive this change. One force is 'away from traditional fuels': push-factors, and the other is 'towards modern fuels': pull-factors. The premise of this model is that by balancing push- and pull forces, it simulates energy ladder behaviour. First, the pull forces: it is often argued that although efficient cooking options are cheaper on a life-cycle basis, poor households experience a threshold from front-end investment costs of more expensive stoves (Gupta and Ravindranath, 1997). The savings rate of these households is very low, thus capital availability is limited and capital costs are depreciated over a short time period (often only a few months) or against high discount rates. The real interest rate for low-income households is often higher than 36% (Gupta and Ravindranath, 1997) and the discount rate for fuel switching was found to increase exponentially with decreasing income (Reddy and Reddy, 1994). In the model, this dynamic is represented by an economic lifetime over which capital is depreciated, which is an exponential function that increases with rising household expenditure levels towards the technical lifetime of cooking equipment. In formula:

$$ELT_{p,q,EC(t)} = TLT_{EC} \cdot (1 - EXP(\tfrac{-\alpha_p}{1000} \cdot \tfrac{TLT_{REF}}{TLT_{EC}} \cdot Y_{p,q(t)})) \qquad \text{(yr)} \qquad 5$$

in which ELT_{EC} is the economic lifetime and TLT_{EC} (in yr) is the technical lifetime and Y household expenditures per capita (in USD_{2000}/cap/yr). The parameter α determines sensitivity of the economic lifetime to changes in household expenditure. By relating α to a reference technology (T_{REF}, here traditional biomass) the curves for different technologies behave similar at low expenditure levels. We use α to calibrate the model results to historic data.

Second, we look into the push forces, away from traditional energy sources. It is clear that households prefer to use the most convenient fuels, although these might be more expensive than traditional fuels. While fuelwood may also be the cheapest option for high-income households, kerosene or LPG are preferred based on the time involved in collecting and using the fuel and reducing indoor air pollution (ESMAP, 2003). In rural India, 59% of the households collect their own fuelwood; in urban areas this is only 7%. With respect to indoor air pollution, emissions of respirable suspended particulate matter (RSPM) are very high from traditional fuels: the 24-hour averaged exposure level of household cooks is 400 $\mu g/m^3$ [10] (ESMAP, 2003).

In the model, these push forces on cheap-but-inconvenient fuels are incorporated by a fuel-specific penalty which we assume a function of household expenditure levels. Richer households have generally more options to use more expensive fuels, more education and access to information and perceive the disadvantages of cheaper fuels as more important than poor households. Analogously to the economic lifetime formulation in eqn. 5, the penalty (*PEN*) of each fuel is defined as:

$$PEN_{p,q,EC(t)} = PU_{EC} \cdot (1 - EXP(\tfrac{-\beta_p}{1000} \cdot Y_{p,q(t)})) \qquad 6$$

with PU_{EC} the penalty at high income levels and β a factor to determine the sensitivity to changes in household expenditure (Y, in USD_{2000}/cap/yr). The numerical value of U_{EC} can be discussed, but should in principle be related to emissions and time. We use the fuel specific penalty (i.e. PU_{EC} and β) to calibrate the model results to historic data. The penalty is modelled additive to the other costs (capital, O&M and fuel) and related to total annual fuel use for each option. Thus, the total annual costs of each option are capital costs, O&M costs and fuel costs, the perceived annual costs are capital, O&M, fuel and penalty.

Fuel choice for cooking, water heating or space heating is no daily issue for households. Most households have equipment (stoves) for one fuel-type (wood, kerosene, LPG) and only choose another fuel when a stove is broken, worn out or depreciated. Even than, people often choose the similar fuel, due to familiarity or habit. So, transitions in consumer fuel choice often proceed slowly because of the capital stock dynamics and delays in fuel

[10] For reference, outdoor PM_{10} standards are 50 $\mu g/m^3$ and 150 $\mu g/m^3$ in resp. UK and the USA

switching. In the model, we simulate these processes with a capital vintage model for the stock of stoves. The actual market shares in the stock of stoves are the results of marginal investments and depreciation after the technical lifetime. The actual market shares for marginal investments are derived from the indicated (optimal) market shares with a smoothing delay of 10 years (to simulate the sub-optimal investment behaviour of households). The indicated (optimal) market shares (*IMS*) of different energy options (EC=coal, kerosene, LPG, TBIO) are derived from the annual perceived costs with a multinomial logit allocation (see also Appendix 2):

$$IMS_{p,q,EC(t)} = \frac{e^{-\lambda C_{p,q,EC(t)}}}{\sum_{EC=1}^{NEC} e^{-\lambda C_{p,q,EC(t)}}} \qquad \text{(fraction)} \qquad 7$$

in this, λ is the logit parameter and C are the perceived annual costs of the cooking options (in USD_{2000}/hh/yr). The logit parameter (λ) determines how strongly consumers react to changes in perceived cost differences. High values for λ indicate optimising consumer behaviour; while low values for λ indicate a gradual change in consumption patterns and investments in multiple fuels at similar income levels with hardly any influence from costs and prices.

Final energy use for cooking, water heating and space heating is modelled similarly for rural and urban areas (p=u,r) and population quintiles (q=1…5) as function useful energy (*UE*), market shares (*MS*) and fuel specific end-use conversion efficiency (in MJ_{UE}/MJ_{SE}):

$$SE_{p,q,EC(t)} = \frac{UE_{p,q,EC(t)} \cdot MS_{p,q,EC(t)}}{Efficiency_{EC(t)}} \qquad \text{(MJ/capita/yr)} \qquad 8$$

Three issues need some discussion, when implementing this conceptual model for India. First, the use of electricity for water heating and space heating. Evidence shows that at low income levels, people use their cooking equipment for water heating and space heating, but at higher income levels, the ownership of electric water heaters (emersion heaters, boilers or geysers) and space heaters increases and households use LPG for both cooking and water heating (Murthy et al., 2001). Therefore, electricity for water heating and space heating is modelled separately as function of the ownership of water heaters and space heaters (see Section 6) and subtracted from the total energy use for water heating and space heating. Second, almost all kerosene in India is distributed to through the public distribution system (PDS) (Gangopadhyay et al., 2005; Rehman et al., 2005). This means that almost all rural and 50% of urban households have access to subsidised kerosene. In the model, we simulate this effect by forcing households with access to the PDS to use kerosene instead of the market share from the multinomial logit (eqn. 7). Non-electrified households use kerosene for lighting first, while electrified households use it for cooking. Third, we currently do not include efficient renewable cooking options, like improved stoves and

biogas. Although the Indian government developed programs for the distribution of improved stoves over the last decades, we lack adequate data for model calibration. The use of biogas is monitored by the NSSO, but according to the survey data it is hardly used for cooking in India.

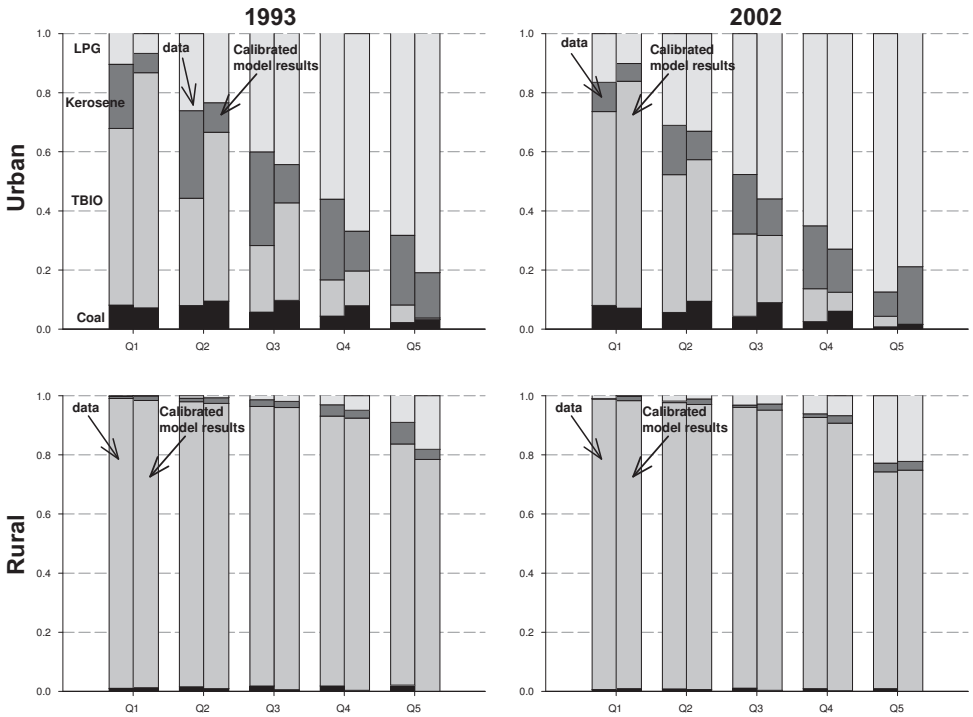

Figure 6.10: historic data (left bars, equal to Figure 6.9) and calibrated model results of household fuel choice for cooking and water heating

Although this model might qualitatively describe the energy ladder behaviour, it is only valuable when it adequately simulates the Indian data. The only available data for calibration are for 1993 and 2002, across income levels (NSSO, 1997, 2004). Using α, β and *PU* as calibration parameters, see eqn. 5 and 6, the shares of the different energy options can be calibrated against historic data. With three calibration-parameters, four energy options, five urban and rural population quintiles, and data for two years, this calibration process has many degrees of freedom. Therefore, we applied an automated model calibration procedure, that repeatedly starts at different random locations in the parameter space and minimises the error between model results and observations (van Ruijven et al., 2008a; van Ruijven et al., 2008c). The error is expressed here as the root mean square error (RMSE, see Appendix 1) between model results and data for the fractions of the energy options (in urban and rural population quintiles), averaged between the two calibration years. The best calibrated sets of parameter values have RMSE values of 9% for urban and 2% for rural areas. Comparison of these calibrated model results and data

learns that the model simulates the generic trends, with the main deviation that it allocates too little market share to kerosene in urban areas (Figure 6.10). The main conclusion of the calibrated parameter values is that urban households apply capital intensive energy options at lower income levels than rural households. We used the factor PU_{EC} to calibrate the model. Unfortunately, the calibrated values of PU_{EC} for rural areas are not in line with emission or time consumption characteristic. Theoretically, the penalty must be higher for traditional fuels than for kerosene and LPG. However, the calibrated PU_{EC} is much higher for LPG than for traditional fuels, which is possibly related to limited availability of LPG in rural areas (see also D'Sa and Murthy, 2004). In future scenarios, we assume the PU_{EC} for LPG decreases towards urban preference levels in 2100, assuming that access to LPG in rural areas increases.

6 Electricity use for lighting and appliances

6.1 Lighting

Lighting is the major electricity end-use at low income levels. The lighting technologies follow a clear preference ladder (Figure 6.11). At low incomes and without electrification, candles and kerosene are the only available options. Once electricity is available, electric lighting is preferred. The barrier of front-end investment costs causes less efficient incandescent bulbs to come first, before fluorescent tubes and bulbs are applied (Reddy and Balachandra, 2006b).

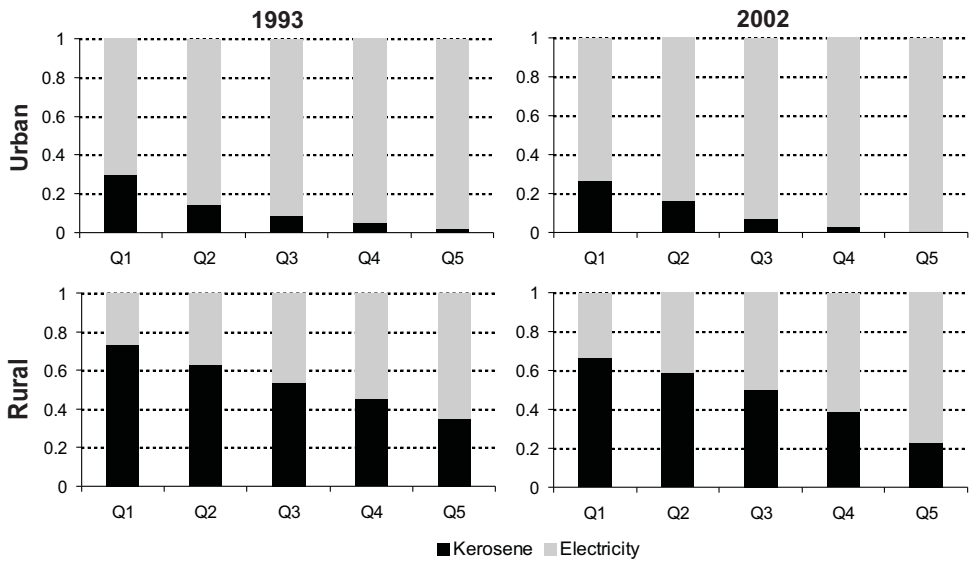

Figure 6.11: Historic data on urban and rural shares of kerosene and electricity as main energy source for lighting in 1993 and 2002 per population quintile (NSSO, 1997, 2004)

In modelling terms, we assume that demand for lighting services is mainly driven by residential floor area, which we modelled as function of income and country-wide

population density (see Section 4.1). Reddy and Balachandra (2006a) identified a series of standard and energy-efficient lighting packages that vary with respect to the number of bulbs and tubes and the usage pattern. The energy efficient lighting packages have higher capital costs, but lower energy use than the standard lighting packages. Originally, these packages were associated different income levels. However, the demand for lighting services is not expected to increase endlessly with income; to be able to extrapolate the demand for lighting services, we linked these lighting-packages to floor space per capita as physical driver. Annual energy use (in kWh/hh/yr) for different energy packages (*EP*=standard or energy-efficient) is defined as:

$$AnnEnergyUse_{q,EP(t)} = \gamma_{p,EP} \cdot F_{p,q(t)} + \delta_{p,EP} \quad \text{(kWh/hh/yr)} \qquad 9$$

with floor space (*F*) in m^2/capita and the parameters γ and δ distinguished for rural and urban areas. Minimum electricity use for standard and efficient lighting is resp. a single 40W or 10W bulb. The use of kerosene for lighting is modelled as function of electrification. All non-electrified households are assumed to use kerosene for lighting: 4 litres per household per month (ESMAP, 2003). Sales of compact fluorescent lights (CFL) in India started to increase in 1997, from very low levels (Kumar et al., 2003). Therefore, we assumed the efficient lighting packages to be only available since 1995 (though at higher cost than standard lighting). Total final energy use for lighting is formulated as:

$$SElighting_{p,q,EP(t)} = Households_{p,q(t)} \cdot AnnEnergyUse_{p,q,EP(t)} \cdot MS_{p,q,EP(t)} \quad \text{(kWh/yr)} \qquad 10$$

Where *EP* denotes the energy package (*EP*=kerosene, standard electricity or efficient electricity). Total capital costs are depreciated over the economic lifetime, which increases towards the technical lifetime, similar to the modelling of other energy options as shown in Eqn. 5. The actual market shares (of the energy packages) are determined from a multinomial logit distribution on marginal investments and a vintage capital stock (see Section 5.2).

6.2 Household appliances

At higher income levels an increasing share of electricity is used for other end-use functions and appliances. With increasing income levels, households show a clear preference ladder for appliances: first a fan is bought, second a TV and third a refrigerator, followed by more energy-intensive appliances, like air coolers, air conditioners and washing machines (Figure 6.12). We clustered the use of household appliances in four end-use functions and use one major energy consuming technology as representative item for its cluster. The end-use clusters are:

1. Space cooling
   Represented by fans, air coolers and air conditioners
2. Food storage and processing
   Represented by refrigerator (includes immersion water-heaters, mixer, hot plate)
3. Washing and cleaning

Represented by washing machine (includes vacuum cleaner, iron)

4. Entertainment and communication
   Represented by TV (includes radio, PC, mobile phone)

For space cooling, we modelled all three appliances explicitly, because of their diverging characteristics. Fans are the first appliance that many poor households buy (Figure 6.12), consuming little energy (Table 6.1); air coolers are more expensive, but not as energy intensive as air conditioners, which are expensive energy consuming appliances.

Electricity use for household appliances depends primarily on two indicators: the ownership of appliances (as fraction of total electrified households) and energy use per appliance (unit energy consumption, *UEC* in kWh/hh/yr or kWh/unit/yr). Therefore, the formulation of annual electricity use of appliances is:

$$SEappliance_{p,q,(t)} = households_{p,q(t)} \cdot ownership_{p,q(t)} \cdot \frac{UEC_{p,q(t)}}{Efficiency_{(t)}} \text{ (kWh/yr)} \quad 11$$

Ownership of household appliances generally shows a logistic (or S-shaped) form over income. We followed Letschert and McNeil (2007) in using the Gompertz-curve as the simplest representation of such form, see eqn. 1, and used non-linear regression to estimate parameter values per appliances cluster and urban/rural area (Figure 6.12). We adjusted the historic ownership data (used in the regression analysis) for electrification levels, price decrease of appliances and the option of multiple ownership (for details see van Ruijven et al., 2008d). Electrification levels are a natural upper limit for appliance ownership; the historic saturation level of many appliances increased over time, which can (among others) be explained from decreasing prices. Finally, several appliances are likely to be available in multiple units in households. We included this explicitly in the ownership curve for fans; for air coolers and air conditioners this is implicitly included in the unit energy consumption (Table 6.1). It should be noted that the regression is mainly based on a one-time measurement across different expenditure levels (because of limited data availability), the development of appliance ownership within a certain expenditure group over time might have a different shape.

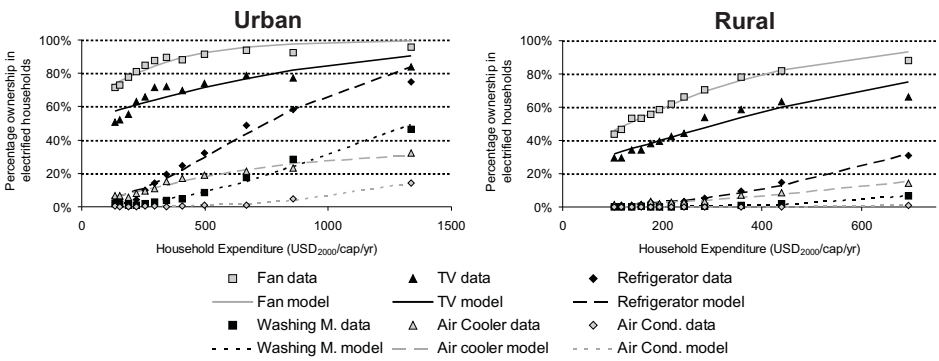

Figure 6.12: data and results of regression model for appliance ownership in rural and urban electrified households in 2002

The next step is unit energy consumption (*UEC*) of the different appliances. Following Letschert and McNeil (2007), we distinguish between appliances with a rather constant *UEC* (fan, TV, washing machine), appliances with a time-dependant *UEC* (refrigerator, driven by expected increasing market share of larger models) and appliances with an income-dependant UEC (air cooler and air conditioner, driven by the use of multiple units, increasing unit cooling capacity and increase in hours of use). For fans, we explicitly account for ownership of multiple units as a function of household floor space. UEC of air conditioners is assumed to be a logarithmic function of household expenditure, with an upper level based on cooling degree-days (Section 3.4) and a minimum energy consumption of 400 kWh/hh/yr (Isaac and Van Vuuren, 2008; Letschert and McNeil, 2007; Murthy et al., 2001). For air coolers, we assume a similar pattern with household expenditure, adjusted for the difference in annual power consumption (McNeil and Iyer, 2008; Murthy et al., 2001).

Table 6.1: Assumptions on unit energy consumption (UEC) of household appliances in India

Appliance	UEC (kWh/hh/yr)		Source
	2000	2030	
Fan	145	145	(Murthy et al., 2001)
Air Cooler	UEC_{AC}*300/2160		UEC_{AC} adjusted for power use
Air Conditioner	CDD*(0.865*ln(Y-ppp)-6.04)		(Isaac and Van Vuuren, 2008)
Food Storage (refrigerator)	500	650	(Letschert and McNeil, 2007)
Cleaning (washing machine)	190	190	(Murthy et al., 2001)
Entertainment (TV)	150	150	(Murthy et al., 2001)

A final step is the improvement of appliance energy efficiency. We can distinguish two processes here. First, efficiency improves (autonomously, i.e. without extra costs) over time as result of technology development and increased efficiency standards. Second, more efficient appliances are often available against higher costs. In this model version, we have included the first autonomous process of autonomous efficiency improvement on the basis of estimates from Letschert and McNeil (2007) and Rong et al. (2007). An alternative option, to include both autonomous and price-induced efficiency improvement, is to define a cost-supply curve of energy-saving measures. However, this requires extensive data collection and, hence, might be useful for future further model development.

7 Model performance

We can compare the simulation results of residential energy use over time to the historic data of the IEA energy balances 1971-2003 (IEA, 2005). The IEA energy balances only specify the amount of fuels used by the residential sector, without information on end-use functions. Although the IEA data are regarded rather certain[11], they should be treated carefully because India does not submit official energy balances to the IEA and fuelwood data are inherently uncertain. Recently, the IEA improved the quality of its Indian energy data with bottom-up statistics from the NSSO[12] (IEA, 2007e). The simulation results of our

[11] Uncertainty ranges for IEA energy balances are not published
[12] These improvements are not included in Figure 6.13

model are based on the described bottom-up analysis, using regression to historic data and calibration on partial-models (i.e. fuel use for cooking, water heating and space heating). We did not calibrate our model to the IEA data, so this section only involves 'comparison'.

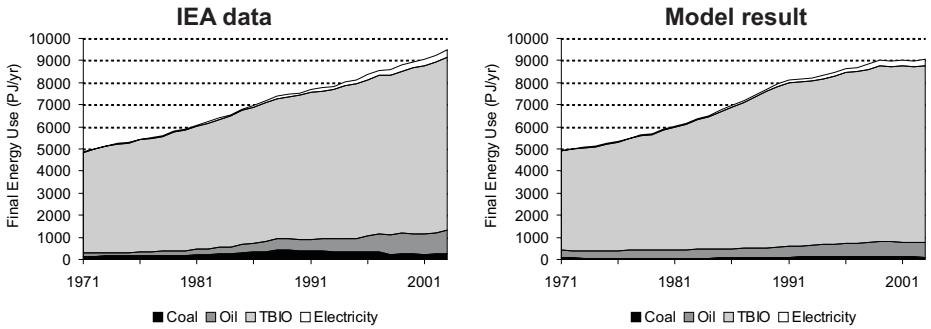

Figure 6.13: historic data (IEA, 2005) and model simulation results for historic total fuel use in the Indian residential sector

The model results on fuel use, i.e. the sum of cooking, water heating, space heating and kerosene for lighting (Figure 6.13), show that the model simulates the total use of fuels in the range of the IEA energy balance data. Expressed as the Normalised Root Mean Square Error (see Appendix 1), the error between data and model results over the whole period 1971-2003 is 2.7%[13]. For individual fuels, the model simulates a low market share for coal and higher market share for oil during the 1970s. The latter is mainly related to kerosene use for rural lighting and cooking. Historic energy use for lighting might be overestimated, because we assume that people always light their houses, whereas in reality many families might use some candles and go asleep early. Although the simulations of households depending on coal as main cooking fuel are calibrated to the NSSO data (Section 5.2), the use of coal is less in the simulation results than in IEA data. Because the NSSO specifically collects data on the main fuel, it might be that coal is usually applied as secondary fuel (in ovens) and does not show up in the NSSO data. A more detailed look into fuel use for the main end-use functions shows that cooking is the main energy consuming activity of Indian households (Figure 6.14). This is, of course, closely related to the enormous amount of (inefficiently applied) fuelwood use.

The results for electricity use are generally in line with historic data as well (Figure 6.14), but the model underestimates the increasing electricity use in later years. Therefore, the NRMSE for the simulation of total electricity use the period 1971-2003 is 13.8%[14]. If we focus on end-use functions, lighting was the major electricity end-use until 1990; since then, fans became more important and currently, electricity use for televisions and refrigerators is rapidly increasing.

[13] The best fit for residential fuel use in India of the existing top-down energy demand module of TIMER was found to be 6% (see van Ruijven et al., 2008a)
[14] The best fit for residential electricity use in India of the existing top-down energy demand module of TIMER was found to be 31% (see van Ruijven et al., 2008a)

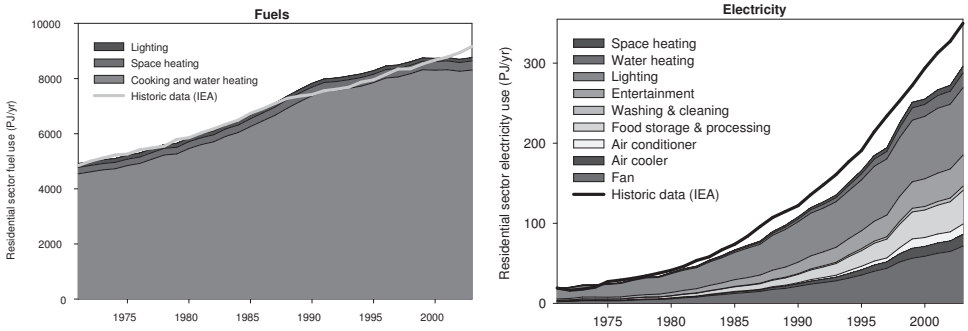

Figure 6.14: Historic residential sector fuel and electricity use (IEA, 2005) and model simulation results of energy use for several end-use functions

8 Scenario analysis: the impact of electrification and income distribution

We aim to analyse the impact of electrification and income distribution on future energy use. Therefore, we construct two scenarios on the basis of a single baseline scenario. The baseline scenario is the OECD Environmental Outlook (OECD-EO) scenario (Bakkes et al., 2008; OECD, 2008). The Indian population increases towards 1.6 billion with an urbanisation rate of 47%. The all-India average household expenditures increase from 300 USD_{2000}/cap/yr in 2000 to 2350 USD_{2000}/cap/yr (comparable to Turkey, South Africa or the Slovak Republic in 2005). Indian residential fuel prices in this scenario increase slightly with 20% towards 2050. Electricity is mainly produced from coal, although natural gas, nuclear and hydropower are increasingly applied, slowly decreases the carbon emission factor of electricity.

Based on this baseline scenario, we constructed two variants, in line with the IPCC/SRES storyline axis on equity (B) versus market-efficiency (A) orientation (IPCC, 2000a; Shukla et al., 2003). In the equity oriented scenario (OECD-B) policies are effective in providing income to the poorest groups, the gap between rural and urban expenditure levels decreases and the GINI coefficient decreases towards values that are currently found for Italy and Scandinavia (World Bank, 2007). Extra effort is made for (rural) electrification, aimed at decreasing the dependency on kerosene for lighting. The market oriented scenario (OECD-A) follows the development strategy of loosening economic policy to stimulate richer groups, while aiming at a trickle down of economic development. This scenario leads to an increasing gap between rural and urban expenditure levels, the GINI coefficients increase to values that are currently observed for China, the USA and Mexico, and policy attention fades away from rural electrification. For comparison, we also present the results of the original TIMER OECD-EO scenario, which are derived from the existing TIMER energy demand model[15].

[15] Several energy scenario studies have been published for India (e.g. Planning Commission, 2006; Shukla et al., 2003). However, because none of these studies published results at the sectoral level, we cannot compare our results of these studies without making heroic assumptions.

Table 6.2: scenario assumptions for OECD-B and OECD-A scenarios on Indian residential energy use

Variable	2005		OECD-B (2050)		OECD-A (2050)	
	Urban	Rural	Urban	Rural	Urban	Rural
Ratio to average expenditure	1.46	0.82	1.3	0.9	1.6	0.7
GINI coefficient	34	28	26	20	45	35
Electrification effort	1.0	1.0	1.1	1.1	0.9	0.9

Urban annual per capita household expenditures increase in the OECD-B scenario towards 1290 to 4800 USD_{2000}/cap/yr in 2050 (Figure 6.15, upper graphs); in the OECD-A scenario this is 740 to 8100 USD_{2000}. For rural areas, the equity oriented OECD-B projects 1080 to 2950 USD_{2000}, while the efficiency oriented OECD-A leads to 490 to 2990 USD_{2000}. So, for the rural rich, the situation is comparable in both scenarios, while the urban rich earn almost twice as much in the OECD-A scenario. The difference between the scenarios is most prominent in the low-income quintiles: in rural areas their expenditures in OECD-A are half the value of OECD-B, for the urban poor the difference is about one-third.

Electrification increases in both scenarios to considerably higher levels than in 2005. The difference between the scenarios is especially important in rural areas (Figure 6.15, middle graphs). Electrification rates for rural poor households are 70 to 80% in the OECD-A scenario, and over 90% in the OECD-B scenario. The development of incomes also influences fuel choices. However, rural areas are projected to rely mainly on traditional fuels for the next decades. In the OECD-B scenario, the use of traditional (solid) fuels in 2050 is limited to about 20% of the lowest urban and rural households. In the OECD-A scenario, however, the urban poorest quintile still relies for 80% on traditional fuels in 2050 and traditional fuels are common in the four poorest rural quintiles (Figure 6.15, lower graphs).

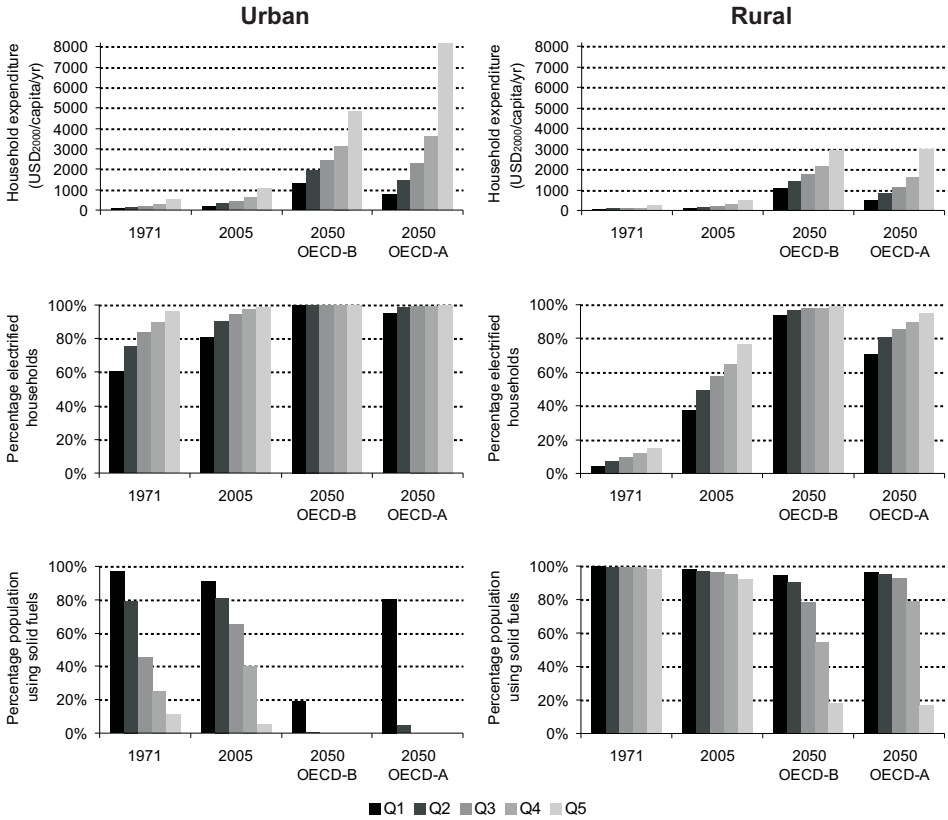

Figure 6.15: Household expenditures per capita (upper graph), household electrification levels (middle graphs) and percentage of the population that relies on solid fuels (lower graphs) in rural and urban population quintiles in the OECD-B and OECD-A scenarios

What is the impact of these developments on total energy use of the residential sector? The total absolute amount of residential energy use increases considerably in both scenarios: from 9.5 EJ in 2005 towards 15.5 EJ/yr in OECD-B and 16.5 EJ/yr in OECD-A in 2050 (Figure 6.16). However, the energy mix is considerably different. In 2050, traditional biomass counts for 34% of final energy use in the OECD-B scenario, while it counts for about 45% of final energy use in the OECD-A scenario. Oil use is higher in the OECD-B scenario, because it is the primary substitute traditional fuels. Electricity use is 1.2 EJ/yr higher in the OECD-B scenario, where more households have access to electricity and ownership of fans and televisions is significantly higher. Compared to the original TIMER OECD-EO scenario, this new model projects considerably higher consumption of electricity (about half of which is for air conditioning). The transition from traditional fuels to oil is in the same order of magnitude.

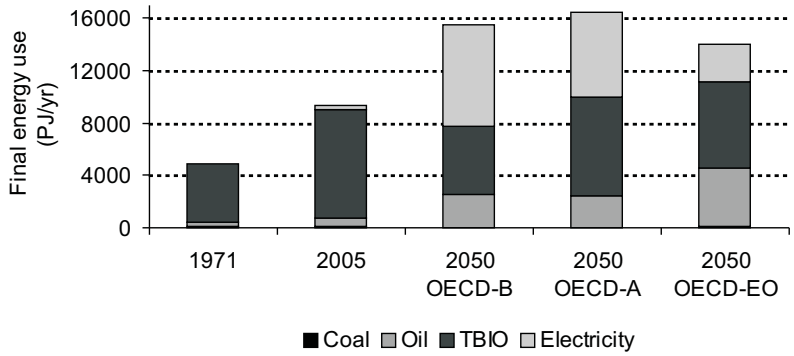

Figure 6.16: Total residential energy use in the OECD-A and OECD-B scenarios and the TIMER OECD-EO scenario. Note that the OECD-EO scenario has not been calculated with this model but is taken from another study (Bakkes et al., 2008; OECD, 2008) and presented here for comparison.

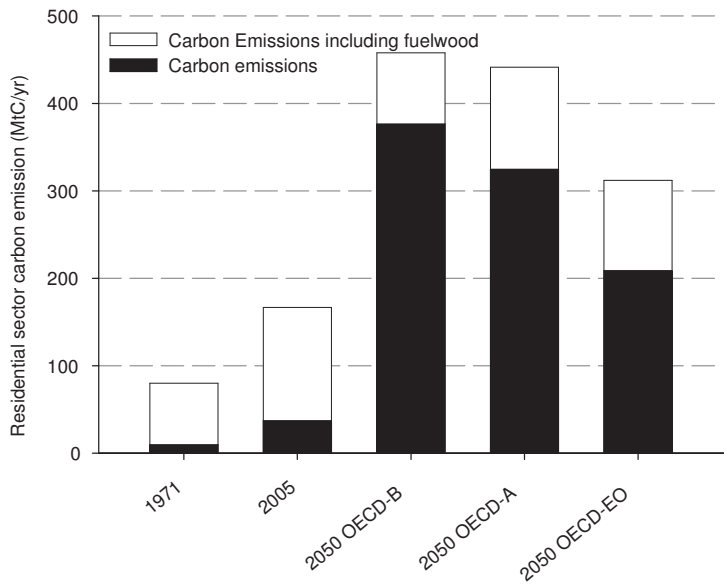

Figure 6.17: Total residential sector carbon emissions in the OECD-B and OECD-A scenarios, including and excluding emissions from fuelwood. Note that the OECD-EO scenario has not been calculated with this model but is taken from another study (Bakkes et al., 2008; OECD, 2008) and presented here for comparison.

While residential final energy use increases by 65-75% between 2005 and 2050, carbon emissions from fossil fuels in 2050 are projected to increase to 9-10 times the 2005 level (Figure 6.17). If we take carbon emissions from fuelwood into account, assuming that 60% of fuelwood is sustainably harvested (based on Reddy and Balachandra, 2006a), the present

day emissions are much higher and the increase towards 2050 is 'only' a factor 3. The structure of carbon emissions is the main difference between the scenarios. In the OECD-B scenario, traditional biomass use causes minor carbon emissions in 2050, whereas it counts for 26% of the emissions in the OECD-A scenario. Another major difference between the scenarios originates in the relatively high carbon emission factor of electricity in India, due to the reliance of the electricity system on coal. The projected growth in electricity use, especially in the OECD-B scenario, leads to a strong increase in carbon emissions, whereas lower electrification levels in OECD-A limit carbon emissions from electricity. The total carbon emissions from fossil fuel are considerably higher than the projection of the TIMER OECD-EO scenario. This difference is mainly driven by the higher demand for (carbon intensive) electricity (see Figure 6.16).

9 Discussion and Conclusion

In this paper, we described a bottom-up model for residential energy use in India, starting from the dynamics of development and energy use. In this model, urbanisation and heterogeneous income distribution are treated explicitly and urban and rural energy systems are modelled separately. We also included the development processes of decreasing household size and electrification. The model determined residential energy use for five end-use functions: cooking, water heating, space heating, lighting and appliances (including space cooling). Fuel use follows the energy ladder: cleaner, more convenient, but also more expensive energy options are preferred at higher income levels. Ownership of appliances follows the observed Indian preference ladder: fan, TV, refrigerator, and heavier appliances. This detailed model provides a more insightful picture of present and future energy use. The nature of the model allows for bottom-up estimations of future efficiency improvements.

We found that this model, developed from many locally available sources and survey data, simulates historic residential fuel use reasonably well with an NRMSE value of 2.7%, The simulation of historic electricity use is not as good, with an NRMSE of 14%. However, on both fuel and electricity use, this model performs better than the existing top-down TIMER energy demand model, which had minimum error values of resp. 6% and 31% for the Indian residential sector.

We explored the consequences of some variables that are usually not considered in global energy models and that might be very important for developing countries: income distribution and electrification. We used two scenarios, based on the TIMER OECD Environmental Outlook scenario. We found in these scenarios that total Indian residential energy use might increase 65-75% compared to 2005, whereas total carbon emissions increase to 9-10 times the 2005 level. We also found that the variation in income distribution and electrification significantly influences future projections. The projected energy mix in 2050 is different for both scenarios and reliance on solid fuels, and thus indoor air pollution and health issues, diverges between the scenarios. More equal income distribution mainly influences income-levels of the poor and leads to a more rapidly phase-out of traditional fuels. So, while equal income distribution and rural electrification are

good for decreasing poverty, there is a trade-off in terms of higher CO_2 emissions due to increase electricity use. At the same, higher income for the poor, lead to much less indoor air pollution.

Some remarks should be made on this model and the scenarios. Model development for developing regions is clearly hampered by lack of data. Although it is known that several issues are important for energy use, there are hardly any data available on these issues to identify model relations. For instance, data on household electrification are scarce, since the government officially measures electrification of villages; also, electricity use in countries like India suffers from many black-outs and brown-outs, but information on duration (and location) of these outages is not available. Further, the quality of the data is questionable. Survey data rely heavily on the education and consistency of the interviewers and on the honesty of answers. Due to this data-shortage, we made some 'heroic' assumptions during the development of this model. Most of these assumptions (e.g. electrification levels, unit energy consumption of appliances, heating energy intensity) were based on available information from recent years and extrapolated historically towards 1971. The model that we developed here has a bottom-up character, but at a more aggregated level than most traditional bottom-up models. It does not include detailed stocks on housing or appliances and is limited to the major trends and issues. In summary, although the data are rather weak, we were able to develop a model with more determinants and dynamics of residential energy use in developing countries than most existing global energy models and compared to historic data, our new model performs substantially better for India then the previously existing energy demand module of the TIMER model.

Appendix 1: household expenditure distribution model

Inequality of income distributions is often expressed in the GINI coefficient (Cypher and Dietz, 1997). This is a statistical summary for the Lorenz curve: defined as the ratio between the 'surface between the line of perfect equality and the Lorenz curve' and 'the surface below the line of perfect equality' (Figure 6.18). The GINI coefficient has values between zero and 100, with zero being total equality and 100 total inequality.

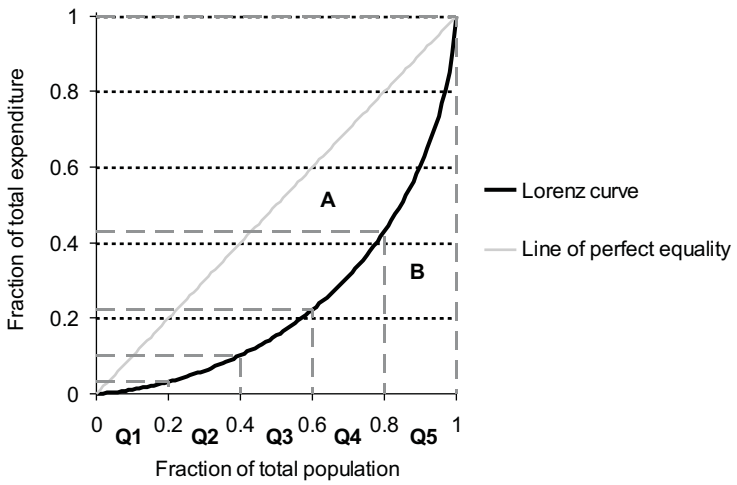

Figure 6.18: Lorenz curve and fractions of total household expenditure per population quintile

It is shown in several studies that the distribution of income over population is lognormally distributed; hence, the logarithm of income follows a normal distribution (Campano and Salvatore, 2006; Heaps et al., 1998; Kemp-Benedict et al., 2002). Based on this observation, a method was developed to link the GINI coefficient to the standard deviation in the lognormal distribution (σ) and derive the expenditure levels of population quintiles from the Lorenz curve (Humberto Lopez and Servén, 2006; Rutherford, 1955).

If σ denotes the standard deviation of log income, Aitchison and Brown (1957) show that the assumption of lognormallity implies that the GINI coefficient (G) is given by:

$$G = 2N\left(\frac{\sigma}{\sqrt{2}}\right) - 1 \qquad 12$$

with N denoting the cumulative normal distribution. Because the GINI coefficient is usually available in datasets (for different moments in time), it is useful to reformulate this into:

$$\sigma_{(t)} = \sqrt{2}N^{-1}\left(\frac{1+G_{(t)}}{2}\right) \qquad 13$$

with N^{-1} the inverse of the cumulative normal distribution. The Lorenz curve (L), as function of the cumulative population fraction (*P*) is given by:

$$L_{P(t)} = N\left(N^{-1}\left(P\right) - \sigma_{(t)}\right) \qquad 14$$

Because there is a direct relation between the GINI coefficient and the Lorenz curve, a change in GINI coefficient ($G_{(t)}$, hence $\sigma_{(t)}$) is directly reflected in the Lorenz curve. This allows us to determine the income shares of different quintiles of the population, based on the Lorenz curve. The fraction of expenditure (*Y*) of each population quintile (*q*) is given by:

$$Y_{q(t)} = L_{(0.2q)(t)} - L_{0.2(q-1)(t)} \text{ for q=1…5} \qquad 15$$

If we feed this model with historic GINI coefficients, we can evaluate its performance by comparing the model prediction (*M*) and observations (*O*) on the shares of total expenditure allocated to the population quintiles. The fit between model prediction and observations of the fraction of each population quintile (*q=1…5*) in urban and rural areas (*p=u,r*) in total expenditure can quantitatively be expressed as the root mean square error (*RMSE*):

$$RMSE_{p(t)} = \sqrt{\frac{\sum_{q=1}^{5}\left(M_{q(t)} - O_{q(t)}\right)^2}{5}} \qquad 16$$

This measure has values between zero (perfect simulation) and infinite (random). Because we evaluate normalised fractions of total expenditure, the *RMSE* represents the percentage deviation between model and observations. We found that the lognormal model simulates the observations very well, with *RMSE* values between 0.8-2.3% for different years (van Ruijven et al., 2008d).

Appendix 2: probit, logit and multinomial logit models

In this paper, we use several algorithms that originate from econometrics: the probit model (see electrification, Section 4.2) and the multinomial logit model (see investment allocation, Section 5.2). This appendix provides a brief mathematical introduction to these models. For more information see Woolridge (2000) or Murray (2005).

The probit and logit models are both sophistications of the linear probability model (LPM). Both the probit, logit and LPM are binary response models, aimed at variables that can take only two values (e.g. electrification, a house can only be electrified or non-electrified, see Section 4.2). These models analyse the probability (*P*) that a response variable (y) will have the binary value of 1 as function of the explanatory variable(s) (x): $P(y=1|x)$. In the LPM, this means:

$$P(y=1\,|\,x)=\beta_0+\beta_1x_1+\ldots+\beta_kx_k \qquad 17$$

in which $\beta_{(0,1,\ldots,k)}$ represents the relative sensitivity for the explanatory variable. This model has the disadvantages that *P* can take values below zero and above one, and that the partial effect of any explanatory variable is constant. These limitations are overcome by another class of binary response models that have the form:

$$P(y=1\,|\,x)=G(\beta_0+\beta_1x_1+\ldots+\beta_kx_k) \qquad 18$$

where *G* is a function that takes only values between zero and one: $0<G(z)<1$ for all real numbers z; and z is determined by the function $\beta_0+\beta_1x_1+\ldots+\beta_kx_k$. Several nonlinear functions have been suggested for $G(z)$, but the vast majority of applications uses the probit model and the logit model. In the logit model, $G(z)$ is the logistic function:

$$G(z)=\frac{\exp(z)}{1+\exp(z)} \qquad 19$$

which is the cumulative distribution function for a standard logistic random variable. In the probit model, G(z) is the standard normal cumulative distribution function (cdf):

$$G(z)=\Phi(z)=\int_{-\infty}^{z}\phi(v)dv \qquad 20$$

And $\varphi(z)$ is the standard normal distribution function:

$$\phi(z)=(2\pi)^{-\frac{1}{2}}\exp(-\tfrac{z^2}{2}) \qquad 21$$

Both these functions are increasing functions, having the highest growth rate at *z=0* and a maximum value of *G=1* (Figure 6.19).

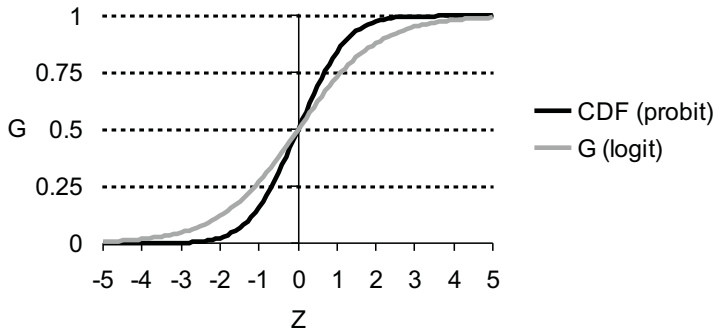

Figure 6.19: graph of the logistic function (used in the logit model) and the cumulative normal distribution function (cdf, used in the probit model).

The multinomial logit model is an extension of the binary logit model with multiple options, which still have to sum to a probability of 1. The probability for each option (*i*) out of *n* available options is given by:

$$P_i = \frac{\exp(z_i)}{\sum_{i=1}^{n} \exp(z_i)} \qquad 22$$

in which z_i is a vector that characterises each option. In this model, the probability for each option is a logistic function, whose exact form depends on the characteristics (*z*) of the option itself and the alternative options (**Error! Not a valid bookmark self-reference.**).

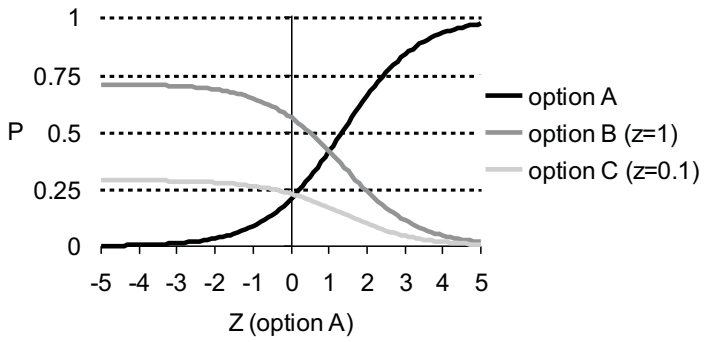

Figure 6.20: graph of the multinomial logit function for three options. Options B and C have constant values for z while the z value of option A varies on the x-axis

Chapter 7: The potential role of hydrogen in energy systems with and without climate policy[1]

Abstract
Introduction of hydrogen in global energy system can lead to lower CO_2 emissions (high end-use efficiency; low-carbon production of hydrogen) but might also to increase CO_2 emissions (producing hydrogen from coal). We used the long-term energy model TIMER 2.0, to study the use and production of hydrogen and its influence on global CO_2 emissions. This is done using a set of scenarios with assumptions on technology development, infrastructural barriers and climate policy. We found that even under optimistic assumptions hydrogen plays a minor role in the global energy system until the mid 21st century – but could become a dominant secondary energy carrier in the second half of the century. Hydrogen is mainly produced from coal and natural gas. Hence, hydrogen rich scenarios without climate policy increase CO_2 emissions up to 15% by 2100 compared to the baseline. However, if climate policy is assumed, CO_2 from fossil feedstock based hydrogen production is captured and sequestrated, which indicates that an energy system that includes hydrogen is much more flexible in responding to climate policy.

[1] Published in International Journal of Hydrogen Energy, 2007, 32(12). Co-authors: Detlef van Vuuren and Bert de Vries. The authors wish to thank the members of the IMAGE 2.2 team for their contributions to this paper. We appreciate the advice of Stefan Dekker, Monique Hoogwijk and Evert Nieuwlaar in earlier stages of this research. We further thank Leonardo Barreto, Ivo Bouwman, Arend de Groot and Joost Quakernaat for their advice on hydrogen energy systems.

1 Introduction

For at least several decades, the idea of hydrogen-based energy systems has attracted the attention of engineers and environmental scientists. Interest first surged in the early 1970s in response to the first oil crisis and the growing concerns about environmental issues (Caprioglio, 1974; Lucas, 1976; TNO, 1975). The perceived advantages at that time were its nearly zero emissions (improving air quality) and the possibility of local production on the basis of a variety of fuels (decreasing dependence on imported oil) (Dunn, 2001; Lovins, 2003). Interest subsided after the oil price decline in the mid-1980s but resurged in the early 2000s due to its potential role in reducing greenhouse gas emissions (see for instance initiatives from both public and private parties: Arnason and Sigfuasson, 2000; European Commission, 2003; GM, 2002; Shell, 2001; U.S. Department of Energy, 2002)).

While the contribution of hydrogen in improving urban air quality and dependence on imported oil is obvious, its role in reducing climate change is less straight forward. On the one hand, the high end-use efficiency in fuel cells and the possibility to produce hydrogen from non-fossil sources or clean fossil fuels (fossil fuel combustion in combination with carbon-capture-and-storage, CCS) – could reduce greenhouse gas emissions from the energy system (Azar et al., 2003; Barreto et al., 2003; Ogden, 1999a). On the other hand, hydrogen can also be produced from relatively cheap coal without CCS technology, which leads across the whole chain to a considerably higher *carbon/energy* ratio than today's energy technologies (Edmonds et al., 2004). In addition, the question remains whether hydrogen-based technologies will ever be cheap enough to be an effective competitor to fossil-based and non-fossil-based technologies. These contradictory arguments contribute to the uncertainty in the contribution of hydrogen to the mitigation of greenhouse gas emission.

Model-based scenario studies have been designed to assess the role of hydrogen in future energy systems and the potential consequences for future carbon emissions and climate policy. For this purpose, global energy models have been extended to also cover hydrogen-based technologies. These include, for instance, the MESSAGE (Barreto et al., 2003), MiniCam (Edmonds et al., 2004) and GET (Azar et al., 2003) models. Such scenario studies, however, have not led to a single, consistent view on potential hydrogen-based energy systems. GET and MESSAGE model runs indicate a very important role of hydrogen in reducing greenhouse gas emissions (Azar et al., 2003; Barreto et al., 2003). Other scenarios indicate a possible increase in such emissions as a result of increasing coal uses (Edmonds et al., 2004). These model results confirm the technical analysis, indicating the existence of quite diverse technological pathways. Apparently, the projected future role of hydrogen depends on specific model assumptions – or even model structure – and the type of scenario considered (e.g. baseline or mitigation).

To explore the relationship between assumptions and outcomes for hydrogen-based energy systems in global energy models in more detail, we have performed a series of model experiments in the TIMER 2.0 model. In these experiments, we specifically look into the question which uncertainties influence the potential role of hydrogen in future energy

systems and to what extent, and how the potential role of hydrogen is related to climate policy.

This article describes the results of this analysis. We first summarise the results of a literature survey on assumptions for production technologies, infrastructure development and different end-use functions and related technologies. Values found in literature have been translated into pessimistic, intermediate and optimistic scenarios for hydrogen technology development. These three sets of assumptions are used as input for model experiments and scenario construction with the TIMER 2.0 model, using the TIMER B2 baseline scenario as reference (see *Section 3.2*). Model runs are presented for 6 different cases: the baseline and a climate mitigation scenario, each in combination with the 3 hydrogen variants mentioned above. This set allows us to explore most of the potential H_2-scenarios which seem to matter on the basis of present-day insights.

2 The future of hydrogen: what does scientific literature say?

2.1 Ranges of assumptions in literature as basis for scenarios

There is a vast literature on the future possibilities of hydrogen energy. Some use full-fledged energy models, others are based on partial analyses or expert views. Focus, method and results show significant differences. Several scenario studies looking specifically into the role of hydrogen project a major role for this energy carrier in future energy systems – although timing and intensity of introduction differ significantly (Table 7.1 for a subset of these scenarios). But other scenario studies, the short-term energy projections of the IEA among them, hardly pay attention to hydrogen (International Energy Agency, 2004). As with several other aspects of future energy systems, there is a lively debate on pro's and con's of hydrogen based energy systems (Clark II and Rifkin, 2006; Hammerschlag and Mazza, 2005; Keith and Farrel, 2003; Lovins, 2003; Morris, 2003).

As a basis for our model experiments and scenario construction, we have done a careful analysis of published long-term hydrogen studies (van Ruijven, 2003a). In the brief overview in this paper, we focus on a sub-set, for which the main characteristics are shown in Table 7.1. We discuss the assumptions and results of these studies in relation to three important issues: 1) the type of technologies used to produce hydrogen, 2) the type of technologies and applications in end-use, and 3) the technical and economic aspects of infrastructure developments.

Table 7.1: Comparison of several hydrogen studies that use long-term global energy models

	Barreto et al. (2003)	Azar et al. (2003)	Edmonds et al. (2004)
Model	MESSAGE-MACRO	GET 1.0	MiniCAM
Scenario	IPCC/SRES B1-H_2	IIASA/WEC C1[2]	IPCC/SRES B2
Climate Target		400 ppmv	550 ppmv
Time	Initiated 2000 10% market 2030	Initiated between 2030 and 2050	Initiated 2010 30% market 2060
Production	1. Small-scale SMR and off peak electrolysis 2. Large-scale SMR with CO_2-seq. -3. Biomass and solar thermal	1. Small-scale SMR 2. Large-scale SMR and Coal with CO_2-seq. 3. Solar	1. Coal / Gas / Biomass 2. CO_2-seq.
Applied in sectors	Transport Residential/Service Industry	Transport	Transport
End-use Technology	Micropower (also from vehicles) CHP from FC plants	Fuel Cells	Fuel cells and direct combustion
Infrastructure		Pipeline	Short pipelines, trucks, trunk lines

2.2 Production

Currently, hydrogen is widely used in oil refineries, produced by steam methane reforming and coal gasification. However, most hydrogen production technologies for energy purposes (so, large-scale and low-cost) are currently still in the laboratory phase, or at best in the demonstration phase. In literature, some studies include only those in the demonstration phase (Barreto et al., 2003; Ogden, 1999b), while others also include anticipated future technologies such as biophotocatalytics and photolysis (U.S. Department of Energy, 2002). While the latter category can be important on the long term, their assessment implies a quantification bordering on speculation.

Interestingly, there is convergence regarding the initial development of a hydrogen energy system. Natural gas plays an important role, almost all transition scenarios start with small-scale production of hydrogen from natural gas via steam methane reforming (SMR), possibly in combination with electrolysis during off-peak hours (Azar et al., 2003; Barreto et al., 2003; Ogden, 1999b). In the long-term, literature shows three different possible configurations of the large-scale hydrogen energy system:

1. large-scale production of hydrogen from fossil sources, mainly coal and natural gas (Barreto et al., 2003; Edmonds et al., 2004; Ogden, 1999b; Turton and Barreto, 2006);
2. a situation with climate constraints, when a fossil based hydrogen system can be combined with CO_2 capture and sequestration (CCS) (Edmonds et al., 2004); and
3. renewable hydrogen production, based on biomass gasification, direct solar thermal hydrogen production and electrolysis from solar or wind electricity (Barreto et al., 2003).

[2] This is an ''ecologically driven'' scenario which assumes that technological development leads to efficiency improvements, so that per capita energy demand in developed countries is reduced.

These configurations do not necessarily exclude each other, most studies found a succession of hydrogen production technologies, mainly first fossil based and second towards a CCS or a renewable based system.

Table 7.2: Ranges of hydrogen production technology characteristics from literature

	Barreto et al. (2003)	Azar et al. (2003)	Edmonds et al. (2004)
Model	MESSAGE-MACRO	GET 1.0	MiniCAM
Scenario	IPCC/SRES B1-H_2	IIASA/WEC C1[3]	IPCC/SRES B2
Climate Target		400 ppmv	550 ppmv
Time	Initiated 2000 10% market 2030	Initiated between 2030 and 2050	Initiated 2010 30% market 2060
Production	1. Small-scale SMR and off peak electrolysis 2. Large-scale SMR with CO_2-seq. -3. Biomass and solar thermal	1. Small-scale SMR 2. Large-scale SMR and Coal with CO_2-seq. 3. Solar	1. Coal / Gas / Biomass 2. CO_2-seq.
Applied in sectors	Transport Residential/Service Industry	Transport	Transport
End-use Technology	Micropower (also from vehicles) CHP from FC plants	Fuel Cells	Fuel cells and direct combustion
Infrastructure		Pipeline	Short pipelines, trucks, trunk lines

The costs of producing hydrogen consist largely of feedstock and investment costs. Ranges for the specific investment cost and efficiency estimates for hydrogen production technologies reported in literature for the next few decades are given in Table 7.2. Future hydrogen production costs are generally assumed to be lower than current values as a result of technology development. For small-scale SMR, costs are generally significantly higher than that of large-scale SMR but some authors expect cost declines down to the level of large-scale SMR. We developed our scenarios, which we describe later, from these literature data (*Appendix B*). We only used solar thermal hydrogen production as climate neutral backstop technology and excluded nuclear thermal.

2.3 End-use

The primary end-use technology associated with hydrogen is the fuel cell. Since fuel cells produce both heat and power, possible applications are almost infinite, and hence, literature on future hydrogen energy applications describes a wide range of possibilities. The main advantage of fuel cells is in vehicular applications, as they double the efficiency of transport compared to current internal combustion engines (ICE). Another advantage is that these fuel cells theoretically can also deliver electricity to the grid while the car is parked. This application of micropower influences the central power production and makes fuel cells more profitable (Barreto et al., 2003; Dunn, 2001). Most authors therefore project the most significant break-through of hydrogen (if any) in the future transport sector (even without electricity delivery).

[3] This is an ''ecologically driven'' scenario which assumes that technological development leads to efficiency improvements, so that per capita energy demand in developed countries is reduced.

A smaller number of authors expect the application of hydrogen energy in other economic sectors as well. The possibility of small-scale combined heat and power production is attractive for households and offices that can install their own fuel cell (Barreto et al., 2003; Lovins, 2003). Expectations for hydrogen in the industrial sector are more moderate. As many industrial applications can be served directly by electricity, hydrogen is expected only to fulfil niche-functions (Barreto et al., 2003).

So far, fuel cells are produced at a small-scale at high costs, but mass-production is expected to bring major cost reductions (Thomas et al., 1998; Tsuchiya and Kobayashi, 2004). The premature stage of fuel cell technology makes literature data somewhat speculative. As shown in Table 7.3, literature on current cost is relatively consistent, estimating fuel cell cost about 1100 – 1500 $/kW. However, estimations of future costs vary heavily, some studies project moderate cost reductions, while others foresee enormous breakthroughs with mass-production.

An aspect of fuel cells that is currently under debate is the efficiency in vehicular applications. As current ICE's have a tank-to-wheel efficiency of 15-21%, and a future expected maximum of 25% (ICE-Hybrids excluded), the theoretical efficiency of fuel cells in mobile applications is definitely higher than current technology. However, as fuel cells in cars will seldom work at maximum power, estimates of the effective fuel cell efficiency are lower. Some authors project the real efficiency to be 30-36% (van den Brink, 2003), 36-41% for an North-American driving cycle (GM, 2001) and 44-49% for an European driving cycle (GM, 2002). We used the whole range that we found in literature for the development of our scenarios (*Appendix B*).

Table 7.3: Ranges of fuel cell characteristics from literature

Technology	Current Capital Cost	Future Capital Cost	Efficiency	Source
Proton Exchange Membrane (PEM) mobile	1200 – 1500 $/kW	45 – 600 $/kW	30 – 60 %	(IEA/AFIS, 1996; Ogden, 1999b; Thomas et al., 1998)
PEM stationary	1400 $/kW		60%e/40%th	(Tillemans and de Groot, 2002)
Solid Oxide Fuel Cell (SOFC) stationary	1100 $/kW		45%e/35%th	(Tillemans and de Groot, 2002)

2.4 Infrastructure

The introduction of hydrogen in an energy system requires substantial changes in infrastructure. Although hydrogen is currently produced and transported on a small-scale for industrial purposes, large investments are needed to develop a complete infrastructure for energy applications. Most publications agree that this is the main barrier for the development of a hydrogen economy, and generally, transition studies and government route maps foresee a first period of small-scale hydrogen use in niche markets, without a need for distribution networks. From these small-scale experiments and pilot projects, the application and demand for hydrogen can increase, reaching a stage in which large-scale production becomes affordable (Azar et al., 2003; European Commission, 2003; Ogden, 1999b; U.S. Department of Energy, 2002). As shown in Table 7.1, the attention paid to

infrastructure development varies widely between long-term studies. Some authors explicitly include several infrastructure options and their costs (Azar et al., 2003), while others only state that infrastructure is an important aspect of hydrogen energy systems (Barreto et al., 2003).

The main uncertainties in the literature on hydrogen infrastructure are costs and the form in which hydrogen is transported (gas, liquid or metal-hydrates). As hydrogen is a rather voluminous gas at normal temperature and pressure, it has to be either pressurised or liquefied. Currently, hydrogen for industrial applications is transported by trucks (liquid) or pipelines (pressurised gas). Future hydrogen energy systems can be based on both these technologies, depending on the cost development and the demand densities (Azar et al., 2003; Ogden, 1999b). In any case, the transport infrastructure costs will contribute considerably to the hydrogen price (Table 7.4). Pipelines are the cheapest way of hydrogen transport, but are only affordable in case of a high hydrogen demand density. Distribution as a liquid by truck is also relatively cheap, but then storage and liquefaction add up to the price. To deal with these uncertainties, we simulated two steps in infrastructure development in our model (*Section 3.4*) and varied the costs of transport and distribution in the scenarios (*Appendix B*).

Table 7.4: Hydrogen infrastructure costs

Technology	Cost	Source
Storage (3 days)		
Liquid	6 – 18 $/GJ	(Dutton, 2002; Ogden, 1999b)
Compressed Gas	2 – 4.5 $/GJ	(Dutton, 2002; Ogden, 1999b)
Metal Hydrides	3 – 7 $/GJ	(Dutton, 2002)
Transport		
Pipeline	0.1 – 0.5 $/GJ/100 km	(Ogden, 1999b)
Liquid Truck	0.2 – 1.5 $/GJ/100 km	(Padro and Putsche, 1999)
Gas Truck	4.9 – 29.4 $/GJ/100 km	(Padro and Putsche, 1999)
Metal Hydrides Truck	2.6 – 16.4 $/GJ/100 km	(Padro and Putsche, 1999)
Distribution		
Refuelling Station	4 – 6 $/GJ	(Ogden, 1999b)

3 Modelling Hydrogen in Timer 2.0

3.1 The TIMER 2.0 Model

We used the TIMER 2.0 model to explore the possibilities of hydrogen in future energy systems. The TIMER 2.0 model is the energy sub-model of the Integrated Model to Assess the Global Environment, IMAGE 2.2 (IMAGE-team, 2001) that describes the main aspects of global environmental change. TIMER is a system-dynamics energy model that simulates year-to-year investment decisions based on a combination of bottom-up engineering information and specific rules on investment behaviour, fuel substitution and technology. TIMER 2.0 (van Vuuren et al., 2006b) is a revised version of the TIMER 1.0 model (de Vries et al., 2001), with main differences being extension of renewable energy modelling (Hoogwijk, 2004), carbon capture and storage and hydrogen (van Ruijven, 2003b).

In the TIMER 2.0 model the demand for end-use energy is related to the economic activity in five sectors: industry, transport, residential, services and other. The demand formulation includes autonomous and price-induced changes in energy-intensity. Energy supply is based on fossil fuels (coal, oil, natural gas), biomass, solar and wind power, hydropower and nuclear power. Fossil- and biofuels can be traded among 17 world regions. The production of each primary energy carrier includes the dynamics of depletion and learning-by-doing. To this framework of sub-models we added a hydrogen model, which is connected to all primary energy supply models, the electricity model and the energy demand model.

3.2 The TIMER 2.0 B2 Scenario

The baseline scenario used here is the TIMER 2.0 B2 scenario. This scenario, based on the IPCC SRES B2 scenario, assumes a continuation of present day trends, with medium values for population and economic growth. In the implementation of the scenario, for the period 2000-2030, we have used the assumptions and results of the IEA reference scenario to roughly calibrate our scenario against (thus the same population and economic growth, and roughly similar energy use and emission trends). From 2030 onwards, population follows the UN medium scenario, while economic growth rates are based on the original B2 scenario. The global population stabilises around 2100, at 10 billion people. The global growth rate of GDP per capita starts at 2% per year and declines slowly to 1.5% after 2050. Most currently low-income regions have relatively high growth rates for GDP per capita and energy use already early in the century. The African regions form an exception – here economic growth rates above global average only occur after 2040. Primary energy use, globally, increases from 400 EJ today to 1200 EJ in 2100. In the first half of the century, natural gas use rises rapidly. However, in the second half of the century, oil and natural gas prices are relatively high (as result of depletion of low-cost resources). As a result, trends reverse: coal starts to gain market share in the electricity and industrial sector and represents 40% of all energy consumed by the end of the century. Carbon emissions increase from 6 GtC/yr today to 18 GtC/yr around 2100. Compared to most scenarios published today, these should be regarded as values slightly above the medium. In the default implementation of this scenario no penetration of H_2 as a major energy carrier is assumed.

3.3 The TIMER-H_2 model

The TIMER-H_2 model involves the production, demand, infrastructure and technology dynamics of hydrogen related technologies, as described below (Figure 7.1). In brief, hydrogen production costs are determined from capital costs, fuel costs and (if relevant) CO_2 sequestration costs. The costs of energy services from hydrogen for the end-user are the sum of these hydrogen production costs (also regarding end-use efficiency) and the end-use capital cost and infrastructure costs. The market-share of hydrogen is determined by the relative differences of the energy service costs on the basis of hydrogen and the same costs based on other energy carriers. The demand of hydrogen equals the market share times sectoral energy demand. Subsequently, hydrogen demand is met through investments into hydrogen production capital. Finally, there is a feedback loop from technological learning, as hydrogen production capital cost decline with increasing cumulative installed capacity.

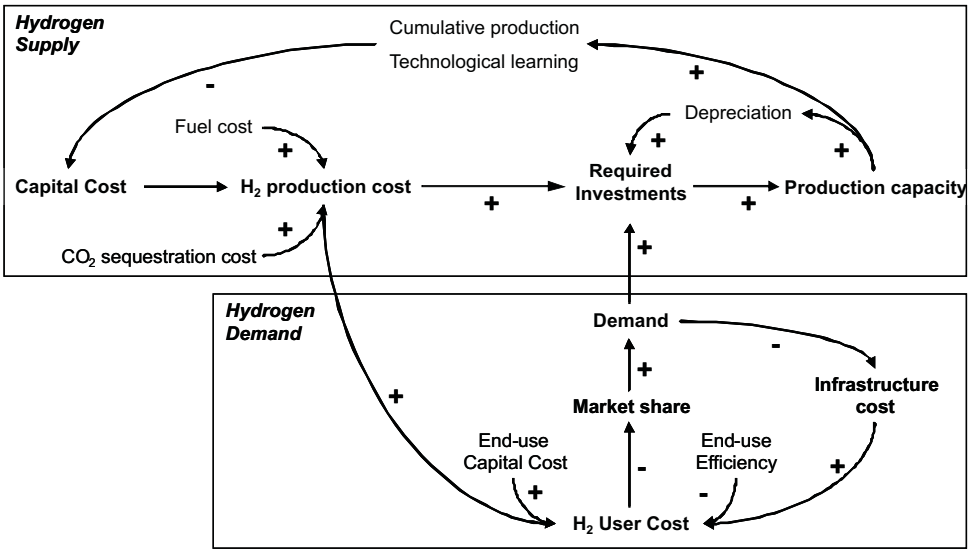

Figure 7.1: Overview of the TIMER-hydrogen model. Arrows indicate influence factors or inputs for calculation

3.3.1 Hydrogen production

In TIMER 2.0, hydrogen can be produced from coal gasification, partial oxidation of oil, steam reforming of natural gas, gasification of biomass, electrolysis and direct solar thermal production of hydrogen. For the production of hydrogen from natural gas, the model distinguishes between both large-scale and small-scale steam methane reforming (SMR). This is in order to simulate a transition period in which there is no infrastructure and (more expensive) small-scale SMR is the only available technology for stationary applications of hydrogen energy. The capacity, investments and depreciation of hydrogen production technologies are simulated by a vintage stock model, assuming a life-time of 30 years. The investment shares of hydrogen production technologies are based on the mutual cost differences, weighted in a multinomial logit formula (*Appendix A*). The costs of feedstock for hydrogen production (coal, oil, natural gas, biomass electricity and solar) and the dynamics of carbon sequestration resources and capacity are modelled elsewhere in TIMER.

For each of the technologies, technological progress is simulated by learning-by-doing curves, describing the dynamics of decreasing cost as a function of increasing cumulative production capacity (Argote and Epple, 1990; Rogner, 1998). The concept is applied to the capital cost of hydrogen production technologies. We assumed technological learning to be based on global cumulative production capacity, with variations in specific cost reduction based on openness between regions and relative contribution of a region to the global cumulative production capacity. Parameterisation of technological learning is derived from Barreto et al. (2003), with variations in scenarios. We were not able to find literature estimates of learning parameters for solar thermal and small scale SMR. For these technologies we used a hybrid-learning method: initially the costs of solar thermal and small-scale SMR decrease with a constant rate, between 0.4 and 1.5 %/yr, simulating R&D

developments in the pre-introduction period. When these technologies become competitive and production capacity is installed, endogenous technological learning takes over. Technology for carbon capture and sequestration is modelled as add-on to the base-technology, using extra capital- and O&M costs and decreasing the hydrogen production efficiency. For SMR we assumed that CO_2 is only captured from the pure process stream and not from fuel combustion (88% of total CO_2 captured). Coal gasification and POX involve only a process stream (as energy is provided within the process itself) and 95% of total CO_2 can be captured. Our assumptions, based on (Hendriks et al., 2002) are slightly more positive than the recently published overview by (Damen et al., 2006), but must be seen as 'future values'. The scenario-assumptions on hydrogen production technologies are based on literature data as shown in Table 7.2 and elaborated per scenario in Appendix B.

3.3.2 Hydrogen end-use

The total energy demand in TIMER 2.0 is based on assumptions on changes in population, economic activity and energy efficiency improvement. Based on mutual differences in useful energy costs, the market share of secondary energy carriers is allocated based on a multinomial logit formula (*Appendix A*). We defined useful energy as the energy that is available to fulfil a demanded energy service, corrected for differences in end-use efficiency between different energy carriers. Thus, hydrogen can penetrate into five end-use markets. Another option is mixing hydrogen into the natural gas grid. Without creating difficulties for the end-user (both safety and equipment adjustment), this is only possible up to a maximum level of 5% on energy basis (Hendriks et al., 2002). It can reasonably be assumed that this option is only attractive for end-use in the residential and service sectors. Similar to other end-use market allocation, the share of hydrogen in natural gas is based on relative costs via a multinomial logit with an upper constraint.

The most important assumptions on end-use are those on the cost and efficiency of fuel cells. We assume exogenous cost decline series for fuel cells. For the industry sector we assumed that Solid Oxide Fuel Cells (SOFC) will be applied (Reijnders et al., 2001; Wurster and Zittel, 1994). For other, both stationary and mobile applications we assumed Proton Exchange Membrane (PEM) fuel cells (Ogden, 1999b; Thomas et al., 1998; Tillemans and de Groot, 2002). In the transport sector we consider also variations in efficiency of PEM fuel cells, as discussed in *Section 2.3*. We only assumed differences in technology, without taking into account the non-energy cost and differences in service characteristics (e.g. a revolutionary new vehicle design with fuel cells). The assumptions for end-use parameters are based on the ranges presented in Table 7.3 and can be found in Appendix B.

Although clean fuels are sometimes exempted from energy taxes, it is assumed that on the longer run taxes on energy are needed to maintain the necessary infrastructure. Therefore, in the pessimistic and intermediate scenario we assume an energy tax to be applied to hydrogen. For the transport sector we used the regional taxes on oil, in the other sectors we used the average value of taxes on other energy carriers. These taxes are exogenous and region-, time- and scenario-dependent and based on IEA statistics. Depending on the region, they amount 1-15 $/GJ in the transport sector and 0.2-1.5 $/GJ in the other sectors.

A similar approach is applied to biofuel, often a direct alternative to hydrogen. In the optimistic scenario we assumed no taxes on hydrogen, to create an optimistic case for both technology development and policy.

3.3.3 Hydrogen distribution: the transition storyline

Transport and distribution of hydrogen is a major issue in the transition to a hydrogen energy system. In our model we distinguish two steps in the hydrogen chain: transport and distribution. We defined the transport step as the distance from large-scale plants to residential areas or refuelling stations. Therefore, transport only applied to hydrogen produced on a large-scale and includes the costs for a hydrogen transport network (e.g. pipelines or trucks). The distribution step includes the final distribution of hydrogen, e.g. the small-scale network in residential areas or the refuelling station itself. The costs of distribution are added to both large-scale and small-scale produced hydrogen (Figure 7.2).

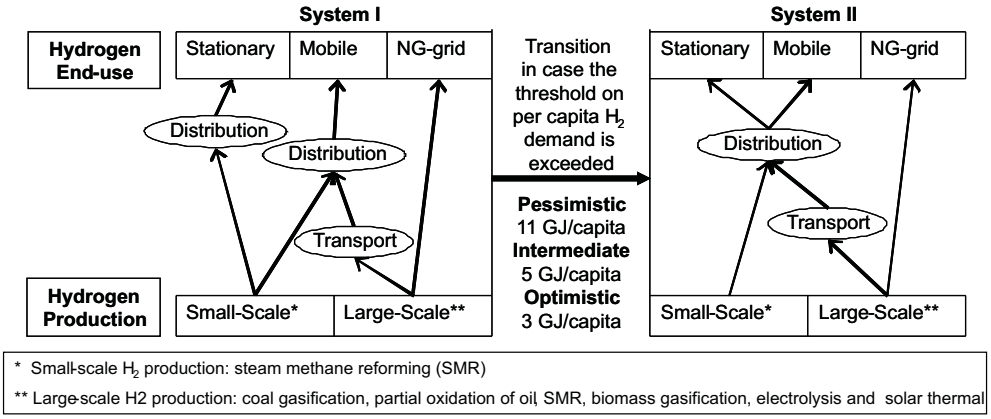

Figure 7.2: Transition in transport and distribution of hydrogen

Because the development of a hydrogen transport infrastructure is expensive, hydrogen for stationary applications will initially only be produced from small-scale steam methane reforming plants near end-use locations. It is only when hydrogen demand density rises above a certain threshold, investments in large-scale infrastructure (pipelines) will be made and stationary applications can be served by both small-scale and large-scale hydrogen plants. We assume that hydrogen demand per capita is a proxy for demand density and use, based on data from Ogden (1999b) and Thomas et al. (1998), a threshold of 3 (optimistic) to 11 (pessimistic) GJ/cap. For the transport sector we assume that hydrogen can initially be produced at all scales, since demand is dispersed and can be provided by truck. Hydrogen mixed into the natural gas grid is assumed to be produced only from large-scale production facilities. This transition at above a certain threshold value is shown in Figure 7.2.

The transport and distribution costs for hydrogen are likely to change in time. We have linked these cost to the hydrogen demand per capita as well, since a higher hydrogen demand density leads to shorter transport distances and the transport technology will become cheaper when it is widely applied. Several options for transport of hydrogen were

analysed. Based on a spatial analysis by Mintz et al. (2002) and the ranges presented in Table 7.4, transport costs in the pessimistic scenario decline from 12 to 6 $/GJ, in the intermediate scenario from 10 to 3 $/GJ and in the optimistic scenario from 10 to 2 $/GJ.

3.4 The TIMER-H_2 Scenario Set

We used values found in literature into pessimistic, intermediate and optimistic scenarios for hydrogen technology development. In the pessimistic set of assumptions, we describe a world in which no major hydrogen-related breakthroughs are established and transitional dilemma's, like the chicken-egg problem with demand, supply and infrastructure development, are not solved. Technologies and costs continue to improve slowly between now and 2100 towards the lower range of technology parameters found in literature (Table 7.2-7.4 and Appendix B). In the intermediate scenario, some promising improvements in technology are made, but after a while new boundaries are met. In particular, in the first decades of the scenario fuel cells rapidly become cheaper. However, after this initial break-through, further progress slows down. In the production phase, no major new costs reduction are achieved – and partly because the major development of fuel cell markets does not occur - production capacity stays limited and hydrogen production technology does not learn as much as was hoped for. Some hydrogen distribution infrastructure is developed for the transport sector, but apart from few niche markets transition is costly. In this scenario, technologies improve to the lower range of technology estimates by 2050 but improve more slowly in the second half of the century towards more intermediate values. Finally, in the third optimistic scenario, breakthroughs in hydrogen technology are realised and transitional issues are vigorously solved. Fuel cells are mass-produced at low cost, hydrogen production technology becomes cheaper and better through learning and distribution infrastructure is developed rapidly at low costs. In this scenario, technologies are assumed to improve rapidly to reach an intermediate range by 2030 and the most optimistic values in literature in 2100. We assumed these technology improvements as an exogenous process, and did not take into account any related costs, for instance R&D investments. It should be noted that we vary assumptions on the hydrogen technology itself and that developments in other technologies (e.g. batteries, hybrid-vehicles) are assumed similar in all scenarios.

These three sets of assumptions are combined with the TIMER 2.0 B2 scenario, as described in *Section 3.2*. One additional dimension is added: the existence of climate policy. All scenarios were run in a default case without climate policy and under the constraint that greenhouse gas concentrations will be stabilised at 450 ppmv CO_2-equivalent. While different emission profiles exists to go to 450 ppmv CO_2-equivalent, we have used an emission path from the FAIR model (den Elzen and Lucas, 2005), as described in van Vuuren et al. (2007). This profile can be interpreted as median scenario in timing, without major overshoot. Recently published studies on the probability distribution of climate sensitivity suggest that such low stabilisation levels are required in order to have a reasonable chance of reducing global mean temperature change to 2 degrees above pre-industrial levels (den Elzen and Meinshausen, 2005). For this study, this ambitious stabilisation target (compared to most literature published on mitigation scenarios) is chosen to have a clear signal from climate policy on the development of the energy system.

One additional scenario is run in case of climate policy to explore specifically the role of excluding CCS in the optimistic hydrogen scenario (as CCS technology costs and acceptance are also uncertain). This implies that the model is run for 9 different cases. First of all, the B2 baseline and the three hydrogen variants without climate policy: the H_2 Pessimistic case (*NoCP Pes*), intermediate case (*NoCP Int*) and optimistic case (*NoCP Opt*). As we found that under the *NoCP Pes* scenario no penetration of hydrogen occurs, this scenario is actually equal to the baseline (and is thus used for this purpose throughout the paper). The second scenario set is identical but now with a climate policy constraining the CO_2-equivalent concentration to 450 ppmv by 2100: *Cp Pes*, *CP Int* and *CP Opt*. The last case is the one without the possibility of carbon capture and sequestration (*CP Opt NoCCS*).

4 Results

4.1 Scenarios without climate policy (NoCP)

4.1.1 Hydrogen Production

Figure 7.3 shows the costs of the various options to produce hydrogen in OECD Europe in the three scenarios without climate policy. In principle, for all options there is a downward pressure on costs as a result of learning-by-doing. In terms of the differences between the intermediate and optimistic scenario, a higher progress ratio and lower starting values for investment costs under the optimistic scenario contribute to making hydrogen production more competitive than under the intermediate scenario. This in turn leads to more investments, driving technologies further down the learning curve. By the end of the century the observed cost differences are for more than half caused by the differences in cumulative capacity; the costs differences as a result of different progress ratios play a smaller role. In addition to the decrease of capital costs from learning effects, total production costs may increase as feedstock costs (in particular oil and natural gas) are expected to increase over the century.

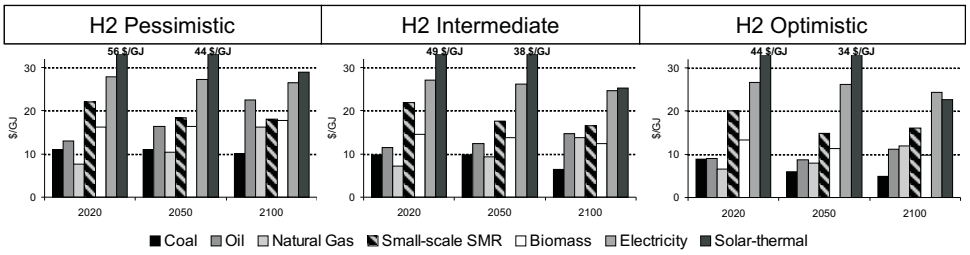

Figure 7.3: Hydrogen production cost before transport and distribution and before tax, for several technologies in OECD Europe and without climate policy

Figure 7.3 shows that hydrogen production from coal and natural gas is for most of the century the cheapest option. Initially hydrogen can be produced from large-scale SMR at about 5-10 $/GJ. These costs remain more-or-less constant in the first 50 years, as a result of decreasing investment costs on the one hand and increasing natural gas prices on the

other. The latter effect dominates by the end of the century, raising production costs to over 10 $/GJ in all scenarios. This means that in the second half of the century, hydrogen production from coal is the cheapest technology, at costs declining to about 5 $/GJ in the optimistic scenario. The small-scale methane reform option has relatively high production costs as a result of unfavourable economies of scale and lower efficiency. Nevertheless, this option may well be cost-effective in the residential/services sector where the hydrogen can be produced at the demand site without additional transport costs. The options to produce hydrogen from oil, electricity and solar-thermal are hardly competitive in any to the scenarios without climate policy. Hydrogen produced from biomass is among the low costs options in the second half of the century in the intermediate and optimistic case.

Hydrogen production is shown in Figure 7.4 (upper graphs). Hydrogen starts to be produced in the second half of the century – where under some of the scenarios hydrogen becomes competitive (see further in this section). In the pessimistic case, hydrogen remains too expensive – and thus there is no consumption. The production shares shown in Figure 7.4 do obviously directly reflect the costs shown in Figure 7.3. The hydrogen production in the scenarios is almost exclusively based on coal and natural gas.

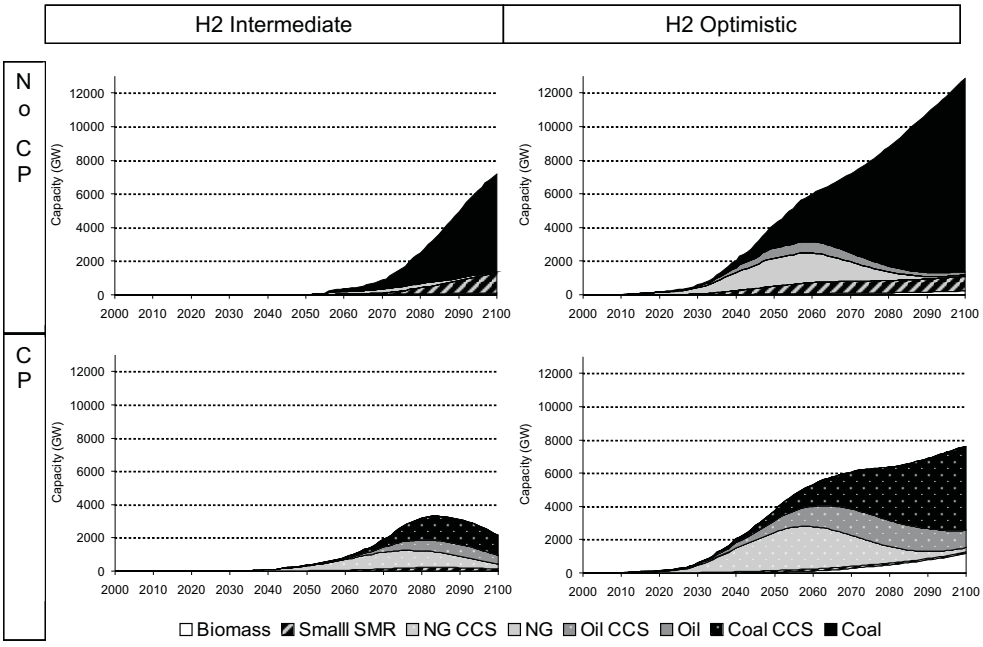

Figure 7.4: World hydrogen production capacity for the intermediate and optimistic hydrogen scenarios with and without climate policy (CP). With pessimistic assumptions on hydrogen technology and cost, no penetration occurs

Of course, hydrogen production cost and hence market prices differ across regions due to differences in coal and gas production costs, technology level and trade opportunities. In the Middle East and the Former Soviet Union (FSU), abundant natural gas resources lead to

relatively low costs for natural gas-based routes even in the longer term. Regions with large coal resources and less natural gas, in particular East Asia, South Asia and Southern Africa, have the coal-based route as the cheapest hydrogen production technology already at the beginning of the century.

Interregional fuel trade is possible in the TIMER-model if there is a large enough price differential (van Vuuren et al., 2006b). Yet, in none of our scenarios significant amounts of hydrogen are traded between regions. This result is also found by Baretto et al. (2003) and is due to the high costs of hydrogen transport over long distances – in our model simulations 80% higher than of natural gas transport (Ogden, 1999b). Besides, a region needs a large-scale hydrogen infrastructure before it can start importing or exporting. However, hydrogen trade causes a significant increase in international coal-trade compared to the baseline scenario, in particular towards OECD Europe, South East Asia and South America.

4.1.2 Hydrogen end-use

The price of hydrogen for end-users varies per region and sector, due to differences in production technologies, transport and distribution cost and different energy taxes. Figure 7.5 shows a breakdown of the hydrogen price in the transport sector of OECD Europe. In our results, transport is the first sector where hydrogen penetrates the market. The figure shows that production costs represent about 50% of all end-use costs (excluding taxes). The other half is formed by transport and distribution cost (again excluding taxes). The figure also shows that end-use taxes could represent a major share of end use prices. Globally compared, energy taxes are highest in the transport sector of OECD Europe, which causes a significant difference between the intermediate (tax equal to oil) and optimistic (no tax) scenarios. In all other regions and sectors these differences are much smaller. We found that, although the energy tax has a significant impact on the hydrogen cost, it does not influence the penetration of hydrogen in the Pessimistic scenario.

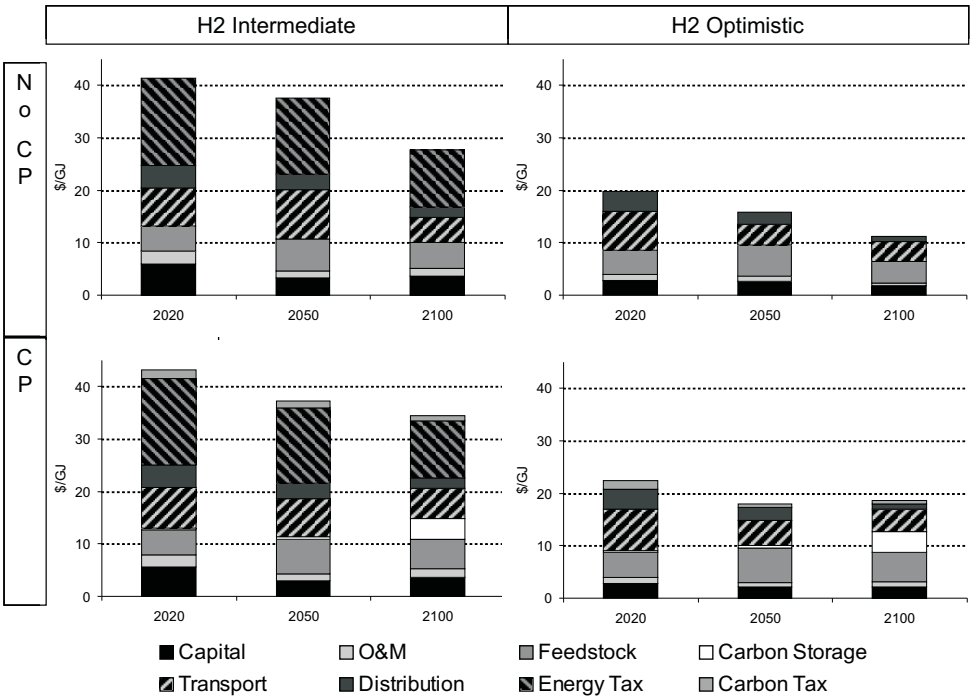

Figure 7.5: Breakdown of hydrogen cost for end-use in the transport sector of OECD Europe in the intermediate and optimistic hydrogen scenarios with (upper) and without (lower) climate policy (CP). With pessimistic assumptions on hydrogen technology and cost, no penetration occurs.

The direct alternative of hydrogen in the transport sector, oil, has an end-use price of about 15 $/GJ in the OECD European transport sector. However, because hydrogen is more efficiently applied in fuel cells, the useful energy price of hydrogen is in the *NoCP Int* scenario 30% higher than oil in 2020, about equal in 2050 and 30% lower in 2100. In the *NoCP Opt* scenario, useful energy cost hydrogen in the transport sector of OECD Europe are 30% lower than oil in 2020 and 80% in 2100.

Thus, with our assumptions, hydrogen is in the *NoCP Int* scenario only competitive in the transport sector, although some hydrogen is also mixed into the natural gas grid and thus indirectly delivered to the residential and service sector (Figure 7.6 upper left). In the residential and service sector, hydrogen cannot compete in the combined heat-and-power (CHP)/fuel cell application with natural gas and electricity. In the *NoCP Opt* scenario, hydrogen technology improves so much that it penetrates not only the transport but also the residential and service sector markets (Figure 7.6 upper right). Large-scale use for transport takes off around 2015 and is completed at the end of the century. In the built environment hydrogen becomes globally a major final end-use carrier by the end of the century, providing 45% of the residential and 35% of the services sector – although electricity (24% and 57% resp.) and natural gas (7% and 4% resp.) keep a significant market share as well.

Even now, however, there is no large-scale penetration of hydrogen in the industry sector as it can still not compete with coal, biomass and to some degree oil in this market.

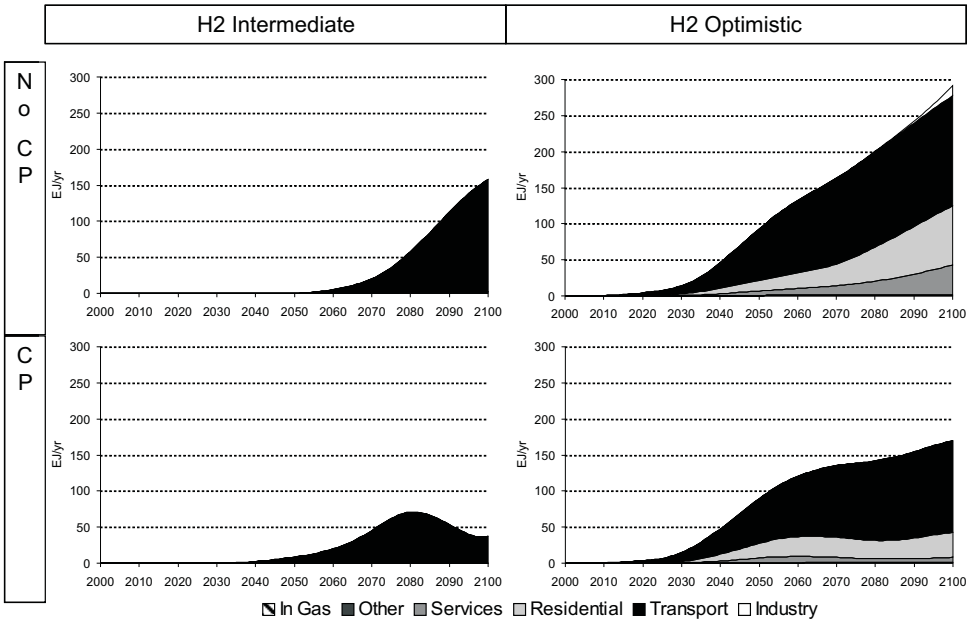

Figure 7.6: World hydrogen end-use for the 5 sectors in the intermediate and optimistic hydrogen scenarios with (upper) and without (lower) climate policy (CP). With pessimistic assumptions on hydrogen technology and cost, no penetration occurs.

A closer look at the results indicates that OECD Europe, Eastern Europe and Japan are the first regions where hydrogen is introduced in all scenarios with hydrogen penetration. This early introduction of hydrogen can be explained from higher energy prices and taxes in these regions, which are not levied on hydrogen in the *NoCP Opt* scenario and are thus an implicit subsidy for hydrogen. At the end of the 21st century the worldwide penetration of hydrogen into final energy consumption is about 40% in the optimistic scenario, with 50-60% in Canada, OECD Europe and Japan and less than 35% in Africa and South Asia. Because hydrogen has in the intermediate scenario a higher price and thus is less competitive viz-à-viz other options which are introduced in response to rising oil and gas prices, penetration is significantly less: worldwide 20% in 2100, with 25-30% in Canada, USA, OECD Europe and Oceania and less than 15% in Africa.

4.1.3 Primary Energy Use

The simulation experiments suggest that the introduction of hydrogen can have important strategic and environmental consequences for the world energy system. It can reduce local emission as it is a clean fuel, in particular urban pollution from transport. It may also shift energy trade patterns as it can substitute for oil while being produced from coal or natural gas. However, the resulting primary energy use may for this very reason worsen the problem of climate change. As Figure 7.7 shows, coal use is in the *NoCP* scenarios with

hydrogen significantly higher than in the baseline scenario (*upper middle and right vs. upper left graph*). It also accelerates the use of natural gas, causing a more rapid depletion and subsequent decline in use of this relatively low-carbon fuel. Hydrogen thus brings a new golden era for coal: by 2100 coal satisfies 60% of world energy demand.

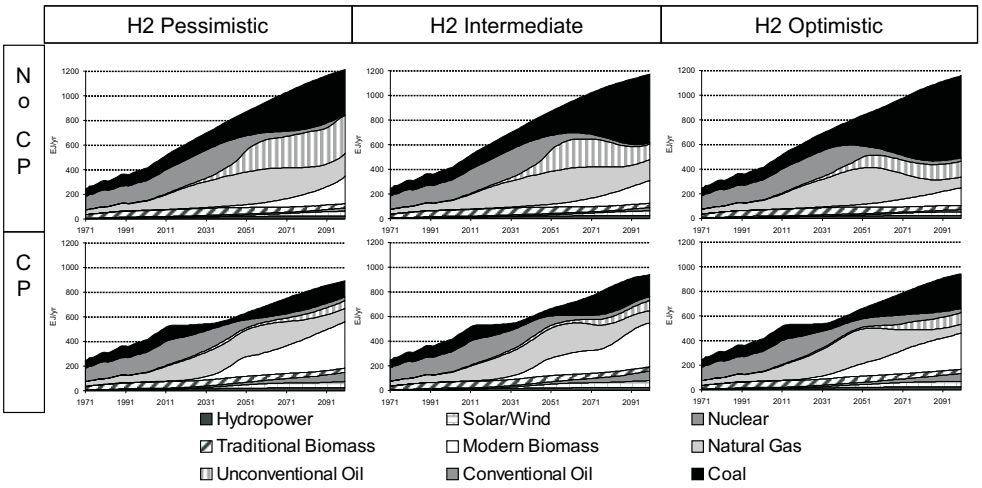

Figure 7.7: World primary energy use in all hydrogen scenarios with (upper) and without (lower) climate policy (CP). With pessimistic assumptions on hydrogen technology and cost, no penetration occurs.

What are the consequences of such a scenario? First, it presumes that such vast amounts of coal – in the order of 28 billion ton per year, half of which for hydrogen – can be produced and processed. In the model, this production mainly occurs in the USA and East Asia. Obviously, coal mining and transport at this scale will cause huge mass flows with environmental consequences. Second, it has consequences for CO_2 emissions. In fact, until 2080 the differences in carbon emission between the pessimistic (no H_2), intermediate and optimistic case are small because both coal and natural gas use increase at the expense of oil (Figure 7.8, coal with a higher carbon content and gas with a lower carbon content). However, in the scenario without hydrogen penetration emissions start to decline after 2080 as a result of the growth of non-carbon options such as nuclear, wind/solar, biomass. Interestingly, a successful hydrogen penetration implies, without climate policy, that as a result of increased coal use, carbon emissions keep growing in the last part of the 21st century. Thus CO_2 emissions of the intermediate and optimistic scenarios are respectively 6% and 15% higher than the baseline scenario.

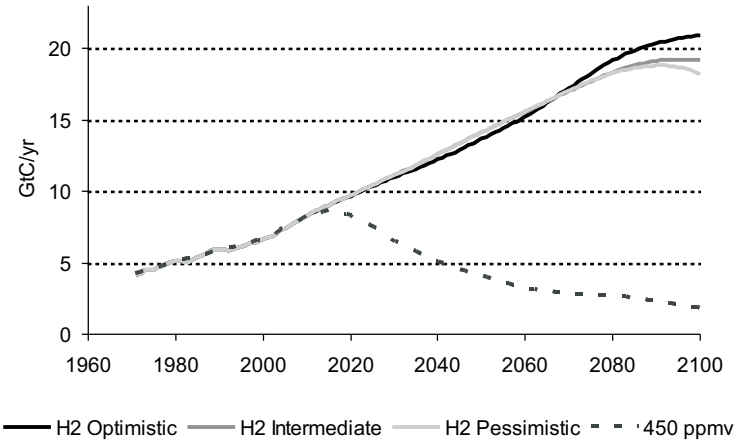

Figure 7.8: Global CO_2 emission from all hydrogen scenarios without climate policy. With pessimistic assumptions on hydrogen technology and cost, no penetration occurs

4.2 Scenarios with climate policy (CP)

To explore the relationship between hydrogen-based energy systems and climate policy in more detail, we have simulated three additional scenarios in which the CO_2-equivalent concentration is stabilised at 450 ppmv by the end of the century. This is an ambitious goal and it requires the introduction of a rapidly increasing carbon tax. The carbon tax serves in the TIMER model simulations as a generic way to stimulate all kinds of measures to reduce carbon emissions – all elements of more detailed climate policy formulations, such as increasing energy efficiency, stimulating renewable and nuclear energy options and the introduction of carbon capture and sequestration (CCS) (van Vuuren and de Vries, 2001).

One of the most striking results is that less hydrogen is used in the scenarios with climate policy. This can be explained from two dynamics: first, due to energy savings the total demand for energy is lower with climate policy (see e.g. Figure 7.7) and second, hydrogen now competes directly with biofuels. As the costs of hydrogen rise with climate policy, because of CCS technology and rest-emissions, the costs of biofuel stay the same. In the *CP Int* scenario, the share of biofuel in the transport sector decreases at the expense of hydrogen. In the *CP Opt* scenario hydrogen is pushed aside by biofuels in the built environment, as it stays the main energy carrier in the transport sector.

Figure 7.9 shows the carbon tax (or carbon-price) profiles which are required to force the carbon emissions along a 450 CO_2-equivalent concentration profile. Our results show that hydrogen introduction can actually play an important role in climate policy (as suggested by the large differences between scenarios). The reason is that once the energy system (and in particular the transport sector) has hydrogen penetration, the additional costs to produce hydrogen from fossil fuels with CCS are limited compared to hydrogen production without

CCS. Without hydrogen, reducing CO_2 emissions to very low levels is complicated by the high-costs reductions in the transport sector.

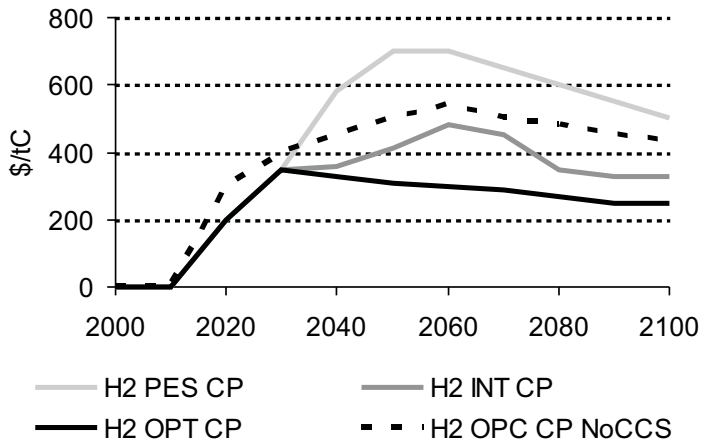

Figure 7.9: Global carbon price in the hydrogen scenarios with climate policy. With pessimistic assumptions on hydrogen technology and cost, no penetration occurs

In the *CP Int* scenario, hydrogen is produced from fossil fuel CCS technologies. Hydrogen costs in end-use remain competitive and the world can by the end of the century use twice as much coal as at present despite the climate constraint (Figure 7.7 lower middle graph). This leads to the significantly lower carbon tax (Figure 7.9) which is also reflected in the low additional costs of climate policy in hydrogen end-use prices (Figure 7.5, lower graphs). The favourite hydrogen-based carbon emission reduction options are first gas- and then coal-conversion with CCS (Figure 7.4 lower left graph). It the CP Opt scenario the hydrogen-coal-CCS chain is being introduced at an exceedingly large scale. Primary energy use is for some 30% based on coal (Figure 7.7 lower right graph) which is converted to hydrogen while capturing and storing in the order of 4.5 billion ton of carbon per year. The hydrogen is used for over 75% in the transport sector (Figure 7.6 lower right graph). This can be induced by a rather modest carbon tax, as is seen from Figure 7.9. The way to use hydrogen while at the same time reducing carbon emissions is the large-scale conversion of natural gas into hydrogen with CCS, starting already around 2020, and gradually switching feedstock from gas to oil and from 2050 onwards to coal (Figure 7.4 lower right graph).

Evidently, this expansion of the hydrogen economy hinges on the availability of carbon capture and sequestration (CCS) options at the presumed declining cost levels used in this simulation. It also presumes that the associated risks are acceptable in those regions where it will occur at the largest scale: USA, East Asia, OECD Europe and South Asia. As CCS plays such a dominant role in our results, while the technology itself still needs to be tested at large scale, we have also simulated a scenario in which CCS is assumed to not available. As one would expect, there is now a rapid growth in the use of non-carbon options for

electric power generation such as nuclear and wind/solar (Figure 7.10 right graph). At the same time the use of hydrogen-from-biomass in the transport sector increases rapidly because the cost-effective options of hydrogen from fossil fuels with CCS is no longer available (Figure 7.10 left graph). Hydrogen production from fossil energy carriers becomes much less attractive. Only hydrogen from natural gas is competitive in some markets and starts even much earlier now, around 2020, than in the other scenarios. Later on, also the SMR-option becomes interesting because its disadvantage with regard to CCS, namely that a costly CO_2 distribution network is required, does not matter anymore. As a result, world hydrogen demand is lower than in the other optimistic scenario variants and world coal use nearly vanishes.

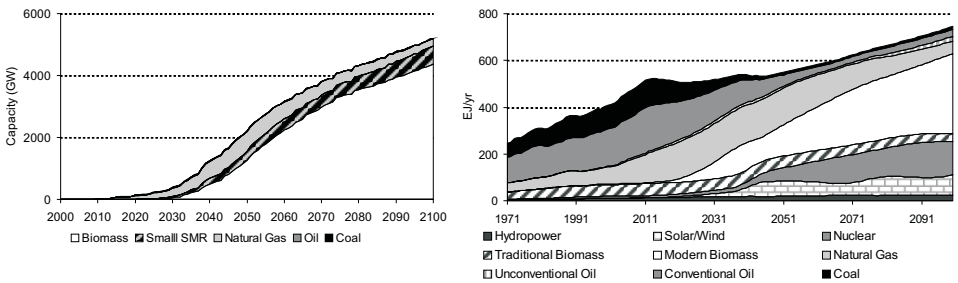

Figure 7.10: Overview of the optimistic hydrogen scenario with climate policy and without CCS: global hydrogen production capacity (left) and global primary energy use (right).

4.3 Impact of hydrogen on future energy systems

4.3.1 Carbon Intensity

The results in the previous section show that the environmental consequences of hydrogen use for carbon emissions are ambivalent. Without climate policy, carbon emissions are likely to increase with hydrogen use but at the same time it creates relatively cheap carbon mitigation options. Figure 7.11 compares the influence of hydrogen on carbon intensity of primary and secondary energy flows. Without climate policy, the primary carbon intensity increases with hydrogen use, as coal is substituting oil and natural gas. Secondary energy carbon intensity decreases with hydrogen use as hydrogen, with zero carbon content, substitutes for oil. With climate policy, primary energy intensity is similar for all scenarios, because carbon emissions are constrained to a 450 ppmv stabilisation scenario. Secondary energy carbon intensity still decreases by the use of hydrogen.

This finding is in contrast with Barreto et al. (2003), who developed a sustainable hydrogen scenario with a strongly decreasing primary carbon intensity, due to production of hydrogen from solar thermal and natural gas. However, it is in agreement with the scenarios described in Edmonds et al. (2004), who also found that coal is an attractive hydrogen feedstock without climate policy.

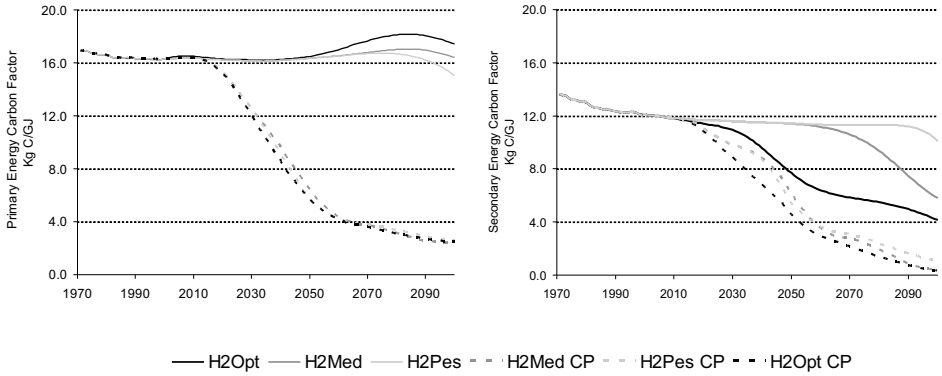

Figure 7.11: Global primary energy carbon factor (left) and secondary energy carbon factor (right) for all hydrogen scenarios with and without climate policy

4.3.2 Configuration of the future hydrogen energy system

In section 2.2 we described three main configurations with respect to future hydrogen production that can be identified from the literature: large-scale production of hydrogen from fossil sources, mainly coal and natural gas; a fossil-based hydrogen system with CCS; and renewable hydrogen production, based on biomass gasification, direct solar thermal hydrogen production and electrolysis from solar or wind electricity. Using the optimistic scenario, we were able to simulate three variants of these configurations. The variant without climate policy produces hydrogen from coal; the variant with climate policy produces hydrogen from coal with CCS or, if CCS is not available, from biomass and natural gas. We then analysed the total system costs, defined as the annuitized total capital costs in the energy system relative to the baseline scenario. The results are plotted against the penetration of non-carbon options in primary energy (Figure 7.12 left part) and hydrogen in secondary energy (Figure 7.12 right part).

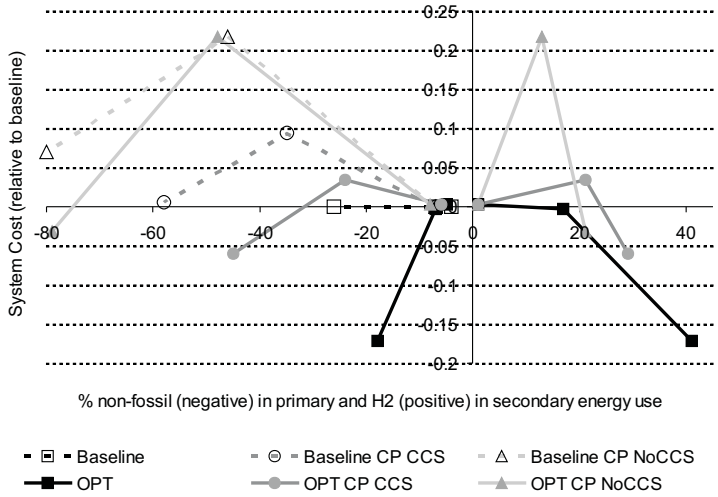

Figure 7.12: Comparison of different hydrogen energy system configurations (world) on costs, hydrogen penetration of secondary energy and contribution of non-fossil energy sources in primary energy, for 2020, 2050 and 2100.

Without climate policy, the line coincident with the x-axis represents the baseline scenario, which has about 30% contribution from non-fossil sources (wind, solar, nuclear, modern biomass) by 2100 and no hydrogen penetration. With optimistic assumptions (*NoCP OPT*), hydrogen could penetrate the global secondary energy market up to 40% by 2100, at 17% lower over-all energy system costs and almost halving the contribution of non-fossil sources. With a climate constraint, the baseline scenario (Baseline CP CCS) shows an increased contribution from non-fossil sources, to almost 60% by 2100 and an increase of costs compared to the baseline without climate policy. In this case, the introduction of hydrogen again decreases the share of non-fossil energy sources and lowers the over-all energy system costs with 8% by 2100. Evidently, if the carbon capture and sequestration (CCS) option is not available for whatever reason, the market penetration of non-fossil sources increases further and energy system costs increase significantly for the baseline scenario (Baseline CP NoCCS). However, combined with optimistic hydrogen assumptions (*OPT CP NoCCS*), the share of non-fossil energy sources is not influenced and costs decrease below the non-climate baseline scenario by 2100.

5 Comparison with other studies

As has been emphasised throughout this paper, there are many uncertainties in any assessment of the prospects of hydrogen as an energy carrier. Some of these have been addressed by using a range (optimistic-intermediate-pessimistic); others are dealt with in the form of scenarios. A third way is to compare our results with studies done by others – although one cannot exclude collective bias. We chose the fraction of hydrogen in secondary energy markets over time and worldwide as the indicator for comparison (Figure

7.13). Included are only scenarios which expect any role at all for hydrogen, which in itself is a biased representation. Nevertheless, some lessons can be drawn. .

The fraction of secondary energy used in the form of hydrogen is in our optimistic scenario higher than in the scenarios by Edmonds et al. (2004) and Azar et al. (2003), but still lower than in the one by Barreto et al. (2003). If we relax the optimistic assumptions on hydrogen costs, our simulated pathway drops even below the scenarios of Edmonds et al. (2004) and Azar et al. (2003).

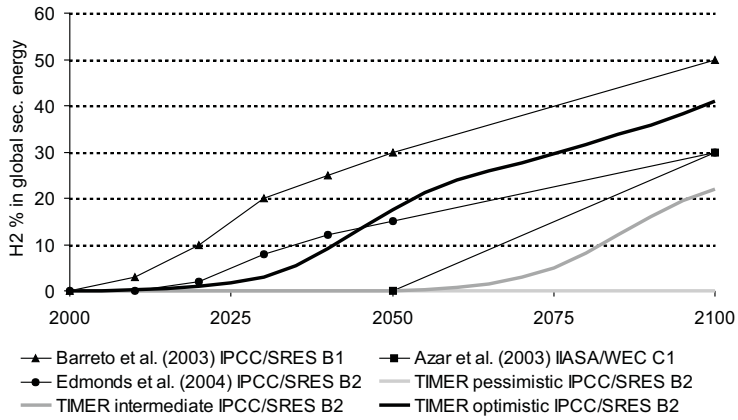

Figure 7.13: Comparison of hydrogen use in several long-term studies. Studies focusing only on the transport sector are included under the assumption that this sector counts for 30% of the total secondary energy use

A more detailed comparison with the study by Edmonds et al. (2004) suggests several similarities. Although in TIMER the hydrogen energy system initially develops slower than in the MiniCAM model, both indicate coal gasification as the main hydrogen production technology - and both therefore calculate an increase in CO_2 emissions and point at the enhanced potential role of CCS as the main consequence of hydrogen in mitigation scenarios. The study by Barreto et al. (2003) is much more optimistic on the future role of hydrogen in the global energy system. This may be a consequence of the assumed high environmental awareness in the B1-H_2 scenario that they developed. Another difference is the application of micropower CHP systems from mobile fuel cells, an option not included in our simulations. A comparison with Azar et al (2000) is more difficult, as their model simulates the transport sector only. Yet, their results for the transport sector are similar to those in our optimistic scenario and project a major shift from oil to hydrogen in the second half of the century.

6 Conclusion

In this analysis we present results of model-based explorations to the role of hydrogen in future energy systems under various assumptions on technology development and climate policy. Contrary to existing literature, we included a wide range of uncertainties in our

scenarios, resulting in a broader overall context that explains existing studies from a different perspective. The results lead us to the following conclusions.

Hydrogen will probably not play an important role before mid-21st century in the world energy system, neither with nor without a climate policy. Thereafter it can become a major secondary energy carrier but only under optimistic assumptions. The transport sector is the key market; even under less optimistic assumptions hydrogen might play a role here. Air pollution from combustion of fossil fuels might be an additional motivation to use hydrogen in the transport sector. The best prospects are in OECD Europe and Japan, where energy prices are relatively high due to high taxes and low indigenous resources. The build-up of a large-scale hydrogen infrastructure, in particular for transport, plays a crucial role.

Coal- and natural-gas-based technologies seem to be economically most attractive for hydrogen production, with and without climate policy. In particular coal gasification and steam methane reforming are cost-competitive. Partial oxidation of oil, biomass gasification, electrolysis and solar thermal hydrogen production are more expensive and play consequently a minor role. Under carbon constraints, the fossil-fuel-based hydrogen production technologies are still the most attractive combined with carbon capture and sequestration (CCS); if CCS is not available, the preferred hydrogen path shifts towards biomass and natural gas.

Three typical configurations in future hydrogen production can be distinguished in different scenarios. We reproduced the three typical configurations also found in the literature and found them related to assumptions on climate policy and technology availability. Without climate policy, we found large-scale hydrogen production from fossil sources (like Edmonds et al., 2004); with climate policy, we found large-scale hydrogen production from fossil sources with CCS (like Edmonds et al., 2004); in case of climate policy but with CCS not available, we found the development of a renewable energy based hydrogen production system (like Barreto et al., 2003).

Without climate policy, CO_2 emissions from energy systems with hydrogen are likely to be higher than those of systems without hydrogen. The reason for this result is that hydrogen is produced at the lowest cost from coal – hence, coal will be a substitute for oil in the primary energy supply and deliver hydrogen as a secondary energy carrier, particularly for the transport sector.

Energy systems with hydrogen respond more flexibly and at lower marginal abatement cost to climate policy. The reason for this is related to the previous conclusion: the use of hydrogen provides new and presumably cheap carbon emission reduction options in the form of centralised CCS.

Appendix 1: Key characteristics of the TIMER 2.0 model

The formula that allocates the market share among energy carriers in the sub-models of TIMER 2.0 is the *multinomial logit model*:

$$IMS_i = \frac{e^{-\lambda C_i}}{\sum e^{-\lambda C_i}} \qquad 23$$

IMS_i is the indicated share of total investments for energy carrier i, λ is the so-called logit parameter that determines the sensitivity of markets to price changes and C_i is the cost of energy carrier i. The latter may include other factors than the price of the energy carrier, such as premium factors and cost increases due to carbon taxes. In this analysis we used no premium factors on hydrogen. It should be noted that the multinomial logit is used to determine shares in new investment, which implies that the actual market shares respond much slower.

The concept of *learning-by-doing* describes the dynamics of decreasing cost with increasing cumulative production. The measure for technological learning is the progress ratio (PR), which is derived from the experience curve. This curve is generally described as:

$$y = y_0 * C^{-\pi} \qquad 24$$

In this equation y is the unit cost as a function of the output, y_0 is the cost of the first unit produced, C is the cumulative production over time and π is the learning coefficient. The factor 2^{π} is called the progress ratio (PR), which is mostly used to indicate the learning capacities of a technology (Harmon, 2000).

Appendix 2: Key assumptions for the hydrogen scenarios

Table A 6: Scenario assumptions on hydrogen production efficiency

	Coal gasification	*Oil (POX)*	*Gas (SMR)*	*Biomass gasification*	*Electrolysis*	*Solar thermal*	*Small-Scale SMR*
	Pessimistic						
2005-2100	*60%*	*50%*	*75%*	*50%*	*75%*	*N/A*	*75%*
	Intermediate						
2005	*60%*	*50%*	*75%*	*50%*	*80%*	*N/A*	*75%*
2050	*62.5%*	*70%*	*82%*	*62.5%*	*82%*	*N/A*	*82%*
2100	*65%*	*75%*	*85%*	*65%*	*85%*	*N/A*	*85%*
	Optimistic						
2005	*60%*	*70%*	*75%*	*50%*	*80%*	*N/A*	*75%*
2030	*62.5%*	*72.5%*	*82.5%*	*62.5%*	*82%*	*N/A*	*82%*
2100	*67.5%*	*77.5%*	*87.5%*	*67.5%*	*85%*	*N/A*	*85%*

Table A 7: Scenario assumptions for hydrogen production investment cost parameters

Variable	*Coal gasification*	*Oil (POX)*	*Gas (SMR)*	*Biomass gasification*	*Electrolysis*	*Solar thermal*	*Small-Scale SMR*
	Pessimistic						
Initial Inv. cost	*1150 $/kW*	*700 $/kW*	*400 $/kW*	*1150 $/kW*	*575 $/kW*	*2875 $/kW*	*3000 $/kW*
PR	*0.88*	*0.88*	*0.88*	*0.88*	*0.88*	*0.88*	*0.88*
	Intermediate						
Initial Inv. cost	*1000 $/kW*	*600 $/kW*	*350 $/kW*	*1000 $/kW*	*500 $/kW*	*2500 $/kW*	*3000 $/kW*
PR	*0.84*	*0.84*	*0.84*	*0.84*	*0.84*	*0.84*	*0.84*
	Optimistic						
Initial Inv. cost	*900 $/kW*	*550 $/kW*	*300 $/kW*	*900 $/kW*	*450 $/kW*	*2250 $/kW*	*2700 $/kW*
PR	0.785	0.785	0.785	0.785	0.785	0.785	0.785

Table A 8: Assumptions on carbon capture and sequestration

Technology	*Capital Cost ($/kW)*	*Efficiency loss (%)*	*CO_2 Capture (%)*
Coal (Gasification)	*197*	*3*	*95*
Oil (POX)	*185*	*2*	*95*
Natural Gas (SMR)	*76*	*2*	*88*

Table A 9: Scenario assumptions for hydrogen transport cost

Hydrogen demand	*Pessimistic*	*Intermediate*	*Optimistic*
0 (GJ/capita)	*12 $/GJ*	*10 $/GJ*	*10 $/GJ*
20 (GJ/capita)	*10 $/GJ*	*6.5 $/GJ*	*5 $/GJ*
50 (GJ/capita)	*8 $/GJ*	*5 $/GJ*	*2 $/GJ*
70 (GJ/capita)	*6 $/GJ*	*3*	
100 (GJ/capita)	*6 $/GJ*	*3*	

Table A 10: : Scenario assumptions for local hydrogen distribution cost

t	*Industry*	*Transport*	*Residential*	*Services*	*Other*
	Pessimistic				
2005	*2 $/GJ*	*6 $/GJ*	*3 $/GJ*	*2 $/GJ*	*3 $/GJ*
2100	*1 $/GJ*	*4 $/GJ*	*2 $/GJ*	*1 $/GJ*	*3 $/GJ*
	Intermediate				
2005	*2 $/GJ*	*5 $/GJ*	*3 $/GJ*	*2 $/GJ*	*3 $/GJ*
2050	*1 $/GJ*	*3 $/GJ*	*2 $/GJ*	*1 $/GJ*	*3 $/GJ*
2100	*0.75 $/GJ*	*2 $/GJ*	*1.5 $/GJ*	*0.75 $/GJ*	*3 $/GJ*
	Optimistic				
2005	*1 $/GJ*	*4.5 $/GJ*	*2 $/GJ*	*1 $/GJ*	*3 $/GJ*
2030	*0.75 $/GJ*	*3 $/GJ*	*1.5 $/GJ*	*0.75 $/GJ*	*3 $/GJ*
2100	*0.50 $/GJ*	*1 $/GJ*	*1 $/GJ*	*0.50 $/GJ*	*3 $/GJ*

Table A 11: Scenario assumptions for fuel cell investment cost and transport sector efficiency

t	*Industry*	*Residential*	*Service*	*Other*	*Transport*	*FC η transport sector*
	Pessimistic					
2005	*1500 $/kW*	*1400 $/kW*	*1400 $/kW*	*1500 $/kW*	*1200 $/kW*	*36 %*
2100	*800 $/kW*	*500 $/kW*	*500 $/kW*	*800 $/kW*	*250 $/kW*	
	Intermediate					
2005	*1500 $/kW*	*1400 $/kW*	*1400 $/kW*	*1500 $/kW*	*1200 $/kW*	*36 %*
2050	*800 $/kW*	*500 $/kW*	*500 $/kW*	*800 $/kW*	*250 $/kW*	*45 %*
2100	*500 $/kW*	*300 $/kW*	*300 $/kW*	*500 $/kW*	*200 $/kW*	*45 %*
	Optimistic					
2005	*1350 $/kW*	*1400 $/kW*	*1400 $/kW*	*1500 $/kW*	*1200 $/kW*	*40 %*
2030	*100 $/kW*	*100 $/kW*	*100 $/kW*	*100 $/kW*	*100 $/kW*	*50 %*
2100	*50 $/kW*	*50 $/kW*	*50 $/kW*	*100 $/kW*	*50 $/kW*	*60 %*

Chapter 8: The potential role of hydrogen energy in India and Western Europe[1]

Abstract:
We used the TIMER energy model to explore the potential role of hydrogen in the energy systems of India and Western Europe, looking at the impacts on its main incentives: climate policy, energy security and urban air pollution. We found that hydrogen will not play a major role in both regions without considerable cost reductions, mainly in fuel cell technology. Also, energy taxation policy is essential for hydrogen penetration and India's lower energy taxes limit India's capacity to favour hydrogen. Once available to the (European) energy system, hydrogen can decrease the cost of CO2 emission reduction by increasing the potential for carbon capture technology. However, climate policy alone is insufficient to speed up the transition. Hydrogen diversifies energy imports; especially for Europe it decreases oil imports, while increasing imports of coal and natural gas. For India, it provides an opportunity to decrease oil imports and use indigenous coal resources in the transport sector. Hydrogen improves urban air quality by shifting emissions from urban transport to hydrogen production facilities. However, for total net emissions we found a sensitive trade-off between lower emissions at end-use (in transport) and higher emissions from hydrogen production, depending on local policy for hydrogen production facilities.

[1] Published in Energy Policy, 2008, 36 (5). Co-authors: Lakshmikanth Hari, Detlef van Vuuren and Bert de Vries. The authors wish to thank Jeroen van der Sluijs (UU) and Prof. D.S. Hegde (NITIE) for their comments on earlier drafts of this article and Frank de Leeuw (MNP) for providing data from the AirBase air quality database. We are grateful to the Indira Ghandi Institute of Development Research (IGIDR) in Mumbai for using its facilities and Prof. B. Sudhakara Reddy for his suggestions on this project.

1 Introduction

Hydrogen energy is often mentioned as a potential solution for several challenges that the global energy system is facing. The first advantage is the fact that hydrogen use results in nearly zero emissions at end use, thus improving air quality. Secondly, hydrogen opens up the possibility of (decentralised) production on the basis of a variety of fuels, diversifying energy supply. The latter may contribute to reduce the dependence on imported oil (Dunn, 2001; Lovins, 2003). Hydrogen energy can also play an important role in the mitigation of greenhouse gas emissions (Barreto et al., 2003; Edmonds et al., 2004; van Ruijven et al., 2007). However, the required technology is currently only emerging, hydrogen is still more expensive than other options and the infrastructure for widespread use still needs to be developed.

The future of hydrogen therefore depends critically on whether the above mentioned barriers are reduced. This is partly determined by the context of the system in which hydrogen is introduced; we here focus on the difference between energy systems in developed and developing countries. This difference is, for instance, important for the reasons for making a transition. For developed regions, issues like competitiveness (being the first), greenhouse gas emission mitigation and energy security play a major role (McDowall and Eames, 2006). For developing regions, the potential to reduce air pollution emissions and improve energy security may be more important. Barriers are also likely to be different. While the affordability of hydrogen energy technology may be a more limiting factor in developing countries than in developed countries, the rapid growth of infrastructure in some developing countries (China and India) may create important opportunities.

The evolution of the world energy system is complex, which is an argument to use models in the exploration of alternative pathways. However, at the global scale, such models are aggregated and might not deal effectively with regional differences. Hence, one should investigate the regional outcomes in more detail. In this article, we explore the potential role of hydrogen energy in two selected regions: India and Western Europe[2].The focus on only two regions implies that we are able to account for available information on the local situation. These two specific regions were chosen because earlier research showed that Western Europe might become an early adopter of hydrogen energy (van Ruijven et al., 2007), while India is one of the first (high-growth) developing countries that is seriously looking at hydrogen energy (Bist, 2006). We analyse the impact of hydrogen on the main arguments in its favour: climate policy, energy security and urban air pollution, using scenario results for demand, production and system structure as modelled in the TIMER global energy model (de Vries et al., 2001; van Ruijven et al., 2007; van Vuuren et al., 2006b). The aim of this analysis is to further specify and differentiate the potential role of hydrogen in the context of different energy systems.

[2] For the geographical definition of this region, see: www.mnp.nl/image

In this paper, Section 2 provides a brief overview of existing energy scenarios for India and Western Europe. Section 3 describes the main drivers and barriers for hydrogen energy and their relevance for both regions. Section 4 discusses the current research and planning on hydrogen energy in both regions. Section 5 focuses on the modelling of hydrogen energy systems and Sections 6 and 7 discuss the results of the model simulations and the impact of hydrogen on its main driving arguments. Section 8 finalises the paper with a discussion and conclusion.

2 Energy scenario literature for India and Western Europe

2.1 Energy scenarios

By comparing available regional energy scenarios for India and Western Europe it is possible to obtain a better insight in the energy system context of these specific regions. A recently published study by the Indian Planning Commission on Integrated Energy Policy (Planning Commission, 2006) explores the future development of the Indian energy system using two economic growth scenarios. A broader set of four scenarios was published by Shukla et al. (2003), implementing the IPCC-SRES scenarios for India, using two axes of possible future developments: high and low market integration and centralised and decentralised governance. The IEA World Energy Outlook (WEO) 2006 provides two energy scenarios on the basis of a single socio-economic projection: a reference and a policy scenario (IEA, 2006).

For Europe[3] several scenario studies have been published as well, describing a broad range of possible energy futures. We here limit the comparison to the IEA World Energy Outlook (IEA, 2006) and a set of European baseline scenarios from the PRIMES model (Mantzos et al., 2004). The latter explores the impact of different levels of economic growth, energy prices and policy options on energy technologies and transport modes.

The baseline scenario for the this study is the second OECD Environmental Outlook baseline scenario: TIMER OECD-EO (Bakkes et al., 2008; OECD, 2008). This scenario assumes no new explicit policies; it involves continuation of current policies and implicitly assumes the existence of an environmental Kuznets curve on emission factors of developing countries. With respect to energy, it is based on the IEA WEO scenario (IEA, 2004b), which is regarded a medium scenario on energy supply and demand. Below, we compare the energy scenarios for India and Europe with the TIMER OECD-EO scenario. We limit this comparison to the period until 2030, because this is the time horizon of most discussed scenario studies. However, in the rest of this article, we use a time horizon up to the year 2050.

[3] One particular issue with studies on Europe is the variation in geographical definitions. Official European Union studies often use the definitions of EU15 and EU25 countries, the IEA uses OECD Europe as it is at this moment (including several Eastern European countries and Turkey) and the TIMER/IMAGE model includes the region of OECD Europe as it was around the year 2000 (comparable to EU15 plus Norway and Switzerland) and the region of Eastern Europe (together these regions are comparable to the EU25).

2.2 Economy and Population

Economic projections for India are characterised by high GDP growth rates, varying between 4% per year in the *IB2 Self-reliance* scenario (Shukla et al., 2003) and the IEA-WEO and up to 9% per year in *IA1 High Growth* (Shukla et al., 2003) and the Planning Commission scenarios. In absolute terms, this corresponds to an increase in GDP from 467 billion USD_{1995}/yr in 2000 to a range of 1750-5600 billion USD_{1995}/yr in 2030. In the same period, the Indian population is expected to grow by about 1.1% per year, to a total of 1.4 billion people in 2030 (IEA, 2006; Planning Commission, 2006). This means that growth rates for GDP per capita are lower than for total GDP: between 3% and 7% per year, or an increase from 460 to 1240-3800 USD_{1995} per capita per year. The TIMER OECD-EO scenario is in the middle of this range, projecting a GDP per capita of 2400 USD_{1995}/yr in 2030.

For Western Europe, economic growth projections decrease from 2.3% (2004-2015) to 1.8% (2015-2030) per year in the IEA-WEO and vary between 1.9-2.6% per year in the PRIMES study. In absolute terms, the Western European GDP is projected to increase from 9000 billion USD_{1995}/yr in the year 2000 to 18000-23000 billion USD_{1995}/yr in 2030. Population growth estimates for Europe are in the range of 0.1-0.2% per year, increasing from currently 380 million people to 390-415 million people in 2030. This implies per capita GDP growth projections of 1.7 to 2.7% per year, or in absolute terms from 27000 USD_{1995}/yr per capita in 2000 to 45000-56000 USD_{1995}/yr in 2030. The TIMER OECD-EO scenario is on the lower bound of this range.

2.3 Energy

For India, the comparison of energy use projections is somewhat complicated by the fact that some studies include non-commercial energy, while others do not. The Planning Commission projects a 5 to 7 fold increase of primary energy use between 2000 and 2030, excluding non-commercial energy. The other studies are more moderate, projecting TPES to increase 2 to 3 fold between 2000 and 2030. The TIMER OECD-EO scenario is in line with the average of the other studies (excluding the Planning Commission), projecting a factor 2.3 increase of the total Indian energy use between 2000 and 2030 (Figure 8.1, left graph).

In the Indian primary energy mix of the TIMER OECD-EO scenario, coal is projected to remain dominant, followed by oil and biomass. Nuclear and renewable energy sources show a rapid increase in India, but are not projected to reach the European 2003 level by 2050 (see Table 8.1 and Table 8.2). Biomass energy, which is mainly used for cooking in rural households, made up almost 40% of the total energy use of India in the year 2000; although its share is generally expected to decline, its evolution is one of the main uncertainties in energy use projections. Currently, India already depends strongly on imports of oil and for the future it is expected that imports will increase to almost the total oil consumption in the country (Table 8.1). Also natural gas, which is increasingly applied in India's transport sector, is expected to be imported up to almost 90% by 2050.

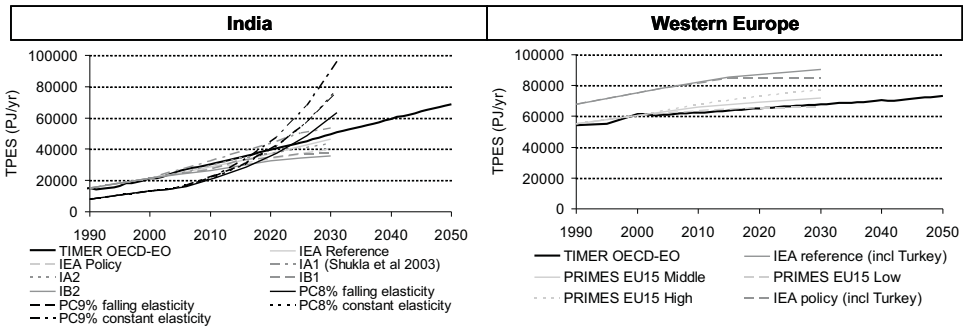

Figure 8.1 Total Primary Energy Supply in several scenarios for India and Western Europe. The different levels for Europe in 1990 are due to different regional definitions. The different levels for India are due to the exclusion of non-commercial fuels by the Planning Commission.

The energy scenarios for India do hardly involve any role of hydrogen. The Planning Commissions recommends the government to develop a research program for hydrogen, as they regard it a promising energy carrier for the long-term future. The IEA-WEO 2006 expects fuel cells (running on hydrogen) to count for 1% of global electricity production by 2030, but it does not explicitly mention the involved regions. Hydrogen application in the transport sector is indicated 'promising after 2030' (IEA, 2006). The TIMER OECD-EO scenario does not involve any hydrogen energy applications in India before 2050.

Table 8.1: Total Primary Energy Supply in India (EJ/yr)

		Coal	Oil	Natural Gas	Biomass	Nuclear	Solar/Wind	Hydro	Total
2000		7.1	4.8	0.9	8.5	0.2	0.0	0.3	21.6
	Import	8%	67%						18%
2030		22.0	12.2	2.8	13.6	1.4	0.1	0.7	51.8
	Import	8%	91%	50%	7%				29%
2050		29.7	20.7	7.0	12.8	1.7	0.5	0.8	72.1
	Import	10%	99%	88%	4%				41%

Historic data: IEA energy balances, future data: TIMER OECD Environmental Outlook scenario.Nuclear energy is converted to primary energy using 33% efficiency; numbers for solar, wind and hydro are the energy content of electricity produced.

For Europe, the projections considered here provide a range of 8-27% increase in TPES in 2030 compared to 2000. The TIMER OECD-EO scenario is on bottom of this range, as it projects an increase of 10% between 2000 and 2030 (Figure 8.1). Europe's main primary energy carriers are oil and natural gas, followed by coal and nuclear (Table 8.2). The high and increasing share of imported energy, especially coal and oil, indicates that indigenous resources in Europe become more expensive while being depleted. The production of renewable energy sources such as biomass, solar/wind, geothermal and hydro is projected to increase steadily.

Although the PRIMES scenario study does not foresee any role for hydrogen in the baseline scenario, the scenarios '*mainstream policy lines: energy efficiency and renewables'* and '*combined policy'*, project a total installed capacity of about 56-58 GW of hydrogen based fuel cells for the EU25 in 2030 (Mantzos et al., 2004). The TIMER OECD-EO scenario does not show any hydrogen in Western Europe before 2050

Table 8.2: Total Primary Energy Supply in OECD Europe (EJ/yr)

		Coal	Oil	Natural Gas	Biomass	Nuclear	Solar/Wind	Hydro	Total
2000		10.0	25.2	11.8	2.0	9.1	0.0	1.6	59.9
	Import	46%	57%	41%	1%				39%
2030		12.5	18.4	23.8	10.4	8.4	2.0	2.0	71.8
	Import	72%	57%	59%	48%				50%
2050		17.7	22.9	24.5	5.8	7.4	3.9	2.3	79.6
	Import	66%	61%	65%	23%				51%

Historic data: IEA energy balances, future data: TIMER OECD Environmental Outlook scenario. Nuclear energy is converted to primary energy using 33% efficiency; numbers for solar, wind and hydro are the energy content of electricity produced.

3 Drivers and barriers for hydrogen energy in India and Western Europe

3.1 Drivers

In a recent literature overview of hydrogen studies, four main drivers towards a hydrogen energy system were identified: 1) climate change, 2) energy security, 3) air pollution and 4) competitiveness (McDowall and Eames, 2006).

3.1.1 Climate Change

India and Western Europe play different roles in the climate policy debate. The Western European energy system emits currently about 1 Gt carbon per year, which is about 15% of the global carbon emissions from energy use. The TIMER OECD-EO scenario projects a slow increase, up to 1.2 GtC/yr in 2050 (9% of the projected global carbon emissions, see Figure 8.2). The European Union countries have carbon emission reduction targets under the Kyoto protocol and the European Council accepted proposals for stringent reductions of greenhouse gas emissions (Council of the European Union, 2007).

India's emissions are currently 0.3 Gt carbon per year from energy use, which is 4% of the global emissions. However, future projections foresee a large increase in Indian carbon emissions, leading to 1.2 GtC/yr in 2050 (similar to Western Europe and 9% of the projected global emissions, see Figure 8.2). For India, no official climate policy has been adopted. Some authors (e.g. den Elzen and Meinshausen, 2005) argue that on the longer term participation of India in climate policy is needed in order to reach global stabilization targets. However, there has been no statement by the Indian government in this direction.

In an earlier study, we found that the role of hydrogen with respect to CO_2 emissions is ambiguous (van Ruijven et al., 2007). On the one hand, hydrogen can make energy systems more flexible in responding to climate policy, because it makes the option of carbon capture and sequestration available to the transport sector. On the other hand, hydrogen production from coal is the cheapest option, causing an increase in CO_2 emissions on the long-term, without climate policy.

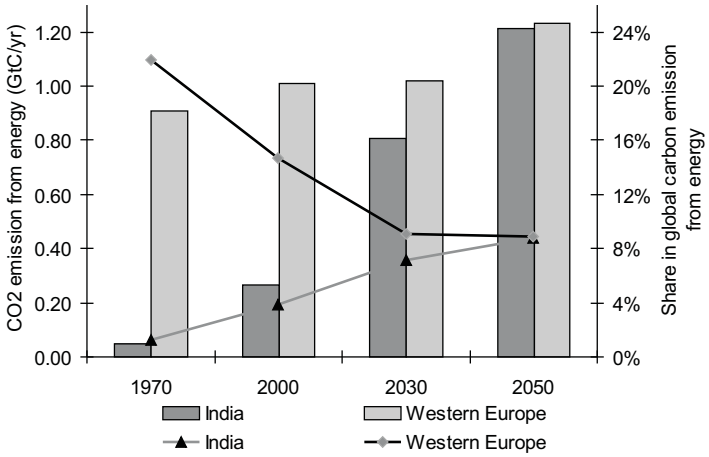

Figure 8.2: CO_2 emission from energy use for India and Western Europe for the TIMER OECD Environmental Outlook scenario; absolute (bars, left axis) and relative to the total global energy-based carbon emission (lines, right axis)

3.1.2 Energy Security

Energy security is a relevant issue for both India and Western Europe. Figure 8.3 shows the absolute trade flows and the share of imported fuels in total domestic use. India, which is currently importing over 60% of its oil, faces the potential situation that it imports all its fuels for the transport sector by 2050. By 2030, India is projected to import more barrels of oil per year than Western Europe; in 2050 Indian oil import is expected to be almost twice the European inflow of oil. Western Europe is already a major importer of energy, and is expected to keep importing 50 to 70% of its fossil energy. Natural gas imports are increasing rapidly in both regions in the TIMER OECD-EO scenario. Also imports of coal are expected to keep increasing.

In an overview of hydrogen scenario studies, McDowall and Eames (2006) state that hydrogen is expected to be adopted in regions without significant indigenous oil or gas reserves, like India and Western Europe. Especially in scenarios with limited trade, the more expensive indigenous energy resources of these regions are expected to drive the use of hydrogen. We use long-term supply-costs-curves of oil (and other fossil energy sources) in the TIMER model, based on Rogner (1997), but the ultimate resource size and cost estimates are still highly uncertain (e.g. Campbell, 2002). This has consequently a large influence on the future energy mix and carbon emissions (van Vuuren, 2007).

Application of hydrogen in the transport sector can potentially decrease imports of oil and increase the use of indigenous coal or gas reserves, which is relevant for both Europe and India. However, without hydrogen, Europe is already expected to import a major share of its coal and gas in the future and India's gas imports may reach 90% by 2050 as well. Production of hydrogen from these sources might cause additional imports.

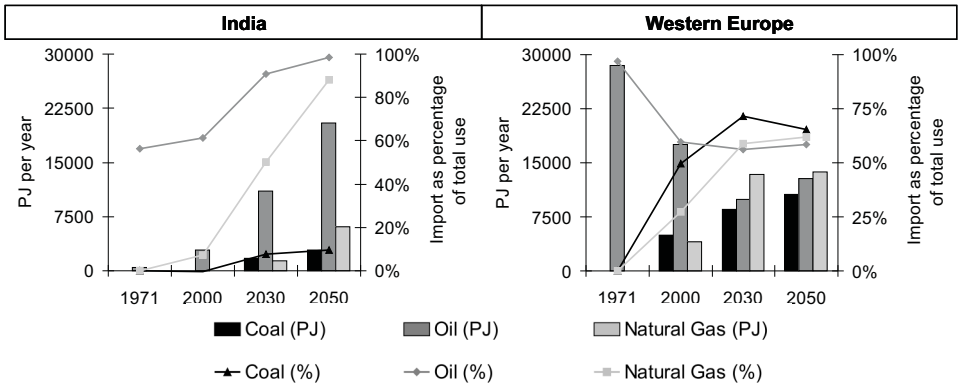

Figure 8.3: Energy Import for India and Western Europe, in absolute numbers (bars, left axis) and as percentage of the total inland consumption (lines, right axis) for the TIMER OECD Environmental Outlook scenario

3.1.3 Urban Air Quality

Urban air pollution may be a third driver for the introduction of hydrogen in the energy system, because it is a major concern in both India and Western Europe. Recent data on the concentration of air pollutants (NO_2, SO_2 and PM10) show that urban air pollution is generally higher in India than in Europe (Table 8.3). Annual average concentrations of NO_2 are slightly higher in Europe; concentrations of SO_2 and especially particulate matter (PM10) are higher in India than in Europe. The trends in India reveal that in the early years of the 21st century, several major Indian cities have improved air quality by converting three-wheelers and buses to compressed natural gas (CNG). However, since 2004 the trend is (often) increasing again (Central Pollution Control Board, 2004), driven by the growing amount of vehicles. The future of air quality in India is highly uncertain; on the one hand, the notion of an environmental Kuznets curve generally indicates that it might improve above a certain welfare level (Garg et al., 2003); on the other hard, the increasing number of vehicles might outweigh improvements in technology. Hydrogen energy might decrease air pollution from end-use, but emissions from hydrogen production depend on local standards.

Table 8.3: Urban air quality in the 10 largest cities of India (left, for 2004) and Western Europe (right, for 2005), annual average concentration of NO_2, SO_2 and PM10 in µg/m

City	Population (million)	NO_2	SO_2	PM10	City	Population (million)	NO_2	SO_2	PM10
Gr. Bombay	12.59	19	7	77	Paris	9.32	43	8	21
Calcutta	11.02	53	9	237	London	7.65	44	4	25
Delhi	8.42	57	9	432	Berlin	3.45	22	4	27
Madras	5.42	6	5	96	Milano	3.29	55	8	54
Hyderabad	4.34	29	6	178	Athens	3.07	32	11	41
Bangalore	4.13	61	7	173	Madrid	3.01	43	11	29
Ahmedabad	3.31	23	15	231	Naples	2.95			
Pune	2.49	53	31	340	Rome	2.70	41	2	
Kanpur	2.03	20	9	413	West Midlands	2.30	30	3	23
Lucknow	1.67	33	16	391	Gr. Manchester	2.28	43	2	23

Data for India from (Central Pollution Control Board, 2004), Western European data are based on (European Topic Centre on Air and Climate Change, 2005)

3.1.4 Competitiveness

Economic competitiveness as driving argument for a transition to hydrogen energy could be important for both regions. Europe is the home market for some of the world's largest car manufacturers and energy companies, who might benefit from a common and early shift towards hydrogen. In India, the industrial and transport sectors are rapidly developing and becoming a world-leading hydrogen energy technology producer might be one of the challenges. The question whether early investors in hydrogen can capitalise their learning process is highly uncertain and beyond the scope of our model and this article.

3.2 Barriers

In general, the main barriers for the development of a hydrogen energy system are the development of infrastructure and the (present-day) high cost. Also safety, public acceptance and the development of codes and standards are potential obstacles for the large-scale implementation of hydrogen (McDowall and Eames, 2006).

The development of infrastructure is a major task for the implementation of hydrogen in both regions. India is currently expanding its infrastructure for natural gas (Dhar, 2007) and might have a chance for leapfrogging if these gas-pipelines could also transport hydrogen. However, the present generation of pipelines is not able to transport hydrogen. This indicates that the transition might be as difficult as in Europe, which already has a densely spread natural gas network, not suitable for the transport of pure hydrogen. Hydrogen can be mixed into existing natural gas grids up to a maximum level of 5% on energy basis (Hendriks et al., 2002), a process that might play a role in the initial phases of a transition.

The high costs of hydrogen technology may play out differently for both regions. Due to differences in GDP per capita, hydrogen energy technology is relatively more expensive for Indian consumers than for Europeans. In our model, we quantified the barriers of infrastructure development and costs (see Section 5). Our quantitative results do not deal with issues like safety and public acceptance, but the storyline for optimistic hydrogen development implicitly assumes that these issues are effectively solved.

4 Existing research and planning for hydrogen energy systems

4.1 Western Europe

One of the most recent European Union (EU) documents on hydrogen energy is the report "Hydrogen Energy and Fuel Cells, a vision for our future", presented in 2003 by the European Union High Level Group for Hydrogen and Fuel Cells. The group envisions a hydrogen-based energy system for Europe in 2050 and recommends five possible actions for the European Union: 1) establish a political framework, 2) formulate a strategic research agenda, 3) develop a deployment strategy for hydrogen, 4) develop a European roadmap for hydrogen and fuel cells and 5) found a European hydrogen and fuel cell technology partnership. The included skeleton proposal for an European hydrogen and fuel cell roadmap foresees that in the period to 2020 the main focus is on research and development, field tests and niche fleets. The group foresees hydrogen energy technology to come to full development after 2020, increasing its market penetration towards a hydrogen oriented

economy in 2050. This means that in 2020 5% of all new vehicles is envisioned to be hydrogen powered; in 2040 this is expected to reach the level of 35% (European Commission, 2003). Beside this vision document, no concrete European plans towards a hydrogen-based energy system exist. The development of a hydrogen energy system is promoted by the European Union, by funding several research and pilot projects. The European Commission increased its support for hydrogen and fuel cell development to 2 billion US dollar over four years (Solomon and Banerjee, 2006). Currently, these projects focus mainly on technology development, but safety and infrastructure development are included as well[4]. One of the most concrete and practical projects is the Clean Urban Transport for Europe (CUTE)-program. This is a demonstration project of 27 fuel cell powered regular service buses over a period of two years (2004-2006) in 9 European cities. The program involves design, construction and operation of the necessary infrastructure for hydrogen production and refuelling. After the first project-period, it was decided to continue the project as HyFLEET-CUTE, operating 47 buses, including 14 H_2-Internal-Combustion-Engine buses[5].

4.2 India

Although India is a leader in the field of renewable energy in the developing world, with a dedicated Ministry of New and Renewable Energy Sources (MNES) for over decades, the entry of hydrogen into the energy scene in India has been fairly recent. So far, it involves only research, development and demonstration (R&D) projects (Solomon and Banerjee, 2006). India set up the National Hydrogen Energy Board (NHEB) in 2003 under the chairmanship of the MNES. Under the program "Hydrogen Vision 2020", India is planning to achieve targets like one million hydrogen fuelled vehicles on the road and a total of 1000-MW hydrogen production capacity by 2020 (Bist, 2006). The National Hydrogen Energy Road Map, a report accepted by NHEB in 2006, estimates that investments of almost 6 billion US dollar would be required: 230 million USD for R&D; and 5.5 billion USD for creating infrastructure for hydrogen production, storage, transportation and distribution (Bist, 2006). Universities and R&D laboratories are undertaking various projects in the field of hydrogen energy with the support from MNES. The AMM Murugappa Chettiar Research Center in Chennai is developing a biological process for the generation of hydrogen from a variety of sugar-containing industrial wastes and designing a special burner to use hydrogen for cooking. Banaras Hindu University in Varanasi has developed hydrogen fuelled two wheelers with hydrogen stored in metal hydride tanks (Chopra, 2006). India's first hydrogen fuelling station, from which the Indian Oil Corporation plans to run at least four vehicles as part of its test programme, was officially opened in October 2006[6].

[4] See website: http://ec.europa.eu/research/leaflets/h2/page_100_en.html
[5] See websites: www.global-hydrogen-bus-platform.com and www.fuel-cell-bus-club.com
[6] see website http://www.iahe.org/News.asp?id=23

5 TIMER hydrogen model and scenarios

5.1 The TIMER model

We use the TIMER 2.0 global energy model to explore the potential role of hydrogen in the energy systems of India and Western Europe. The TIMER 2.0 model is the energy sub-model of the Integrated Model to Assess the Global Environment, IMAGE 2.4, that describes the main aspects of global environmental change (Bouwman et al., 2006). TIMER is a system-dynamics energy model that simulates year-to-year investment decisions based on a combination of bottom-up engineering information and specific rules on investment behaviour, fuel substitution and technology. TIMER 2.0 (van Vuuren et al., 2006b) is an expanded version of the TIMER 1.0 model (de Vries et al., 2001), with the main differences being extension of renewable energy modelling (Hoogwijk, 2004), carbon capture and storage (Hendriks et al., 2004), hydrogen (van Ruijven et al., 2007) and a desaggregation from 17 to 26 world regions. In the TIMER 2.0 model, demand for end-use energy is related to economic activity in five sectors: industry, transport, residential, services and other. The demand formulation includes autonomous and price-induced changes in energy-intensity. Energy supply is based on fossil fuels (coal, oil, natural gas), biomass, solar and wind power, hydropower and nuclear power. Fossil- and biofuels can be traded among 26 world regions. The production of each primary energy carrier includes the dynamics of depletion and learning-by-doing.

5.2 The TIMER-H_2 model

The TIMER-H_2 model involves the production, demand, infrastructure and technology dynamics of hydrogen related technologies (Figure 8.4). In the model, hydrogen can be produced from fossil energy sources (eventually including carbon capture and storage, CCS), biomass, electricity, solar thermal and nuclear heat. Hydrogen production costs are based on capital costs, O&M costs, fuel costs and (if relevant) CO_2 capture and sequestration costs. Hydrogen can be used in five end-use sectors: industry, transport, residential, services and other in which it competes with other secondary fuels. The costs of energy services from hydrogen for the end-user are the sum of hydrogen production costs, end-use capital[7] (fuel cell) and infrastructure costs. The market-share of hydrogen is determined by the differences in relative costs of an energy service on the basis of hydrogen and on the basis of other energy carriers. The total demand for hydrogen equals the market share multiplied by the sectoral energy demand. Subsequently, hydrogen demand is met through investments into hydrogen production capital. Finally, there is a feedback loop from technological learning: hydrogen production capital costs decline with increasing cumulative installed capacity. A more detailed description of this model can be found in van Ruijven et al. (2007).

The role of drivers and barriers for hydrogen in the model, as discussed in Section 3, is indicated in Figure 8.4. The drivers are mainly related to the impact of hydrogen on the energy system: increasing the options for CCS, replacing oil in the transport sector and decreasing emissions of NO_x, SO_2 and particulate matter. Barriers are mainly implemented

[7] The costs of the Fuel Cell (incl. stacks) are annualised over the economic life time of capital in the transport sector: 8 years.

in the form of costs: both the (initially high) cost for hydrogen technologies, but also the costs of infrastructure and distribution. With respect to infrastructure development, the model simulates a delay for the construction of hydrogen production capacity and limits the production options in early stages of hydrogen deployment. To be more specific: in the first phase, hydrogen for stationary applications is only produced from small-scale Steam Methane Reforming (SMR) technology. For the transport sector, large-scale production (from all other energy sources) is possible, but transport of hydrogen takes place by (expensive) trucks. If demand for hydrogen increases, the system enters a second phase, in which pipeline transport becomes cost effective and large-scale production technologies become available for stationary end-use applications as well.

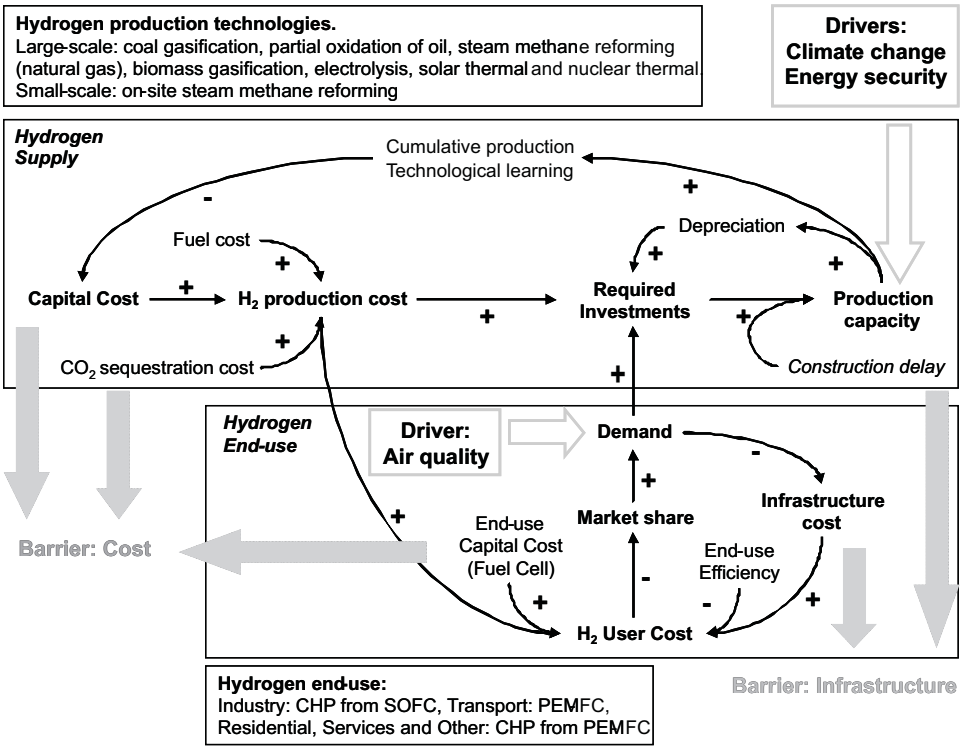

Figure 8.4: Overview of the TIMER-hydrogen model, the relation with drivers and barriers is highlighted by large arrows. Small arrows indicate influence factors or inputs for calculation.

An important assumption in the model is that end-use of hydrogen only takes place in fuel cells. For stationary applications, these fuel cells produce both heat and power (CHP); in transport applications, the electricity is used to drive vehicles. This is not in line with the current research focus on internal combustion engines (ICE), like the extended HyFLEET-CUTE project in Europe and research to three-wheelers and cookers in India. However, fuel cells have higher conversion efficiencies than ICE's, and thus use less hydrogen per unit of delivered *useful* energy (or energy service). Because hydrogen is relatively expensive,

especially in the early phase of the transition, this leads to an economic advantage for fuel cells at the level of *useful* energy, despite their higher capital costs. Therefore, we assumed fuel cells to be the main hydrogen end-use technology. This influences the results on air pollution: direct combustion of hydrogen leads to higher NO_x emissions than other fuels because of the higher flame temperatures.

Because most Indian studies on hydrogen assume the use of international technology (Balachandra and Reddy, 2007; Bist, 2006), we use similar (global) assumptions on hydrogen technology for Western-Europe and India. The most important assumptions can be found in van Ruijven et al. (2007) and in the appendix[8]. We added one technology option for the production of hydrogen to the existing model: nuclear thermal hydrogen production. This is a potential option for future hydrogen production in India (Bist, 2006). In contrast to fossil energy based technologies like coal gasification and SMR, it is only operational at the laboratory scale and it needs time and effort to become available at industrial scale (Crosbie and Chapin, 2003). According to the nuclear industry, the next generation of (uranium-based) nuclear reactors could be used to heat a Sulphur-Iodine (S-I) cycle to thermo-chemically produce hydrogen from water. We based our assumptions for nuclear-thermal hydrogen production on publications of a General Atomics project that used the S-I cycle (Schultz et al., 2003), but this option represents the broader technology-field of nuclear hydrogen production[9].

5.3 The TIMER-H_2 scenarios

In this study, we use the TIMER OECD-EO energy scenario (see Section 6) as baseline scenario and vary only assumptions on hydrogen energy technology development. We use a set of pessimistic, intermediate and optimistic assumptions for hydrogen energy technology development, based on literature estimates of cost and technology development - similar to our earlier global analysis (van Ruijven et al., 2007). The assumptions differ in terms of technology learning rates, but also on costs of infrastructure development and energy taxation. With respect to the latter, in the optimistic scenario we assume no energy taxation of hydrogen. We only vary assumptions on hydrogen technology itself; developments in other technologies (e.g. batteries, hybrid-vehicles) are assumed to be the same in all scenarios. We assume technological improvements to be exogenous and do not take into account any related costs, for instance R&D investments. Below, the hydrogen scenarios are quantitatively described; the quantitative assumptions are provided in the appendix.

- In the pessimistic set of hydrogen assumptions (H2PES), we describe a world in which no major hydrogen-related breakthroughs are established and transitional dilemmas, like the chicken-egg problem with demand, supply and infrastructure development, are

[8] We assumed similar progress ratios for all technologies, because in this stage we do not have reasons for diversification.

[9] In the model, nuclear thermal hydrogen production technology is available from the beginning of the century. However, it is hardly applied, due to limitations to large-scale technologies during the transition.

not solved. Technologies and costs continue to improve slowly between now and 2100 towards the lower range of technology parameters found in literature[10].

- In the intermediate hydrogen scenario (H2MED), some promising improvements in technology are made, but after a while new boundaries are met. In particular in the first decades to come, fuel cells rapidly become cheaper. However, after this initial break-through, further progress slows down in the second half of the century. In the production phase, no major new cost reductions are achieved and, partly because the major development of fuel cell markets does not occur, production capacity stagnates and learning experience in hydrogen production technology is less than was hoped for. Some hydrogen distribution infrastructure is developed for the transport sector, but apart from a few niche markets the transition is costly. In this scenario, technologies improve to the lower range of technology estimates by 2050.
- The third scenario describes the most optimistic case for hydrogen (H2OPT). In this scenario, breakthroughs in hydrogen technology are realised and transitional issues are vigorously solved. A major policy measure is that hydrogen is excluded from the taxation of energy, in order to stimulate its application. With respect to technology development, fuel cells are mass-produced at low cost, hydrogen production technology becomes cheaper and better through learning and distribution infrastructure is developed rapidly at low costs. In this scenario, technologies are assumed to improve rapidly to reach an intermediate range by 2030 and the most optimistic values in literature by 2100.

6 Scenarios for hydrogen energy in India and Western Europe

In the TIMER OECD-EO scenario, the baseline scenario for the hydrogen analysis, the economic and demographic projections are medium compared to other studies (see Section 2). For India, GDP per capita is projected to increase from 460 USD_{1995}/yr in 2000 to 5000 USD_{1995}/yr in 2050, with a population increasing to almost 1.6 billion people. For Europe, GDP per capita is assumed to increase from 27000 USD_{1995}/yr in 2000 to 63000 USD_{1995}/yr in 2050, with slow population growth towards 400 million persons. Total primary energy use increases in both regions towards a level of about 70 EJ per year (Figure 8.1) and CO_2 emissions reach 1.2 GtC per year in both India and Western Europe. Below, we present the results of the hydrogen scenarios. It turns out that hydrogen is only applied in these regions before 2050 under intermediate and optimistic assumptions. Therefore, we exclude the pessimistic hydrogen scenario from further discussion.

An important note is that the global energy model TIMER model includes all world-regions in parallel and that the assumptions on hydrogen and, for instance, climate policy also count for other world regions. Issues like trade and learning spill over are computed for the whole

[10] Although the storylines of the scenarios involve the whole 21st century, we limit our analysis to the period to 2050.

world and cannot be attributed to these two regions only. So, we focus on the regions of Western Europe and India, keeping in mind that the rest of the world is still involved.

6.1 Hydrogen Production

Assuming that competition among the different technologies to produce hydrogen is mainly based on production costs, the results for the optimistic hydrogen scenario show that coal is clearly the cheapest option in both India and Western Europe, although initially natural gas is also attractive (Table 8.4). In both regions, technological learning makes biomass more attractive in the long run, followed by nuclear thermal hydrogen production. The share of fuel costs in the total production costs of hydrogen tends to increase for all technologies; learning-by-doing decreases capital cost, while at the same time depletion of resources increases fuel costs.

Table 8.4: Hydrogen production cost (in $\$_{1995}$/GJ) and percentage fuel cost (%) for the optimistic scenario

India	2010	2030	2050	Western Europe	2010	2030	2050
Coal	8.0	7.5	5.1	**Coal**	9.5	8.6	6.1
	(21%)	(24%)	(39%)		(34%)	(36%)	(50%)
Oil	13.5	13.4	14.3	**Oil**	14.1	13.4	14.0
	(72%)	(73%)	(77%)		(73%)	(73%)	(76%)
Natural Gas	10.2	8.9	7.6	**Natural Gas**	9.6	8.5	8.2
	(78%)	(78%)	(83%)		(77%)	(77%)	(85%)
Biomass	13.6	12.7	11.9	**Biomass**	14.5	14.2	12.5
	(53%)	(51%)	(53%)		(56%)	(56%)	(56%)
Electricity	18.2	19.1	19.3	**Electricity**	28.9	27.2	24.2
	(82%)	(83%)	(83%)		(89%)	(88%)	(87%)
Solar Thermal	47.6	36.5	31.0	**Solar Thermal**	49.9	38.4	32.5
	(N/A)	(N/A)	(N/A)		(N/A)	(N/A)	(N/A)
Nuclear Thermal	12.3	11.8	11.8	**Nuclear Thermal**	12.3	11.9	11.8
	(4%)	(5%)	(6%)		(4%)	(5%)	(6%)
Small SMR	25.2	19.6	14.2	**Small SMR**	25.3	19.4	14.7
	(30%)	(35%)	(44%)		(30%)	(35%)	(47%)

Hydrogen production costs are a combination of fuel cost (shown here between brackets), O&M and (annualised) capital cost

In line with these production costs, coal is the major production technology for hydrogen in India in the optimistic scenario, followed by small-scale and large-scale natural gas (Figure 8.5). In the intermediate scenario, hydrogen remains too costly and it plays no role in the Indian energy system. Hydrogen production in Europe is also mainly based on coal gasification and steam reforming of natural gas (Figure 8.5). In Europe too, there is hardly any demand for hydrogen in the intermediate scenario, although in absolute terms European demand in 2050 is comparable to the Indian demand in the optimistic hydrogen scenario.

6.2 Hydrogen end-use

In which sectors may hydrogen be applied? In India, there is a demand for hydrogen only in the transport sector in the optimistic scenario (Figure 8.5); from 2020 onwards, the share of hydrogen in the Indian transport sector increases to 40% in 2050. The share of hydrogen in total final energy use in India increases to about 6% in 2050. With intermediate cost and technology assumptions, hydrogen cannot compete with other options and does not enter the Indian energy system.

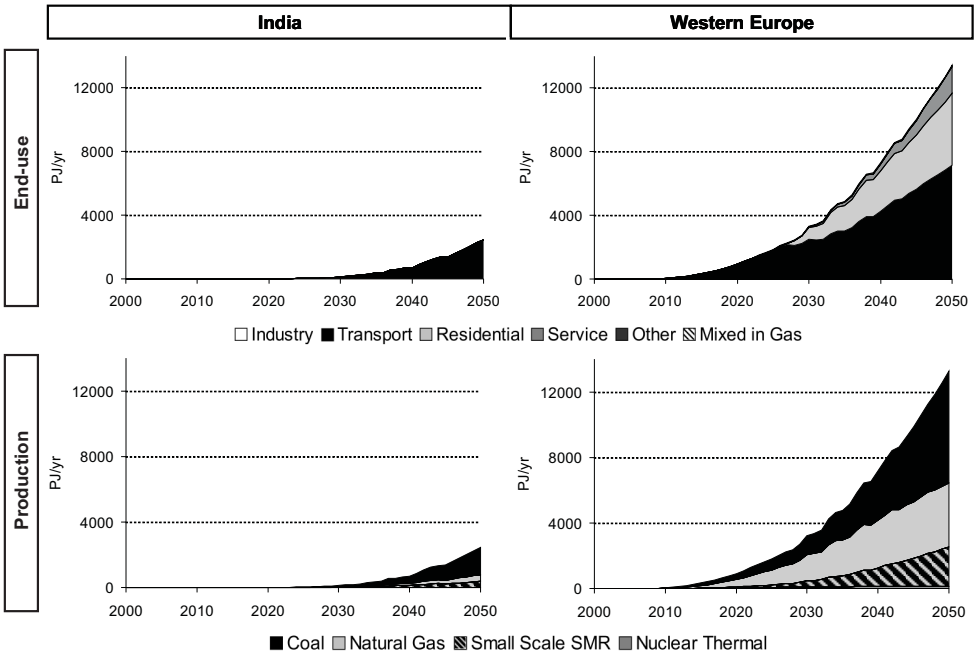

Figure 8.5: End-use (upper graphs) and production (lower graphs) of hydrogen in India and Western Europe under optimistic scenario assumptions without climate policy

In Western Europe, our results show that there might be a role for hydrogen in both stationary and mobile applications (Figure 8.5). In the optimistic scenario, hydrogen demand starts after 2010 and increases rapidly towards 27% market share in 2050, mostly in the transport sector. With increasing hydrogen use in the transport sector, the development of pipeline infrastructure becomes more attractive. Around 2030, the threshold-hydrogen-use for infrastructure development is reached and large-scale produced, pipeline delivered hydrogen becomes available for stationary applications. This causes a rapid introduction of hydrogen in the Western European residential sector: the market share of hydrogen increases to about 40% in 2050. Hydrogen use in the service sector increases more slowly towards 13% market share by 2050. In the intermediate scenario hydrogen only penetrates in the transport sector after 2040 and reaches about 10% market share by 2050. Mixing hydrogen into the natural gas grid shows up in all scenarios in both regions, but represents only a minor share of the demand for hydrogen.

The end-use of hydrogen can also be expressed in terms of installed fuel cell capacity for power generation, a number that is also provided in the PRIMES scenario study for Europe, discussed in Section 2 (Mantzos et al., 2004). This study projects 56-58 GW_e of fuel cells in 2030 in scenarios with a policy focus on energy efficiency and renewable energy for the EU25. The TIMER optimistic scenario involves a similar capacity of 50 GW_e fuel cells in

2030 in Western Europe[11], increasing to 360 GW_e in 2050. The energy scenarios for India do not provide comparable quantitative indicators on hydrogen.

6.3 Energy taxes

One on the main explanations of the difference in hydrogen penetration between India and Western Europe is the level of energy taxes. The optimistic scenario assumes that hydrogen will not be taxed; a policy measure that also plays a role in current European policies to stimulate biofuels (Bomb et al., 2007)[12].

Historically, the Western Europe has the highest energy taxes of the world, which results in a favourable position of hydrogen compared to other fuels (mainly oil and natural gas) if it is exempted from energy taxes. The results of two variants of the existing scenarios, i.e. a H2MED scenario with tax-exemption for hydrogen and H2OPT with hydrogen taxed, show that the tax-exemption explains most of the difference between the intermediate and optimistic scenarios for Europe, while it hardly makes a difference in India (Figure 8.6, left graph). Most likely, energy taxes in developing countries will increase: investments in transport and energy infrastructure need to be financed and higher energy-taxes are one of the options to generate the required finances (de Vries et al., 2007a; van Vuuren et al., 2003). In recent years, energy taxes for the transport sector in India increased, although prices are still about 40% lower than in Europe (IEA, 2007b; Metschies, 2005). Therefore, we also include a case in which India really adopts the Western European energy taxes by 2025 for all fuels other than hydrogen. This shows the impact of the tax exemption measure, as hydrogen penetration reaches 10%, almost twice the percentage of the optimistic scenario[13].

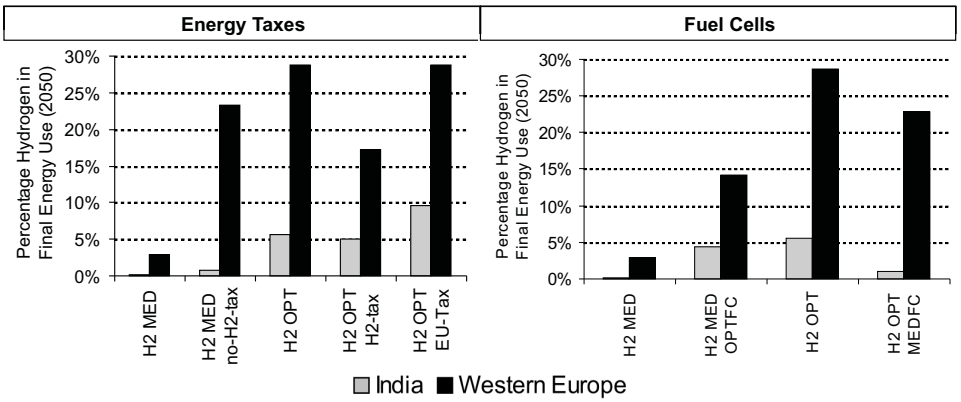

Figure 8.6: Impact of energy taxes and fuel cell technology development on penetration levels of hydrogen in final energy use in 2050 in India and Western Europe

[11] The PRIMES EU25 region includes the IMAGE/TIMER Western Europe and Eastern Europe regions. In the IMAGE/TIMER Eastern Europe region, no stationary fuel cell capacity is projected until 2050.

[12] On the long-term, this assumption might be unrealistic for a fuel that becomes dominant in several sectors, but we aimed to describe the most optimistic case for hydrogen energy.

[13] For Europe, this scenario is equal to H2OPT

6.4 Fuel Cell development

Another key uncertainty in the development of hydrogen energy systems is technology development. With respect to hydrogen demand, the development of costs and efficiency of fuel cells is one of the main factors[14] for which future estimates in literature vary widely. The scenario assumptions are based on the range in literature (see Table A6), and to isolate the impact of fuel cell development, we analyse a variant of the intermediate scenario that includes optimistic assumptions on fuel cells and vice versa (Figure 8.6, right graph). In India, the difference between the intermediate and optimistic scenarios can largely be explained from differences in fuel cell development; it has much more impact than assumptions on energy tax. For Europe, the impact of fuel cell development is of less importance for hydrogen penetration than energy taxation policy. With less fuel cell development there is no European demand for hydrogen from stationary applications, because heat supply from natural gas and oil is more attractive.

7 Hydrogen and climate policy, energy security and urban air quality

7.1 Climate Policy

What could be the role of hydrogen if the world – including Europe and India – would formulate and implement a stringent climate policy? Let us assume, for the purpose of clarity, that an ambitious target of stabilization at 450 ppmv CO_2-eq. is agreed upon by the world community. This would allow global carbon emissions to increase to about 9 GtC/yr in 2015 after which they have to decrease to 4 GtC/yr in 2050 (den Elzen and Lucas, 2003; van Vuuren et al., 2007). Using a cost-optimal allocation scheme with the assumption of global trade in emissions, we can simulate a scenario with such a carbon constraint by introducing a global carbon tax path and examine the reduction of emissions that takes place in each region. For the TIMER OECD-EO baseline scenario (without H_2) this would imply a linearly increasing carbon tax to a level of 700 $/tC, leading to a carbon emission reduction (compared to the baseline) for India and Europe of respectively 70% and 60% by the year 2050.

[14] Other factors include, for instance, the costs and structure of infrastructure, hydrogen production technology development and the availability and development of CCS technology

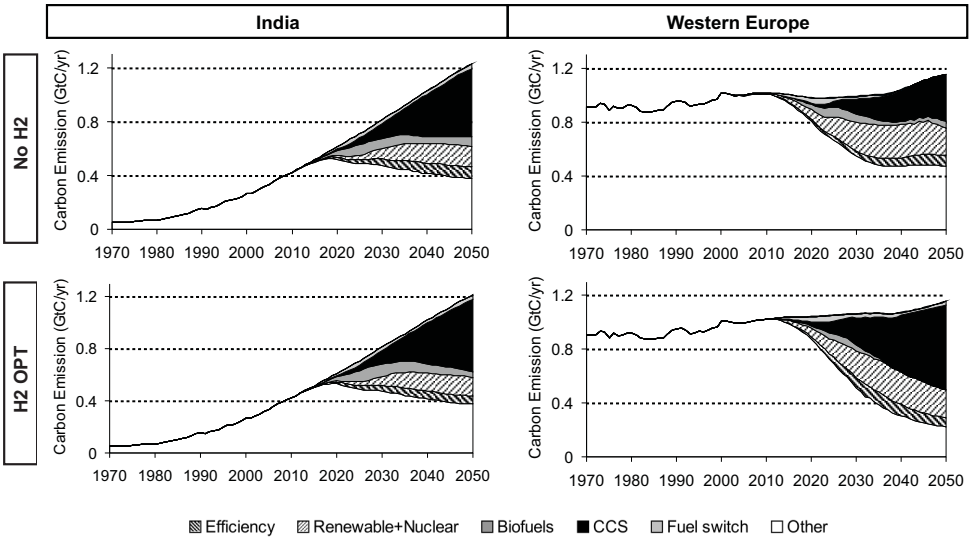

Figure 8.7: Carbon emission reduction measures needed to reach the 450 ppmv stabilisation path for India and Western Europe in scenarios without hydrogen and in the H2OPT scenario

How does such a carbon tax change the energy system and which role does hydrogen play? One would expect in first instance a higher market penetration for hydrogen, as it is a carbon-free fuel. Of course, this may be incorrect: the most preferred route to make hydrogen is from coal, which involves carbon emissions up to 45% higher than using gasoline or diesel from oil. Only if non-carbon options such as renewable or nuclear energy become competitive – which happens earlier because coal is taxed – the hydrogen route will result in lower carbon emissions. Or, alternatively, if CCS is available at costs which keep the coal-to-hydrogen route still (the most) competitive one. Whatever the result, the hydrogen option tends to increase the adaptability of the energy system in case of climate policy.

If we look into the total carbon emissions of the energy system, our simulation results indicate that in India a stringent climate policy will generate drastic changes in the energy system (Figure 8.7 upper left). However, whether the hydrogen option is available does not make a difference (Figure 8.7 lower left). This is because hydrogen plays a minor role in the Indian energy system – only 6% of final energy use in 2050 in the optimistic scenario. It is not competitive with other carbon emission reduction options such as coal-with-CCS for electricity production and biofuels.

For Europe, a stringent climate policy will reduce carbon emissions and hydrogen may make a significant difference (Figure 8.7 upper right and lower right). Without the hydrogen option, carbon emissions in Western Europe stabilize at about 0.5 GtC/yr after 2030. With optimistic hydrogen assumptions, carbon emissions decrease to about 0.3 GtC/yr in 2050 with a global carbon tax rising to only 350 $/tC. This is mainly the result of large-scale implementation of the coal-to-hydrogen-with-CCS route (Figure 8.7 lower

right). Other options, such as renewable and nuclear energy, follow a slightly different path – the prospects for biomass-based transport fuels are negatively affected by the availability of a cheap clean-coal based hydrogen route.

The key difference between India and Europe is that hydrogen is penetrating the energy system at an earlier date in Europe, which implies that most transition barriers – such as high costs and infrastructure development – have assumedly disappeared. This results in a more competitive position in three sectors and thus a larger potential for further penetration as a consequence of climate policy in Europe than in India. Interestingly, the prospects for hydrogen from nuclear energy do not differ in relative sense. With stringent climate policy, both regions may produce about 10-15% of their hydrogen via the nuclear-thermal route in 2050 in both the intermediate and optimistic scenarios. This amounts to 8 GW-H_2 in India and 100 GW-H_2 in European installed capacity by 2050. Nuclear energy becomes competitive as the result of cost increases in fossil fuel due to carbon tax and CCS.

Our simulation results suggest that a stringent climate policy does not accelerate the penetration of hydrogen into the Indian energy system. Evidently, the boost for hydrogen in Western Europe will also affect the potential for hydrogen in other energy markets as learning in hydrogen production technologies spills over to other regions. However, production costs are only a minor part in the cost of hydrogen for end-users (see Table 8.4); the above described impact of energy taxation is more decisive and prevents an increased role for hydrogen in India.

7.2 Energy Security

Another question: will hydrogen decrease the anticipated tensions on the world oil and gas market? To investigate this issue, we compare the fuel trade patterns in Western Europe and India for the scenarios with and without hydrogen (H2PES and H2OPT, see Figure 8.8). One would, again, expect a beneficial effect of competitive hydrogen technology because of its substitution effect in the car fuel market. However, here too, the net effect on fuel trade will depend on how the hydrogen is produced. The simulation results indicate (Figure 8.8) that for optimistic assumptions on hydrogen costs and technology:

- in India, where almost all oil has to be imported, secondary fuel demand for oil in the transport sector will grow much slower and even decline around 2040;
- in Europe, the effect is a temporarily higher oil import than in the baseline, because hydrogen slows down the penetration of biofuels in the transport sector; relative imports of oil also decrease in Europe, from 60% in 2050 without hydrogen to 40% with optimistic hydrogen assumptions;
- because the coal-to-hydrogen route is the most competitive one, with gas-to-hydrogen a good second one, in the longer term coal and gas imports increase in Europe; in India, with its large indigenous coal resources, the net change for coal trade is nearly zero.

The simulation results warrant the conclusion that the availability of competitive hydrogen technology will alleviate most probably the future tensions on the world oil market, largely through fuel diversification towards coal and natural gas. For emerging regions like India, this can mitigate balance-of-payment problems, because imported oil can be substituted by indigenously available coal.

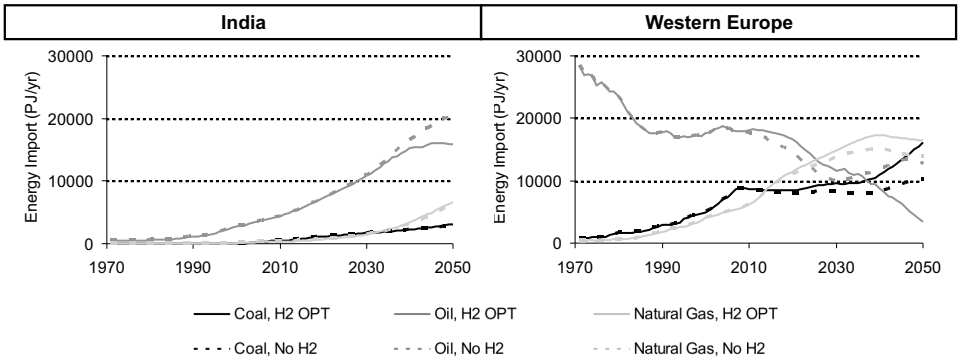

Figure 8.8: Projections for import of fossil energy in India and Western Europe in scenarios with pessimistic (baseline) and optimistic assumptions on hydrogen energy

7.3 Urban Air Quality

A last question to be addressed in this comparison between the prospects of hydrogen for India and Western Europe has to do with air pollution: will hydrogen contribute in a cost-effective way to urban air pollution abatement and what is the role of more stringent environmental policies. This issue is probably the hardest one to answer. Most high-income regions have rather stringent policies for important urban pollutants like NO_x, SO_2 and particulate matter. In low-income regions, environmental policies generally less stringent and future developments are uncertain – although the hypothesis of an Environmental Kuznets Curve suggests more stringent norms with rising income (for discussion, see e.g. (Stern, 2004). Whatever the region: the more stringent and effective environmental policies are, the less difference will hydrogen use make in urban areas, under the assumption that the fuel cell is the dominant end-use technology (see Table 8.5 and 8.6). In this context, the recent shift of three-wheelers and buses towards CNG (see also Section 3.1.3) in many Indian cities indicates two issues. On the one hand, it shows that Indian cities are capable to force a transition towards a different fuel; on the other hand, the resulting air quality improvement decreases the potential benefits of hydrogen. However, there is a second element: how clean will hydrogen production be and how much does it matter where it takes place? If emission standards are low (i.e. India), the net pollution effect may be negative, as emissions at end-use in transport decrease but emissions from hydrogen production increase. This, as with climate and security effects, will depend to a significant degree upon the preferred hydrogen production route and its cost and technology characteristics.

Table 8.5: Annual SO_2 emissions (Tg SO_2) from transport, power and hydrogen production and total energy use for scenarios without hydrogen and with optimistic hydrogen assumptions, and with stringent Air Pollution Policy (APP)

		India		Western Europe	
		2000	**2050**	**2000**	**2050**
Transport	Baseline – No H2	0.34	0.27	0.30	0.17
	N2 OPT		0.11		0.05
	APP – No H2		0.04		0.02
	APP – H2 OPT		0.02		0.01
Power and H2 production	Baseline – No H2	1.38	5.98	1.55	0.35
	N2 OPT		6.01		0.29
	APP – No H2		0.18		0.25
	APP – H2 OPT		0.18		0.21
Total	Baseline – No H2	3.45	11.09	4.45	2.02
	N2 OPT		10.80		1.77
	APP – No H2		0.79		0.49
	APP – H2 OPT		0.77		0.43

Table 8.6: Annual NO_x emissions (Tg NO_x) from transport, power and hydrogen production and total energy use for scenarios without hydrogen and with optimistic hydrogen assumptions, and with stringent Air Pollution Policy (APP)

		India		Western Europe	
		2000	**2050**	**2000**	**2050**
Transport	Baseline – No H2	0.32	0.37	1.88	0.58
	N2 OPT		0.15		0.16
	APP – No H2		0.08		0.43
	APP – H2 OPT		0.03		0.12
Power and H2 production	Baseline – No H2	0.59	2.87	0.56	0.39
	N2 OPT		3.27		0.57
	APP – No H2		0.23		0.17
	APP – H2 OPT		0.26		0.27
Total	Baseline – No H2	1.58	4.41	3.02	1.57
	N2 OPT		4.58		1.22
	APP – No H2		0.71		0.81
	APP – H2 OPT		0.69		0.57

8 Discussion and Conclusion

In this study we used the TIMER global energy model to analyse the potential role of hydrogen in two different world-regions, Western Europe and India, as representatives of high and low income regions. The model permits an exploration of what might happen with the energy systems in these regions if hydrogen technologies are assumed to become available. In order to explore the ranges of possible future developments, we used three different scenarios on the development of costs and technology of hydrogen, based on ranges in literature. Some results are similar in all scenarios, and might be considered plausible impacts of hydrogen on the energy system. Other results are dependent on the specific scenario assumptions and should therefore be approached more carefully and interpreted in the scenario context. Our main findings are:

- Considerable cost reductions and technology development are needed for hydrogen energy technology, in order to play are major role in the energy systems of both India

and Western Europe before 2050. Only in our most optimistic scenario hydrogen is deployed at a large scale.

- Two factors are crucial for the penetration of hydrogen in final energy use:
  a) Energy taxation policy; in many low income regions energy, is hardly taxed or even subsidised. This restricts policy options to stimulate alternative fuels and limits the potential for hydrogen energy application.
  b) Fuel cell technology development; fuel cells are the key technology for the efficient application of hydrogen; the level of cost reductions that can be achieved is very much determining the success of hydrogen energy.

- The availability of a competitive hydrogen option in the energy system has several attractive trade-offs:
  a) Mitigation of carbon emissions can be cheaper; the coal-to-hydrogen route makes carbon capture and storage an available option for the transport sector
  b) There is probably less pressure on the international oil market; as hydrogen substitutes oil in the transport sector, the international demand for oil can be significantly reduced.
  c) Possibly, urban air quality can be improved; this is contingent upon the specific locations of hydrogen application (mostly in urban centres) and production (mostly in less populated areas) and the autonomous policy process of improved emission standards (generally, lower standards in developing countries).

- Prospects for hydrogen are more limited in India than in Europe, mainly due to lower energy prices (and taxes). Therefore, the most direct advantage of hydrogen for India might be that the international oil market potentially relaxes, while at the same time the need for imports slightly decreases. The projections for India show that hydrogen does not play an important role for carbon mitigation and that air quality improvement depends strongly on the improvement of emission standards.

- The model results indicate a high potential for hydrogen in Western Europe. The overall advantage of hydrogen for Western Europe can be summarised as a higher domestic carbon reduction potential at lower cost, decreased oil imports and an attractive option to improve air quality.

Appendix: Key assumptions for the hydrogen scenarios

Table A 12: Scenario assumptions on hydrogen production efficiency

	Coal gasification (%)	*Oil (POX) (%)*	*Gas (SMR) (%)*	*Biomass gasification (%)*	*Electrolysis (%)*	*Nuclear Th. (PJH2/TonneU)*	*Solar thermal*	*Small-Scale SMR (%)*
	Pessimistic							
2005-2100	*60*	*50*	*75*	*50*	*75*	*109*	*N/A*	*75*
	Intermediate							
2005	*60*	*50*	*75*	*50*	*80*	*109*	*N/A*	*75*
2050	*62.5*	*70*	*82*	*62.5*	*82*	*109*	*N/A*	*82*
2100	*65*	*75*	*85*	*65*	*85*	*109*	*N/A*	*85*
	Optimistic							
2005	*60*	*70*	*75*	*50*	*80*	*109*	*N/A*	*75*
2030	*62.5*	*72.5*	*82.5*	*62.5*	*82*	*109*	*N/A*	*82*
2100	*67.5*	*77.5*	*87.5*	*67.5*	*85*	*109*	*N/A*	*85*

Table A 13: Scenario assumptions on initial hydrogen production investment costs ($\$_{1995}$/kW) and technological learning progress ratio

Variable	*Coal gasification*	*Oil (POX)*	*Gas (SMR)*	*Biomass gasification*	*Electrolysis*	*Nuclear Thermal*	*Solar thermal*	*Small-Scale SMR*
	Pessimistic							
Init. Inv. Cost ($/kW)	*1150*	*700*	*400*	*1150*	*575*	*1312*	*2875*	*3000*
Progress Ratio	*0.88*	*0.88*	*0.88*	*0.88*	*0.88*	*0.88*	*0.88*	*0.88*
	Intermediate							
Init. Inv. Cost ($/kW)	*1000*	*600*	*350*	*1000*	*500*	*1312*	*2500*	*3000*
Progress Ratio	*0.84*	*0.84*	*0.84*	*0.84*	*0.84*	*0.84*	*0.84*	*0.84*
	Optimistic							
Init. Inv. Cost ($/kW)	*900*	*550*	*300*	*900*	*450*	*1312*	*2250*	*2700*
Progress Ratio	0.785	0.785	0.785	0.785	0.785	0.785	0.785	0.785

Table A 14: Assumptions on carbon capture and sequestration

Technology	*Capital Cost ($\$_{1995}$/kW)*	*Efficiency loss (%)*	*CO_2 Capture (%)*
Coal (Gasification)	*197*	*3*	*95*
Oil (POX)	*185*	*2*	*95*
Natural Gas (SMR)	*76*	*2*	*88*

Table A 15: Scenario assumptions for hydrogen transport cost ($\$_{1995}$/GJ-$H_2$/ capita)

Hydrogen demand	*Pessimistic*	*Intermediate*	*Optimistic*
0 (GJ/capita)	*12*	*10*	*10*
20 (GJ/capita)	*10*	*6.5*	*5*
50 (GJ/capita)	*8*	*5*	*2*
70 (GJ/capita)	*6*	*3*	*2*
100 (GJ/capita)	*6*	*3*	*2*

Table A 16: Scenario assumptions for local hydrogen distribution cost and refuelling ($\$_{1995}$/GJ)

t	*Industry*	*Transport*	*Residential*	*Services*	*Other*
	Pessimistic				
2005	*2*	*6*	*3*	*2*	*3*
2100	*1*	*4*	*2*	*1*	*3*
	Intermediate				
2005	*2*	*5*	*3*	*2*	*3*
2050	*1*	*3*	*2*	*1*	*3*
2100	*0.75*	*2*	*1.5*	*0.75*	*3*
	Optimistic				
2005	*1*	*4.5*	*2*	*1*	*3*
2030	*0.75*	*3*	*1.5*	*0.75*	*3*
2100	*0.50*	*1*	*1*	*0.50*	*3*

Table A 17: Scenario assumptions on fuel cell investment cost ($\$_{1995}$/kW) and end-use efficiency in the transport sector

t	*Industry*	*Residential*	*Service*	*Other*	*Transport*	*FC η transport sector*
	Pessimistic					
2005	*1500*	*1400*	*1400*	*1500*	*1200*	*36 %*
2100	*800*	*500*	*500*	*800*	*250*	
	Intermediate					
2005	*1500*	*1400*	*1400*	*1500*	*1200*	*36 %*
2050	*800*	*500*	*500*	*800*	*250*	*45 %*
2100	*500*	*300*	*300*	*500*	*200*	*45 %*
	Optimistic					
2005	*1350*	*1400*	*1400*	*1500*	*1200*	*40 %*
2030	*100*	*100*	*100*	*100*	*100*	*50 %*
2100	*50*	*50*	*50*	*100*	*50*	*60 %*

Chapter 9: Summary and Conclusion

1 Introduction and scope

Energy plays a major role in several sustainability issues, such as climate change, depletion of resources and indoor and local air pollution. Historically, global energy use has been dominated by energy consumption in industrialised countries. However, this is changing as energy consumption in developing countries increased from 26% in total global energy use in 1975 to 46% in 2005. Despite the increasing importance of developing countries for global energy use, energy poverty remains an important issue. Two billion people have no or unreliable access to modern energy forms, while recently increasing energy prices have put pressure on the affordability of energy for the poor that have access to modern fuels. In contrast to the situation in industrialised countries, where energy related sustainability problems refer to impacts of energy use (e.g. pollution or depletion), here, energy use is crucial to fulfil basic needs and increase welfare. In recent years, it is increasingly recognised that global climate policy can only be effective if it connects to the policy agenda of developing countries.

Scientific understanding of the dynamics of energy use in developing countries is limited. Information and knowledge are fragmented over many local case-studies. Global databases often have reliable data on issues that are important for industrialised regions (like CO_2 emissions) but lack data on energy poverty issues (like access to electricity). In energy analysis, models are used to explore and understand possible future changes in energy systems. However, only few global energy models account explicitly for the specific dynamics of developing countries. Most energy models are developed in industrialised countries and implicitly assume that the future of developing countries can be derived from experiences in developed countries. First of all, this hypothesis is not necessarily correct as the situation in developing countries is not necessarily comparable and the context for development might have changed. Secondly, it means that currently important energy issues in developing countries are only indirectly or not at all dealt with in these models. Hence, future projections on energy use in developing countries could be unreliable and synergies between development and climate policies cannot be identified and addressed by current global energy models.

Increased resource depletion, import dependence, climate change and air pollution put pressure on the technology choices in the energy system. In some ways, this constrains the future energy systems of developing countries. On the positive side, however, new technologies for energy production and conversion are being developed and applied, mostly aimed at affordable, clean and reliable energy systems. One of the energy carriers that may play an important role is hydrogen, because it can be produced from all other energy

carriers and contributes to the diversification of energy sources. Besides, it has the potential to reduce emission of local air pollutants and greenhouse gases.

Based on this, the problem formulation for this dissertation can be summarised as:

- Energy use in developing countries is increasingly important for many global sustainability issues.
- Global energy models are used to explore possible future developments of the global energy system and provide a basis for (contentious) energy and environmental policies.
- Practically all global energy models are constructed in industrialised regions and focus primarily on issues on the political agenda of today's high-income regions. It is implicitly assumed that energy systems in developing regions can be represented by models that are based on experiences in industrialised regions.
- However, energy systems in developing countries involve different dynamics and the energy policy agenda of developing countries includes several issues that were not important for industrialised regions during the last decades.
- Therefore, current global energy models are not necessarily suited to address several key-issues of energy systems in developing countries.

The main question addressed in this thesis is:

How can the performance of global energy models, especially the TIMER model, be improved such that they better represent and forecast energy system behaviour in developing regions?

Several research questions have been derived from this:

I. *What are the main differences in dynamics between energy systems in developed and developing regions?*
II. *How can we evaluate the performance of the TIMER model at the regional level and can the model be parameterised such that it better simulates energy use in developing regions?*
III. *How can the model structure of TIMER be improved to better represent mechanisms that drive energy use in developing regions?*
IV. *What are the differences in potential roles of new energy technologies, especially hydrogen, between developed and developing regions?*

In this dissertation, we use the global energy model TIMER 2.0 (de Vries et al., 2001; van Vuuren et al., 2006b). This is a scientific and policy-relevant global energy model, which has recently been used in several influential scenario studies. In combination with the FAIR model (den Elzen and Lucas, 2005) it is used to explore different burden-sharing regimes for greenhouse gas mitigation between developed and developing countries. TIMER simulates energy use for 26 world regions; hence, it explicitly includes many developing regions.

2 Summary and conclusion of the chapters

The first part of this thesis explores *research question I.* **Chapter 2** evaluates several generic concepts of energy and development and explores how these relate to the results for Asia of the models that were used in the 2001 Special Report on Emission Scenarios (SRES) of the Intergovernmental Panel on Climate Change (IPCC). The first concept is the *energy ladder*, postulating that households switch to cleaner and more reliable fuels with increasing income. Although this trend is generally observed in long-term data-series, people often use more than one fuel and more explanations than only income play a role in fuel choices. We use the shares of fuelwood and electricity in final energy consumption to analyse the energy ladder in the SRES model results. We find that only three of the six models include fuelwood. These three models show a rapidly declining share of traditional fuels in their scenarios and all SRES models project an increasing share of electricity but with wide variations. In other words, half the models miss an energy source that constitutes up to 80% of energy systems in developing regions. Moreover, the absence of explicit modelling of electrification adds to the uncertainty of electricity use projections.

The second concept that we looked at is the *Environmental Kuznets Curve* (EKC). It hypothesises that 'environmental pressure' follows an inverted U-shape with economic development, increasing at low income levels and decreasing with higher incomes. This concept is sometimes considered a lawlike metamodel, but it is debated in literature because its formulation is often in unclear variables or units (see Chapter 2) and it is observed only for limited regions or periods. The results of the SRES models for Asia follow an EKC for sulphur emissions per capita, but with wide variation between the models. Projections for carbon emission per capita indicate an EKC as well in the SRES scenarios – although these are without climate-policy.

The second part of Chapter 2 analyses a series of key-issues on energy and development with respect to data and historic trends and the relevance for global energy models. Key-issues of transitions within the energy system are *traditional fuels* and *electrification*.

- *Fuelwood* use per capita declines historically, also in regions with decreasing income level. However, at the same time total absolute fuelwood use increased, putting pressure on limited resources. The relevance for global energy models is that fuelwood constitutes a major energy source in developing countries. Traditional fuels are important in current energy policies due to resource scarcity and indoor air pollution/health. Also, the transition from traditional to commercial fuels influences future projections.
- Analysing *electrification* suffers from limited data availability and variation in definitions. In general, access to electricity increases with Gross Domestic Product (GDP) per capita and is higher in urban than in rural regions. Electrification is relevant for global energy models, because it influences the available end-use functions and the structure of electricity generation. Most models assume implicitly that electrification levels increase when projecting increasing future electricity use with rising incomes.

Another series of issues has to do with the description of economic activity: *structural change*, *income distribution* and *informal economies*.

- *Structural change* describes the generally observed trend of changing value added and employment from agriculture to industry and services. However, this process varies clearly between countries (e.g. China is industry-oriented, while India focuses on services). The relevance is that it marks stages of economic development and explains changes in energy intensity. Agriculture is ignored in most global energy models, although it is currently a major energy consuming sector in many developing countries.
- Data on *income distribution* show that developing countries do not necessarily have more unequal distribution, but there is much more variation among low-income countries. The distribution of welfare over the population is relevant, because different income groups have different energy behaviour and determine whether 'the average' is representative.
- The *informal economy* is generally larger in developing countries than in industrialised regions. Understanding of informal activity is essential to adequately describe economic activity. Part of the economic development process is formalisation of the informal economy, hence not all income growth does necessarily coincide with an increase in activities (and thus in energy use). This process is partly related to the question whether to use Purchasing Power Parity (PPP) or Market Exchange Rate (MER)-based income measures as driver in scenario studies. However, as both metrics focus on the formal economy, this relation is only indirect and somewhat complicated. Further study of both the process of formalisation and PPP-based income measures will be needed.

A final series of issues is related to the changing context of development: *depletion of fossil resources, climate change and air pollution*. These issues are likely to influence the development of energy systems in developing countries over the next decades – probably in more and more diverse ways than in industrialised regions during the last decades (the regions and period on which many global energy models are based). Including these issues in global energy models is expected to produce novel insights and increase relevance and credibility of these models for developing regions. However, quantitative modelling may not always be possible due to data constraints and limited available concepts.

Chapter 3 focuses on resource depletion and climate change, two factors that may imply that the development trajectory of low-income countries does not necessarily follow that of high-income countries. It describes the application of a simple system-dynamics model (SUSCLIME) that simulates population, economic activity, energy and climate dynamics in a highly stylized form. The model is used in two variants: 1) using a set of decision rules to allocate investments on the basis of current information, and 2) simulating forward looking agents who optimise some goal function by applying policy measures and assessing future effects of their strategy. We conduct a series of experiments in order to identify strategies to deal effectively with the simultaneous impact of resource depletion and climate change.

We find that low-income countries are more vulnerable to both oil scarcity and climate change. The reason is that they are more vulnerable to energy price increase and volatility and the costs of mitigation of and/or adaptation to climate change in the first, low-productive stages of economic growth. Cheaply imported energy is the preferred option to avoid endogenous resource depletion, but for a low-income country there is the danger of imbalance of payment and spiralling debt. As to climate change, developing countries balance between spending scarce resources on short-term emission reduction in order to avoid long-term damage – or hoping to sustain high economic growth rates in the short-term to be better prepared for adaptation in the long-term. Our experiments suggest that it is attractive for low-income regions to postpone climate policy until a certain income level is reached. However, the economic 'take off' phase of surging income growth, capital accumulation and productivity increase should be combined with climate policy if such policy is to be effective. A co-benefit of a long-term focus on minimising greenhouse gas emissions is that it also slows down oil resource depletion. A short-term policy to reduce oil dependence will, on the other hand, probably have not much synergy with climate policy, because in a world of globally traded oil it will mostly imply fossil fuel imports.

The second part of this thesis focuses on *research question II*, evaluating the performance of the TIMER energy demand model on the regional level. **Chapter 4** describes a method to identify uncertainty from model calibration and the application of this method to transport sector energy use modelling. Starting point is the notion that there are limited data available for the development and calibration of global energy models. Therefore, models from different scientific paradigms can co-exist based on different interpretations of the same data on historic energy use. This model structure uncertainty may result in wide variation in future projections. For example, system-dynamics and physical energy models generally assume that demand for energy services will saturate at some point and find evidence in trends in certain sectors (e.g residential energy use). Economic models in general assume that energy and income remain coupled and find evidence for that in econometric relationships between historic data. However, also within a single model, there can be room for different sets of parameter values that simulate historic energy use equally well, but based on different historic interpretations and resulting in different future projections. The phenomenon that many plausible model implementations co-exist that cannot easily be rejected is called equifinality.

We developed a method to automatically calibrate models and identify sets of parameter values that perform reasonably against historic data. These calibrated sets are obtained by varying the main model parameters within a limited range, while searching to minimise the error between observations and model results. Repeating this procedure many times, initialised at different locations in the parameter space, generates a series of (different) calibrated sets of parameter values. This method is related to both nonlinear regression methods (for instance PEST or UCODE) and sequential Monte Carlo based methods (like GLUE or SimLab).

We applied this method for transport sector energy demand modelling in the TIMER model, for several regions: USA, Western Europe, Brazil, Russia, India and China, for the period 1971-2003. This energy demand model simulates the demand for energy on the basis of three major processes: energy demand as a function of income (structural change), technology development (in energy efficiency) and sensitivity to energy price changes. This model is macro-economically oriented and does not include physical indicators like vehicle ownership and concepts like time- and budget constraints.

We find that the calibrated parameter values are mostly within a limited range of the parameter space and only about 10% of the calibration results are identified as outliers. Hence, we have sufficient confidence in the mathematical adequacy of this calibration method. Forcing the inferred model structure to simulate transport sector energy use on the regional level leads to the identification of several clusters within the parameter space, hence equifinality. We find that the TIMER transport energy demand model generally performs better for Western Europe and the USA than for developing regions. This can be explained from the fact that the model does not account for specific dynamics of energy use in these regions, though the poor data quality for these regions might also play a role. This identified equifinality is mainly related to the question whether structural change or efficiency improvements were the major explanatory factor and, if the latter, whether autonomous technology or energy price changes were most influential. This is not without relevance: the uncertainty in, and diverging interpretations of parameter values significantly influence future energy use projections even for a rather short time horizon (2030). These projections were compared to the OECD Environmental Outlook scenario, which was developed by the TIMER modellers without automated calibration tools and follows the IEA World Energy Outlook projections. Our results suggest slightly lower future transport sector energy use than in the reference scenario.

In **Chapter 5**, we used the above described method to analyse residential energy demand modelling for different regions in TIMER. Also here, the focus is on the existence of different model implementations and the impact on future projections. The structure of the residential model is similar as for transport energy demand: structural change, technology development and price impacts. This means that end-use functions and intermediate physical indicators (like floor space) are not explicitly considered.

We find that the TIMER model also performs better for industrialised regions than for developing countries in the case of residential energy use for the period 1971-2003. Historically, total fuel use in Western Europe and the USA has been declining or constant, which is well-simulated with declining energy intensity. We also find that price impacts are more important for the USA than for Europe, as a result of higher taxes in the latter. For developing countries, adequate calibration is more difficult because energy use in these regions shows divergent trends, reflecting specific local circumstances which are outside the scope of a (global) energy model like TIMER. For instance, Chinese fuel use decreased rapidly during the 1990s due to the phase out of coal, whereas Brazilian fuel use decreased during the 1970s, explained from improved efficiency in traditional fuel use. Similarly, the exponential growth of electricity use can also only partly be reproduced. For instance, in

Brazil it kept rising exponentially even in times of fluctuating economic activity. We could not identify clear cases of equifinality; hence, all calibrated parameter values clustered in a single area or had a flat distribution with model error. Nevertheless, using the (minor) variation in parameter values from the uncertainty analysis suggests a broad range of projections for 2030, often above the reference scenario. It should be noted here that the poor data quality for developing countries also plays a role. We identified options to improve the model and better account for dynamics in developing countries: 1) specify energy end-use functions, 2) better account for decreasing income and 3) explicitly account for local policies.

Chapter 6 focuses on *research question III*. It explores an alternative model structure to include the dynamics of residential energy use in developing regions in the TIMER model, starting with India. To include the heterogeneity in income distribution, energy use is determined for urban and rural areas, each further divided in income quintiles. The model structure is bottom-up, supposing that physical indicators better represent actual activity in developing countries. The model distinguishes five end-use functions: cooking, water heating, space heating, lighting and appliances. Fuel use is assumed to follow the energy ladder: cleaner, more convenient, but also more expensive energy options are preferred at higher income levels. Ownership of appliances follows the observed Indian preference ladder: fan, TV, refrigerator, and heavier appliances. We constructed two scenarios to explore the consequences of two variables that are usually not considered in global energy models and that might be important for developing countries: income distribution and electrification.

We find that this model simulates historic Indian residential energy use better than the existing TIMER energy demand model and provides more insight in the determinants of residential energy use. For instance, electricity end-use is no longer dominated by lighting and increases rapidly as result of increasing ownership of TV's and refrigerators. The future projections indicate that total Indian residential energy use in 2050 might increase 65-75% compared to 2005, whereas total residential carbon emissions in 2050 may increase up to 9-10 times the 2005 level. Variation in income distribution and electrification significantly influences future projections. While more equal income distribution (with the same overall income) and rural electrification lead to less (energy) poverty, we find a trade-off in terms of higher CO_2 emissions due to increased electricity use. However, higher income for the poor also enhances the transition to commercial fuels, which leads to much less indoor air pollution.

The final part of this thesis explores *research question IV*: the potential role of new energy technologies in developed and developing countries. While new technologies are often discussed in the context of industrialised countries, some of these technologies may actually penetrate much faster in some low-income regions due the leapfrogging opportunities stemming from lack of infrastructures and vested interests. Examples are the new car designs recently introduced in India, including the small cheap Tata Nano or the compressed air vehicle Tata OneCAT. We focus here on a single new energy carrier/technology: *hydrogen*.

As an introduction, **Chapter 7** describes the modelling of hydrogen energy in the TIMER model and the construction of set of hydrogen-use scenarios. This chapter analyses the potential role of hydrogen in the global energy system and explores the link with greenhouse gas emissions and climate policy. The model includes hydrogen production from the major primary energy sources. Initially, only expensive options are available, like small-scale steam methane reforming or distribution by truck. Large-scale production becomes attractive if hydrogen use increases and pipeline distribution is economically feasible. Hydrogen end-use can take place in fuel cells in five economic sectors: industry, transport, residential, services and other. Three hydrogen scenarios were constructed on the basis of available literature: a pessimistic, intermediate and optimistic scenario. These scenarios are combined with a stringent climate policy scenario.

We find that without specific stimuli, hydrogen will probably not play an important role in the global energy system before 2050, neither with nor without climate policy. Hydrogen is only introduced before 2050 under optimistic assumptions. Coal and natural gas based technologies were identified as the most attractive hydrogen production options, both with and without climate policy. In the latter case, these technologies are combined with carbon capture and sequestration. Due to the attractiveness of coal, we found that carbon emissions from energy systems with high penetration levels of hydrogen are higher than those of systems without hydrogen in absence of climate policy. However, energy systems with hydrogen respond more flexible and with lower abatement cost to climate policy.

Chapter 8 analyses the potential role of hydrogen in the energy systems of a developing country and an industrialised region: India and Western Europe. It uses the same model and scenarios as described for Chapter 7, elaborated with regional information. The analysis focuses on the main arguments in favour of an energy transition towards hydrogen: climate policy, energy security and urban air pollution.

We find that, even under optimistic assumptions, there is probably a minor role for hydrogen in India before 2050. The scenarios indicate application in the transport sector, while hydrogen production in India is dominated by coal. This limited penetration is largely explained from low energy taxes in developing countries (although Indian taxes increased in recent years). This limits policy options to stimulate alternative fuels through tax exemption. In Europe, hydrogen has some chances under the intermediate scenario, but in the optimistic case it is used in both transport and stationary applications. Hydrogen production in Europe is dominated by coal and natural gas. Climate policy is cheaper with hydrogen, but this is mainly interesting for regions with high penetration rates, like Europe. For India, which is projected to import all its oil in 2050, application of hydrogen in the transport sector directly decreases oil imports. In Europe, hydrogen decreases oil imports, but increases imports of coal and natural gas; hence, diversifying energy use. With respect to urban air pollution, the results are case specific and depending on strictness of emission policy.

3 Conclusion, discussion and recommendations

We conclude that current global energy models have major deficiencies in representing the dynamics of energy systems in developing countries. Qualitatively, these models exclude several issues that characterise energy systems in developing countries. Quantitatively, we find that the energy demand model structure of TIMER performs better for industrialised regions than for developing regions.

We conclude that the performance of global energy models with respect to energy systems in developing regions can be improved by:

1. *Explicitly incorporating key-issues of energy systems in developing countries.*
   a. *Traditional fuel use.* Transitions from traditional to commercial fuels are an essential element of energy systems in developing countries, which can be understood and simulated as function of increasing investment capability to overcome front-end investment barriers.
   b. *Electrification*. Access to electricity influences welfare, energy use and electricity generation, but is hardly described explicitly in models. For modelling, it can be related to income and population density.
   c. *Income distribution*. Income development is found to be relevant for energy consumption projections. It can be represented by simple algorithms to disaggregate average income levels to multiple income groups.
   d. *Urban and rural areas.* Separate modelling of urban and rural energy systems accounts for the increasing difference in energy behaviour between modern urban centres and underdeveloped rural areas.
2. *Using physical indicators as basis for energy modelling*. Informal activities complicate adequate description of economic activity in developing countries. Data on physical activity are increasingly available, enhancing analysis of the causal relations between economic activity and energy use.
3. *Focusing on regional differences in energy trends and policies.* Developing countries are not a homogeneous group. Global results and projections are the sum of regional model outcomes. Hence, model performance can be improved by model calibration to regional data and discussing assumptions and results with regional experts.

Finally, we conclude that the future energy transition in developing countries is likely to be different from the historic energy transition in industrialised regions. Three major differences are the availability of new technologies, depletion of cheap oil resources and climate change. On the short-term, the potential role of new technologies seems limited in developing countries. However, depletion of cheap oil resources and climate change may drive a long-term transition towards coal-based fuels and/or increased energy-efficiency and renewables.

Two issues need some more discussion: *data availability and quality* and the *scope and limitations of this research.* First, analysing energy systems and economic behaviour in

developing countries is known to suffer from a lack of consistently collected and reliable data. Many indicators that are relevant for model development, like the number of households with electricity grid connection or the amount of fuel use, are not measured or inconsistently reported over time. Even an organisation like the Indian NSSO, which has an outstanding tradition in statistical data publication and household surveys, regularly changes the structure of its data-tables and recall periods for surveys. This complicates the formulation of models and the statistical extraction of relations between system-variables. A second issue is the quality of the data. Much of the information that is needed to improve global energy models is available form survey studies, whose quality depends on the questionnaires, samples and training of interviewers. Some may argue that there are too few data to analyse and simulate energy systems in developing countries, but we found that the combination of many different data sources and consultation of local experts provides a workable situation.

The choices that were made in this dissertation influence generalisation of the results and recommendations. This thesis focused on a single global energy model: TIMER, a system dynamics simulation model. Although this model is methodologically different than several other global energy models, the issues that we discussed in this thesis are still relevant for other models (see for instance Chapter 2). Our focus on only three sub-modules of TIMER does not imply that issues of developing countries are not important in other parts of the energy system. Differences between developed and developing regions are related to many aspects of global energy models, for instance energy use, energy supply, infrastructure or operational decisions.

Based on the considerations mentioned above, the following *recommendations* are made. With respect to further development of the TIMER model:

a. *Further implementation of the residential energy use model.* This thesis includes a new model for residential energy consumption in India. This model is applicable in the context of TIMER if it is implemented, tested and applied for other world regions.
b. *Development of a new transport sector energy demand model.* The analysis of calibration uncertainty revealed weaknesses in modelling transport sector energy demand. A new model for transport sector energy, based on physical indicators and the concepts of time and money constraints, could enhance insight and provide more options for regional differentiation.
c. *Explicit representation of infrastructure development.* This dissertation hardly deals with the development of infrastructure. However, the construction and availability of roads, railways, electricity grids and distribution networks for LPG, kerosene or natural gas are essential for energy consumption. The new bottom-up orientated energy use models can be further improved by aggregate indictors for infrastructure and quantification of the relationship between infrastructure and energy consumption;
d. *Elaborate analysis of uncertainty from model calibration.* It was found that uncertainty from model calibration is important for future projections of energy use in the residential and transport sectors. Therefore, we recommend assessing calibration uncertainty in energy use models for other sectors and regions as well.

With respect to global energy modelling in general:

a. *Explicit incorporation of development related dynamics in global energy models.* Traditional fuels, electrification, income distribution and urban/rural differences are relevant issues for energy systems in developing countries. This thesis provides a methodological basis to incorporate these issues global energy models. If these issues are implemented, global energy models can be used to explore potential interaction and synergies of development and climate policies.
b. *Increased attention to regional differences and developments*. World regions vary in their pace of development, preferences and energy issues. Also, technologies are not globally homogeneously applied and vary between regions. For instance, the use of compressed air vehicles might be more likely in developing regions and the potential for energy supply technologies, like concentrated solar power, is not evenly distributed. Regionally important energy issues influence energy policies, which determine future developments. Because global projections are the sum of regional model results, it is important that global energy models are credible and representative at the regional level.
c. *Increased attention for uncertainty from model calibration.* We found that uncertainty from model calibration has major implications for future projections. We developed a tool to identify this form of uncertainty and recommend its application by models that are rooted in the simulation of historic energy use.
d. *Feed global energy models with information from developing countries*. Local data and expert visions are valuable for global energy models. Increased cooperation between global modellers and regional institutes from developing countries might enhance global energy models.
e. *More energy modelling in developing countries.* Local experts have better understanding of relevant energy issues and dynamics of energy systems in developing countries. Development of new energy models from a developing country perspective or the use of global energy models by local research groups would be a valuable addition to the energy modelling community. The AIM model (Kainuma et al., 2003) is an example of such cooperation. This model is coordinated by IGES in Japan and developed and applied by local modelling groups throughout Asia.

Samenvatting en Conclusie

1 Inleiding

Energiegebruik speelt een belangrijke rol bij verschillende duurzaamheidproblemen zoals klimaatverandering, uitputting van hulpbronnen en luchtverontreiniging. De afgelopen decennia is het mondiale energiegebruik gedomineerd door geïndustrialiseerde landen, maar deze trend is kenterend. Het aandeel van ontwikkelingslanden[1] in het mondiale energiegebruik is toegenomen van 26% in 1975 tot 46% in 2005. Ondanks de toegenomen rol van ontwikkelingslanden in het mondiale energiegebruik blijft energiearmoede een belangrijk onderwerp. Twee miljard mensen hebben geen of weinig toegang tot moderne vormen van energie (zoals elektriciteit en LPG) en recente prijsstijgingen hebben de betaalbaarheid van energie voor arme groepen beperkt. In geïndustrialiseerde landen heeft energiebeleid voornamelijk betrekking op de duurzaamheid van energiegebruik (zoals vervuiling of uitputting) maar in ontwikkelingslanden is energie van cruciaal belang om te voorzien in basisbehoeften en om welvaart te genereren. In de afgelopen jaren is duidelijk geworden dat mondiaal klimaatbeleid alleen effectief kan zijn als het aansluit bij de politieke agenda van ontwikkelingslanden.

Het wetenschappelijke inzicht in de dynamiek van energiegebruik in ontwikkelingslanden is beperkt. Informatie en kennis zijn versnipperd over een groot aantal lokale onderzoeken. Mondiale databases hebben vaak betrouwbare gegevens over onderwerpen die van belang zijn voor geïndustrialiseerde regio's (zoals CO_2-uitstoot) maar ontberen gegevens over energiearmoede (zoals toegang tot elektriciteit). In het vakgebied van de energieanalyse worden computermodellen gebruikt om mogelijke toekomstige veranderingen in energiesystemen te verkennen en te begrijpen. Slechts enkele mondiale energiemodellen bevatten echter expliciet de specifieke dynamiek van het energiegebruik in ontwikkelingslanden. De meeste energiemodellen zijn ontwikkeld in geïndustrialiseerde landen en gaan er impliciet vanuit dat de toekomst van ontwikkelingslanden kan worden afgeleid uit (recente) ervaringen in geïndustrialiseerde regio’s. Ten eerste is dit niet noodzakelijk correct: de situatie in ontwikkelingslanden is niet altijd vergelijkbaar met rijke regio’s en de context voor ontwikkeling is gedurende de afgelopen decennia veranderd. Ten tweede betekent het dat belangrijke aspecten van energiegebruik in ontwikkelingslanden (zoals brandhoutgebruik of toegang tot elektriciteit) momenteel slechts indirect of helemaal niet behandeld worden door deze modellen. Daardoor kunnen prognoses van energiegebruik in ontwikkelingslanden onbetrouwbaar zijn en kan potentiële synergie tussen ontwikkelings- en klimaatbeleid niet worden geïdentificeerd en gekwantificeerd door de huidige generatie mondiale energiemodellen.

Veranderende omstandigheden, zoals uitputting van hulpbronnen, afhankelijkheid van import, klimaatverandering en luchtverontreiniging, beïnvloeden de keuze voor

[1] In dit proefschrift zijn ontwikkelingslanden gedefinieerd als alle landen in de laag, middel-lage en middel-hoge inkomensklassen van de Wereldbank, met uitzondering van de vroegere Sovjet Unie en Centraal Europese landen.

technologieën in het energiesysteem. Dit is enerzijds een beperking voor energiesystemen in ontwikkelinglanden, bijvoorbeeld omdat goedkope olievoorraden uitgeput raken en duurdere opties overblijven. Anderzijds worden er momenteel veel nieuwe energietechnologieën ontwikkeld en toegepast, meestal gericht op een betaalbare, schone en betrouwbare energievoorziening. Een van de energiedragers die een belangrijke rol kunnen spelen in toekomstige energiesystemen is waterstof. Het kan worden geproduceerd uit alle andere energiedragers en draagt bij aan diversificatie van energiebronnen. Daarnaast kan het bijdragen aan vermindering van de uitstoot van luchtverontreinigende stoffen en broeikasgassen.

De probleemstelling voor dit proefschrift is:
- Energiegebruik in ontwikkelingslanden wordt steeds belangrijker voor mondiale duurzaamheid;
- Mondiale energiemodellen worden gebruikt voor het verkennen van mogelijke ontwikkelingen in het wereldenergiesysteem en vormen een basis voor (soms omstreden) energie- en milieubeleid;
- Vrijwel alle mondiale energiemodellen zijn ontwikkeld in geïndustrialiseerde landen en richten zich primair de politieke agenda van deze regio's. Er wordt impliciet aangenomen dat energiesystemen in ontwikkelingsregio's kunnen worden gesimuleerd met modellen die zijn gebaseerd op geïndustrialiseerde regio's;
- Energiesystemen in ontwikkelingslanden hebben echter een andere dynamiek en de energiebeleidagenda van ontwikkelingslanden bevat een aantal onderwerpen die in de afgelopen decennia niet belangrijk waren voor geïndustrialiseerde landen;
- Daarom zijn de huidige mondiale energiemodellen niet noodzakelijkerwijs geschikt voor het analyseren van een aantal belangrijke kwesties van energiesystemen in ontwikkelingslanden.

Dit heeft geresulteerd in de volgende hoofdvraag:

Hoe kunnen de prestaties van mondiale energiemodellen, in het bijzonder het TIMER model, worden verbeterd zodat de dynamiek van energiesystemen in ontwikkelingslanden beter wordt vertegenwoordigd en verkend?

Op basis hiervan zijn vier onderzoeksvragen geformuleerd:

I. Wat zijn de belangrijkste verschillen in dynamiek tussen energiesystemen in geïndustrialiseerde landen en ontwikkelingsregio's?
II. Hoe kunnen de representativiteit van het TIMER model op regionaal niveau worden geëvalueerd en kan het model zodanig worden geparameteriseerd dat het het energiegebruik in ontwikkelingsregio's beter simuleert?
III. Hoe kan de modelstructuur van TIMER worden verbeterd zodat de mechanismen van energiegebruik in ontwikkelingsregio's beter kunnen worden vertegenwoordigd?
IV. Wat zijn de verschillen in de potentiële rol van nieuwe energietechnologieën, in het bijzonder waterstof, tussen geïndustrialiseerde landen en ontwikkelingsregio's?

In dit proefschrift wordt gebruik gemaakt van het mondiale energiemodel TIMER 2.0 (de Vries et al., 2001; van Vuuren et al., 2006b). Dit is een wetenschappelijk en politiek relevant energiemodel dat recent is gebruikt in diverse invloedrijke scenariostudies. In combinatie met het FAIR-model (den Elzen en Lucas, 2005) wordt TIMER gebruikt voor het verkennen van verschillende benaderingen voor internationale lastenverdeling voor het klimaatbeleid tussen geïndustrialiseerde- en ontwikkelingslanden. TIMER simuleert het energiegebruik voor 26 wereldregio's en bevat dus expliciet een aantal ontwikkelingsregio's.

2 Samenvatting en conclusies van de hoofdstukken

Het eerste deel van dit proefschrift heeft betrekking op onderzoeksvraag I. **Hoofdstuk 2** evalueert een aantal generieke concepten rond energie en ontwikkeling en verkent hoe deze zichtbaar zijn in de resultaten van huidige mondiale energiemodellen (gebruik makend van de resultaten voor Azië van het Special Report on Emission Scenarios (SRES) van het Intergovernmental Panel on Climate Change (IPCC)). Het eerste concept is de energieladder, die postuleert dat huishoudens kiezen voor schonere en betrouwbaardere brandstoffen als hun inkomen toeneemt. Hoewel deze algemene trend zichtbaar is in lange termijn data, gebruiken huishoudens in de praktijk vaak meer dan één brandstof tegelijk en spelen meer aspecten dan inkomen een rol bij de brandstofkeuze. Of de energieladder is opgenomen in de SRES modellen, is te zien aan de projecties voor de aandelen van brandhout en elektriciteit in het totale energiegebruik. Brandhout is slechts opgenomen in de helft van de SRES modellen en die modellen waarin brandhout is meegenomen voorzien een snelle daling van het brandhoutgebruik. Alle SRES modellen voorzien en groeiend aandeel voor elektriciteit, zij het met veel variatie tussen de modellen. In het algemeen is de energieladder dus waar te nemen in de resultaten van de SRES modellen, maar de helft van deze modellen negeert het gebruik van brandhout en de afwezigheid van expliciete modellering van elektrificatie verhoogt de onzekerheid van elektriciteitsgebruikprognoses.

Het tweede concept is de Environmental-Kuznets Curve (EKC): de hypothese dat 'milieudruk' verloopt als een omgekeerde U-vorm ten opzichte van economische ontwikkeling, toenemend bij lage inkomensniveaus en afnemend bij hogere inkomens. Dit concept wordt door sommigen gezien als een natuurwet, maar het is ook omstreden in de literatuur omdat de EKC slechts wordt waargenomen voor een beperkt aantal regio's of perioden en er veel variatie is in de indicatoren en eenheden. De resultaten van de SRES modellen volgen een duidelijke EKC curve voor de uitstoot van zwavel[2] per hoofd van de bevolking, maar met grote verschillen tussen de modellen. De prognoses voor koolstofuitstoot per hoofd van de bevolking lijken ook een EKC te volgen, ondanks dat deze scenario’s geen klimaatbeleid bevatten.

In het tweede deel van hoofdstuk 2 worden een aantal thema’s op het gebied van energie en ontwikkeling geanalyseerd aan de hand van historische trends en de relevantie van deze thema’s voor mondiale energiemodellen.

[2] Zwavel levert een belangrijke bijdrage aan verzuring

Ten eerste, veranderingen in het energiesysteem: brandhout en elektrificatie.

- Historisch daalt het gebruik van brandhout per hoofd van de bevolking, ook in regio's met een dalend inkomen. Het absolute brandhoutgebruik is echter toegenomen, waardoor de druk op de beperkte houtvoorraden is verhoogd. Brandhout is relevant voor mondiale energiemodellen omdat het de dominante bron van energie is in veel ontwikkelingslanden. Daarnaast vormt het een belangrijk aspect van het huidige energiebeleid in ontwikkelingslanden vanwege de druk op beperkte voorraden en de impact op luchtkwaliteit binnenshuis. Ook is de overgang van traditionele naar moderne brandstoffen van grote invloed op energiegebruikprognoses.
- Elektrificatie is moeizaam kwantitatief te onderzoeken vanwege de beperkte beschikbaarheid van gegevens en de variatie in definities. In het algemeen neemt de toegang tot elektriciteit toe met het stijgen van het bruto binnenlands product (BBP) per hoofd van de bevolking en hebben inwoners van stedelijke gebieden meer toegang tot elektriciteit dan de rurale bevolking. Elektrificatie is van belang voor mondiale energiemodellen, omdat het bepaalt welke eindgebruiksfuncties beschikbaar zijn en wat de structuur van de elektriciteitsproductie is. De meeste modellen veronderstellen impliciet dat het elektrificatieniveau toeneemt met stijgende inkomens.

Een tweede serie onderwerpen is gerelateerd aan de beschrijving van economische activiteit: economische structuurverandering, inkomensverdeling en de informele economie.

- Economische structuurverandering beschrijft de algemene trend van het verschuiven van toegevoegde waarde en werkgelegenheid van de landbouw naar de industrie en dienstensector. Dit proces verschilt echter tussen landen. China is bijvoorbeeld industriegericht, terwijl in India de dienstensector groter is. Dit is relevant voor energiemodellen, omdat het de stadia van economische ontwikkeling kenmerkt en veranderingen in energie-intensiteit verklaart. De meeste mondiale energiemodellen negeren de landbouwsector, hoewel deze in veel ontwikkelingslanden momenteel een belangrijke energiegebruiker is.
- Uit gegevens over inkomensverdeling blijkt dat ontwikkelingslanden niet noodzakelijk een ongelijkere inkomensverdeling hebben, maar wel dat er meer variatie is binnen deze groep landen. De verdeling van welvaart over de bevolking is relevant voor mondiale energiemodellen omdat het energiegebruik van inkomensgroepen verschilt en dit bepaalt of het "gemiddelde" representatief is.
- De informele economie is in ontwikkelingslanden groter dan in geïndustrialiseerde regio's. Het is essentieel om informele activiteiten te begrijpen, zodat economische activiteit adequaat beschreven kan worden. Aangezien een deel van de economische ontwikkeling bestaat uit het formaliseren van de informele economie, hangt niet alle inkomensgroei noodzakelijkerwijs samen met een toename van de fysieke activiteit (en dus van het energiegebruik). Dit onderwerp hangt nauw samen met het gebruik van inkomensprognoses in koopkracht-pariteit (PPP) of Market Exchange Rates (MER) in scenariostudies. Omdat deze beide methoden gebaseerd zijn op metingen van de formele economie, is dit verband slechts indirect en ingewikkeld en verdient het nader onderzoek.

Een laatste serie onderwerpen gaat in op de veranderende context van ontwikkeling: uitputting van fossiele hulpbronnen, klimaatverandering en luchtverontreiniging. Deze veranderingen hebben de komende decennia invloed op de ontwikkeling van energiesystemen in ontwikkelingslanden, waardoor er mogelijk meer diversiteit ontstaat dan de afgelopen decennia in geïndustrialiseerde regio's.

Het implementeren van bovengenoemde onderwerpen in mondiale energiemodellen zal leiden tot nieuwe inzichten en meer relevantie en betrouwbaarheid van deze modellen voor ontwikkelingsregio's. Kwantitatieve modellering is echter niet altijd mogelijk als gevolg van beperkte data en conceptontwikkeling.

Hoofdstuk 3 gaat verder in op uitputting van hulpbronnen en klimaatverandering, twee factoren die impliceren dat het toekomstige ontwikkelingstraject van ontwikkelingslanden afwijkt van de historische ontwikkeling in geïndustrialiseerde landen. Het beschrijft de toepassing van een eenvoudig systeem-dynamisch model (SUSCLIME) dat de dynamiek van bevolking, economie, energie en klimaat simuleert in een sterk gestileerde vorm. Het energiesysteem beslaat hier vier opties: endogene fossiele voorraden, import van fossiele energie, endogene hernieuwbare energie en energie-efficiëntie. Dit model wordt gebruikt in twee varianten:

i. besluitvorming op basis van een aantal beslisregels en huidige informatie en
ii. virtuele actoren kunnen beleidsmaatregelen nemen (belasting, subsidie) en strategieën ontwikkelen om met uitputting en klimaatverandering om te gaan.

Uit deze analyses blijkt dat ontwikkelingslanden kwetsbaarder zijn voor zowel energieschaarste als klimaatverandering. De reden hiervoor is dat ze in de eerste, laag-productieve en energie-intensieve fasen van economische ontwikkeling gevoeliger zijn voor toename van energieprijzen en de kosten van het beperken van en/of aanpassen aan klimaatverandering. Goedkope geïmporteerde fossiele energie is de meest aantrekkelijke optie om uitputting van endogene hulpbronnen te voorkomen, maar voor ontwikkelingslanden schuilt hier het gevaar van onevenwichtige betalingsbalansen en een toenemende schuld. Met betrekking tot klimaatverandering balanceren ontwikkelingslanden (meer dan geïndustrialiseerde landen) tussen korte termijnkosten van emissiereductie en mogelijke impacts van klimaatverandering in de toekomst. De analyses wijzen erop dat het aantrekkelijk is voor ontwikkelingsregio's om klimaatbeleid uit te stellen tot een bepaald inkomensniveau is bereikt. Voor de effectiviteit van klimaatbeleid is het echter wel belangrijk dat dit beleid al plaatsvindt in de economische 'take off' fase van snelle inkomensgroei, accumulatie van kapitaal en productiviteitsverhoging. Een bijkomend voordeel van een lange-termijn visie, gericht op het minimaliseren van broeikasgasemissie, is dat het ook de uitputting van hulpbronnen vertraagd. Een korte-termijnsvisie ter vermindering van de uitputting van endogene fossiele energiebronnen heeft daarentegen niet veel synergie met klimaatbeleid, omdat de import van fossiele energie (of het gebruik van kolen) aantrekkelijker is dan het ontwikkelen van schone alternatieven.

Het tweede deel van dit proefschrift richt zich op onderzoeksvraag II, de evaluatie van de representativiteit van het TIMER energievraagmodel op regionaal niveau. In **Hoofdstuk 4**

wordt een methode beschreven om de onzekerheid van model-kalibratie te bepalen en wordt deze methode toegepast op het TIMER model voor energiegebruik in de transportsector. Er zijn slechts zeer beperkt data beschikbaar voor de ontwikkeling en kalibratie van mondiale energiemodellen. Daardoor zijn vanuit verscheidene wetenschappelijke paradigma's verschillende modellen ontwikkeld, waarin dezelfde historische gegevens verschillend geïnterpreteerd worden. Deze verschillen in modelstructuur leiden tot grote verschillen in prognoses. Systeem-dynamische en de bottom-up energiemodellen nemen bijvoorbeeld aan dat de energievraag verzadigd, gebaseerd op de trends in enkele sectoren (zoals huishoudens). Macro-economische modellen nemen daarentegen aan dat energiegebruik en inkomen gekoppeld blijven, naar aanleiding van econometrische relaties in historische statistieken. Maar zelfs binnen één enkel model kan ruimte zijn voor verschillende sets van parameterwaarden, die het historische energiegebruik vergelijkbaar goed simuleren, maar wel verschillende historische interpretaties impliceren en tot verschillende prognoses leiden. Het verschijnsel dat meerdere plausibele modelimplementaties naast elkaar kunnen bestaan zonder dat deze kunnen worden verworpen wordt aangeduid als 'equifinality'.

In dit proefschrift is een methode ontwikkeld om modellen automatisch te kalibreren en verschillende sets van parameterwaarden te identificeren. Deze sets van parameterwaarden worden verkregen door de belangrijkste modelparameters te variëren binnen een beperkte ruimte en tegelijkertijd de afwijking tussen modeluitkomsten en historische data te minimaliseren. Door deze procedure vele malen te herhalen, beginnend op verschillende locaties in de parameterruimte, kan een groot aantal (verschillende) gekalibreerde sets van parameterwaarden worden gegenereerd. Deze methode is gerelateerd aan zowel non-lineaire regressie methodes (zoals PEST of UCODE) als sequentiële Monte Carlo analyses (zoals GLUE of SimLab).

Deze methode is toegepast op het energiemodel voor de transportsector in het TIMER model voor de periode 1971-2003 en een aantal regio's (de Verenigde Staten, West-Europa, Brazilië, Rusland, India en China). Dit model simuleert de vraag naar energie op basis van drie hoofdprocessen: energie-intensiteit als functie van het inkomen (dit representeert structuurveranderingen), autonome technologieontwikkeling en energieprijs gedreven efficiëntieverbetering. Dit model is top-down, macro-economisch georiënteerd en bevat geen fysieke indicatoren (zoals voertuigbezit) en transport-specifieke concepten (zoals de budgettering van tijd en geld).

Uit de resultaten van deze analyses blijkt dat de meeste gekalibreerde parameterwaarden zich bevinden in een beperkt deel van de parameterruimte en dat slechts 10% van de resultaten 'outliers' zijn. Dit geeft aan dat het optimalisatie algoritme goed functioneert. Het forceren van de bestaande modelstructuur om het historische energiegebruik in de transportsector op regionaal niveau te simuleren, leidt tot de identificatie van meerdere clusters in de parameterruimte: dus equifinality. In het algemeen simuleert het TIMER transportmodel het energiegebruik in West-Europa en de Verenigde Staten beter dan in de ontwikkelingsregio's. Dit kan worden verklaard uit het feit dat het model geen rekening houdt met de specifieke dynamiek van het energiegebruik in deze regio's, maar de

datakwaliteit kan ook een rol spelen. De gevonden equifinality heeft vooral betrekking op de vraag of intensiteitverandering of efficiëntieverbetering de belangrijkste verklarende factor is voor historisch energiegebruik. Bij energie-efficiëntie speelt ook het onderscheid tussen autonome of prijsgedreven verbeteringen een rol. Dit is zeer relevant: de onzekerheid in de parameterwaarden is van wezenlijke invloed op prognoses voor toekomstige energiegebruik op relatief korte termijn (2030). Deze prognoses zijn vergeleken met het OECD Environmental Outlook scenario, dat werd ontwikkeld door de TIMER modelleurs zonder automatische kalibratie en is geijkt op de IEA World Energy Outlook prognoses. De automatisch gekalibreerde resultaten suggereren een iets lager toekomstige transport energiegebruik dan dit referentiescenario.

Hoofdstuk 5 maakt gebruik van dezelfde kalibratie-onzekerheids methode, maar nu toegepast op huishoudelijk energiegebruik. Ook hier ligt de nadruk op de identificatie van verschillende modelimplementaties en de gevolgen daarvan voor vooruitberekeningen. De structuur van het huishoudensmodel is hetzelfde als beschreven voor de transportsector: energie intensiteitverandering, technologische ontwikkeling en de prijsgedreven efficiëntieverbetering. Dit betekent dat specifieke eindgebruiksfuncties (zoals verlichting, koken of apparaten) en fysieke indicatoren (zoals vloeroppervlak) niet expliciet zijn opgenomen in dit model.

Ook voor huishoudelijk energiegebruik simuleert het TIMER model de historische trends beter voor geïndustrialiseerde regio's dan voor ontwikkelingslanden. Historisch gezien is het totale huishoudelijk brandstofgebruik in West-Europa en de Verenigde Staten gedaald of constant gebleven terwijl het inkomen sterk gestegen is. Daarom kan deze trend goed gesimuleerd wordt met een sterk dalende energie-intensiteit. De impact van energieprijzen blijkt belangrijker in de Verenigde Staten dan in Europa, waarschijnlijk als gevolg van hogere belastingen in de laatstgenoemde regio. Voor ontwikkelingslanden is modelkalibratie moeizamer. Het energiegebruik in deze regio's ontwikkelt zich in verschillende richtingen als gevolg van specifieke lokale omstandigheden buiten de focus van een mondiaal energiemodel. Het Chinese huishoudelijke brandstofgebruik nam bijvoorbeeld snel af in de jaren 1990 als gevolg van het uitfaseren van steenkool en de sluiting van vele kleine mijnen. Het Braziliaanse brandstofgebruik daalde juist sterk in de jaren 1970, wat te verklaren is uit efficiëntieverbetering van traditionele houtovens. Ook de exponentiële groei van het elektriciteitsgebruik kan slechts gedeeltelijk worden gesimuleerd. In Brazilië, bijvoorbeeld, hield deze exponentiële trend zelfs aan in perioden van sterk fluctuerende economische activiteit. Dit impliceert dat het elektriciteitsgebruik in ontwikkelingsregio's meer samenhangt met de opbouw van het aanbod (elektrificatie, bouw van centrales) dan met de vraag van de eindgebruikers.

Er zijn in deze analyse geen duidelijke gevallen van equifinality geïdentificeerd; alle gekalibreerde parameterwaarden bevinden zich binnen een beperkt gebied. Toch is deze beperkte variatie in parameterwaarden van grote invloed op de prognoses voor 2030. De prognoses van de automatisch gekalibreerde modelimplementaties zijn over het algemeen hoger dan het referentiescenario (OECD Environmental Outlook). Op basis van deze analyse zijn enkele opties geïdentificeerd voor de verbetering van het model ten aanzien

van de dynamiek in ontwikkelingslanden: ten eerste het expliciet opnemen van eindgebruiksfuncties, ten tweede het beter omgaan met inkomensdalingen en tenslotte expliciet rekening houden met lokaal beleid.

Hoofdstuk 6 behandelt onderzoeksvraag III. Dit hoofdstuk beschrijft de ontwikkeling van een alternatieve modelstructuur voor huishoudelijk energiegebruik in ontwikkelingslanden, te beginnen met India. Om beter met de heterogeniteit in inkomensverdeling om te gaan, wordt het energiegebruik in dit model gesimuleerd voor urbane en rurale gebieden, die elk weer zijn onderverdeeld in inkomenskwintielen[3]. De modelstructuur is bottom-up, er vanuit gaande dat fysieke indicatoren adequater zijn dan monetaire indicatoren om de activiteit in ontwikkelingslanden te beschrijven. Het model onderscheidt vijf eindgebruiksfuncties: koken, warm water gebruik, ruimteverwarming, verlichting en huishoudelijk apparaten. Keuzes in brandstofgebruik volgen de energieladder: hogere inkomensgroepen hebben een voorkeur voor schonere, comfortabelere, maar ook duurdere energieopties. Het bezit van huishoudelijk apparaten is gemodelleerd volgens de waargenomen Indiase voorkeursladder: van ventilator naar televisie, koelkast en zwaardere apparaten. In twee scenario's wordt de impact geanalyseerd van twee variabelen die meestal niet worden meegenomen in mondiale energiemodellen: inkomensverdeling en elektrificatie.

Dit model simuleert het historisch Indiase huishoudelijk energiegebruik beter dan het bestaande energievraagmodel van TIMER en biedt meer inzicht in de determinanten van huishoudelijk energiegebruik. Elektriciteitsgebruik in India wordt bijvoorbeeld inmiddels niet meer gedomineerd door verlichting maar stijgt snel als gevolg van het toegenomen bezit van tv's en koelkasten. Uit vooruitberekeningen blijkt dat het totale Indiase huishoudelijk energiegebruik in 2050 met 65-75% zou kunnen stijgen ten opzichte van 2005, terwijl de CO_2-uitstoot toeneemt tot 9-10 keer het niveau van 2005. Variatie in inkomensverdeling en elektrificatie is van grote invloed op deze prognoses. Hoewel een egalitaire inkomensverdeling (met hetzelfde gemiddelde inkomen) en toegenomen elektrificatie van rurale gebieden leiden tot minder (energie-)armoede, is er een trade-off vanwege hogere CO_2-uitstoot als gevolg van toegenomen elektriciteitsgebruik. Hogere inkomens voor de arme groepen versnellen echter wel de overgang van brandhout naar moderne brandstoffen, wat leidt tot een betere luchtkwaliteit binnenshuis.

Het laatste deel van dit proefschrift gaat in op onderzoeksvraag IV: de mogelijkheden voor nieuwe energietechnologieën. Nieuwe technologie wordt vaak geassocieerd met geïndustrialiseerde landen, terwijl het goed mogelijk is dat een aantal van deze technieken meer kans maakt in ontwikkelingsregio's als gevolg van een gebrek aan infrastructuur en gevestigde belangen. Voorbeelden hiervan zijn nieuwe auto-ontwerpen zoals de kleine goedkope Tata Nano of voertuigen die rijden op gecomprimeerde lucht. De laatste hoofdstukken van deze dissertatie richten zich op de potentiële rol van een nieuwe energiedrager: waterstof.

Ter introductie beschrijft **hoofdstuk 7** de modellering van waterstof in het TIMER model en introduceert een serie waterstofscenario's. In dit hoofdstuk wordt verkend wat de

[3] Dit zijn gelijke groepen van 20% van de bevolking, geordend naar inkomensniveaus

potentiële rol van waterstof in het mondiale energiesysteem is en hoe dit zich verhoudt tot broeikasgasemissies en klimaatbeleid. Het model simuleert de productie van waterstof uit de belangrijkste primaire energiebronnen. Aanvankelijk zijn alleen dure opties beschikbaar, zoals kleinschalige waterstofproductie uit aardgas of distributie met vrachtwagens. Grootschalige productie van waterstof wordt pas aantrekkelijk wanneer het gebruik toeneemt en distributie met pijpleidingen economisch haalbaar wordt. Het eindgebruik van waterstof in het model kan plaatsvinden met brandstofcellen in vijf economische sectoren: industrie, transport, huishoudens, diensten en overig. Op basis van de wetenschappelijke literatuur zijn drie waterstofscenario's ontwikkeld: een pessimistisch, medium en optimistisch scenario, gecombineerd met een strikt klimaatbeleidsscenario.

Dit onderzoek laat zien dat zonder specifieke maatregelen en grote technologische doorbraken, waterstof waarschijnlijk geen belangrijke rol zal spelen in het mondiale energiesysteem vóór 2050, met noch zonder klimaatbeleid. Alleen op grond van zeer optimistische aannames wordt waterstof ingevoerd voor 2050. Steenkool en aardgas lijken de meest aantrekkelijke opties voor de productie van waterstof, zowel met als zonder klimaatbeleid. In het laatste geval worden deze technologieën gecombineerd met CO_2-afvang en -opslag. Zonder klimaatbeleid leidt de grootschalige productie van waterstof uit steenkool tot een hogere CO_2 emissie voor energiesystemen met veel waterstof. Energiesystemen met veel waterstof reageren echter flexibeler op klimaatbeleid, wat kunnen meer CO_2 emissie reduceren tegen lagere kosten.

Hoofdstuk 8 analyseert de potentiële rol van waterstof in de energiesystemen van een ontwikkelingsland en een geïndustrialiseerde regio: India en West-Europa. Hier wordt gebruik gemaakt van hetzelfde model en de scenario’s als beschreven in hoofdstuk 7, aangevuld met regionale informatie. De analyse richt zich op de invloed van waterstof op de belangrijkste argumenten vóór een transitie: klimaatbeleid, voorzieningszekerheid en stedelijke luchtkwaliteit.

Ook hier blijkt dat zelfs onder optimistische veronderstellingen waterstof waarschijnlijk geen belangrijke rol speelt in India vóór 2050. De scenario’s wijzen op een beperkte toepassing in de transportsector, waarbij de productie van waterstof wordt gedomineerd door kolen. Deze beperkte rol voor waterstof is grotendeels te verklaren vanuit de lage energiebelastingen in ontwikkelingslanden (hoewel de Indiase energiebelastingen recent zijn verhoogd, zijn deze nog steeds veel lager dan in Europa). Dit beperkt de beleidsopties voor het stimuleren van alternatieve brandstoffen door middel van belastingvrijstelling. In Europa maakt waterstof een kleine kans in het medium scenario, maar in het optimistische scenario wordt het toegepast in zowel de transportsector als stationaire toepassingen. Waterstofproductie wordt in Europa gedomineerd door steenkool en aardgas.

Klimaatbeleid is goedkoper met waterstof, maar dit is vooral interessant voor regio’s waar waterstof een grote rol speelt, zoals West-Europa. Voor India, waar de verwachting is dat in 2050 álle olie geïmporteerd zal worden, heeft de toepassing van waterstof in de transportsector een direct effect op de olie-import. In Europa vermindert waterstof de import van olie, maar verhoogt het de invoer van steenkool en aardgas. Het leidt dus tot

diversificatie en niet tot vermindering van energie-importen. Met betrekking tot stedelijke luchtverontreiniging zijn de resultaten zeer case-specifiek en afhankelijk van de striktheid van het beleid.

3 Conclusie, discussie en aanbevelingen

Op basis van dit proefschrift zijn drie hoofdconclusies getrokken:

Ten eerste heeft de huidige generatie mondiale energiemodellen grote tekortkomingen met betrekking tot de dynamiek van energiesystemen in ontwikkelingslanden. In kwalitatieve zin negeren deze modellen belangrijke thema's die kenmerkend zijn voor energiesystemen in ontwikkelingslanden. Kwantitatief blijkt dat het energievraagmodel van TIMER, als representatief voorbeeld van dit type modellen, het historisch energiegebruik in geïndustrialiseerde regio's beter simuleert dan in ontwikkelingsregio's.

Ten tweede kunnen de prestaties van mondiale energiemodellen met betrekking tot energiesystemen in ontwikkelingsregio's worden verbeterd door:

a. Het expliciet opnemen van de belangrijkste kenmerken van energiesystemen in ontwikkelingslanden;
    a. *traditioneel brandstofgebruik.* De overgang van traditionele naar commerciële brandstoffen is een essentieel kenmerk van het energiegebruik in ontwikkelingslanden. Dit kan worden verklaard en gesimuleerd als functie van toenemende kapitaalbeschikbaarheid.
    b. *elektrificatie*. Toegang tot elektriciteit is van invloed op welvaart, energiegebruik en de opwekking van elektriciteit. Modellering van elektrificatie kan worden gerelateerd aan inkomen en bevolkingsdichtheid.
    c. *inkomensverdeling*. Inkomensontwikkeling van arme groepen blijkt zeer relevant te zijn voor energiegebruiksprognoses. Inkomensverdeling kan worden gemodelleerd op basis van eenvoudige algoritmen.
    d. *urbane en rurale verschillen*. Expliciete modellering van urbane en rurale energiesystemen doet recht aan het toenemende verschil in energiegebruik tussen moderne stedelijke centra en achterblijvende plattelandsgebieden.
2. Het gebruik van *fysieke indicatoren* als basis voor energiemodellering. Informele activiteit bemoeilijkt de adequate beschrijving van economische activiteit in ontwikkelingslanden. Statistieken van fysieke indicatoren zijn in toenemende mate beschikbaar, waardoor een betere analyse van de causale relaties tussen economische activiteit en energiegebruik mogelijk is.
3. Rekening houden met *regionale verschillen* in trends en beleid. Ontwikkelingslanden zijn geen homogene groep en mondiale modelresultaten zijn de som van regionale uitkomsten. Mondiale modelprestaties kunnen worden verbeterd door modellen te kalibreren op regionale data en door aannames en resultaten te bespreken met regionale deskundigen.

Ten derde wordt op basis van dit proefschrift geconcludeerd dat toekomstige energietransities in ontwikkelingslanden waarschijnlijk anders worden dan de historische

energietransitie in geïndustrialiseerde regio's. Belangrijke verschillen zijn de beschikbaarheid van nieuwe technologieën, de uitputting van goedkope energiebronnen en klimaatverandering. Op de korte termijn lijkt de potentiële rol van nieuwe technologieën in ontwikkelingslanden beperkt. Op lange termijn kunnen uitputting van olie en klimaatverandering echte een transitie stimuleren naar kolengebaseerde brandstoffen en/of een combinatie van energie-efficiëntie en hernieuwbare energie.

Twee kwesties verdienen hier nadere discussie: databeschikbaarheid en -kwaliteit en de reikwijdte en beperkingen van dit onderzoek. Het gebrek aan betrouwbare en consequent verzamelde statistieken, bemoeilijkt het analyseren van energiesystemen en economisch gedrag in ontwikkelingslanden. Veel indicatoren die relevant zijn voor modelontwikkeling, zoals het aantal huishoudens met toegang tot het elektriciteitsnet of het volume van brandstofgebruik, worden niet gemeten of inconsistent gepubliceerd. Zelfs een organisatie als de Indiase NSSO, die een uitstekende reputatie heeft op het gebied van statistische gegevens en enquêtes, verandert regelmatig de structuur van de tabellen en de recall-periode voor enquêtes. Dit bemoeilijkt het ontwikkelen van modellen en de statistische analyse van de relaties tussen systeemvariabelen. Een tweede probleem is de kwaliteit van de data. Een groot deel van de informatie die nodig is om mondiale energiemodellen te verbeteren is afkomstig uit enquêteonderzoeken, waarbij de kwaliteit sterk afhankelijk is van de vragenlijsten, de representativiteit van de ondervraagden en de opleiding van interviewers. Er kan gesteld worden dat er te weinig gegevens beschikbaar zijn om energiegebruik in ontwikkelingslanden te analyseren en modelleren, maar wij hebben door het combineren van veel verschillende bronnen en de samenwerking met lokale deskundigen een werkbare situatie gecreëerd.

De keuzes die zijn gemaakt in dit proefschrift zijn van invloed op de mogelijkheden voor generalisatie van de resultaten en aanbevelingen. Dit proefschrift richt zich op een specifiek mondiaal energiemodel: TIMER, een systeem-dynamisch simulatiemodel. Hoewel dit model methodisch anders is dan een aantal andere mondiale energiemodellen, zijn de onderwerpen die besproken zijn in dit proefschrift ook relevant voor andere modellen (zie bijvoorbeeld hoofdstuk 2). De keuze om slechts drie sub-modules van TIMER te onderzoeken, betekent niet dat de specifieke kenmerken van ontwikkelingslanden niet van belang zijn voor andere delen van het energiesysteem. De verschillen tussen geïndustrialiseerde landen en ontwikkelingsregio’s spelen een rol bij veel aspecten van mondiale energiemodellen, zoals de energievraag, energieaanbod, infrastructuur of operationele beslissingen.

Op basis van deze overwegingen zijn de volgende aanbevelingen geformuleerd:
Met betrekking tot de ontwikkeling van het TIMER model:

a. *Verdere ontwikkeling van het model voor huishoudelijk energiegebruik*. Dit proefschrift bevat een nieuw model voor huishoudelijk energiegebruik in India. Dit model is bruikbaar in de context van TIMER als het wordt geïmplementeerd, getest en toegepast op andere wereldregio’s;
b. *Ontwikkeling van een nieuw energievraagmodel voor de transportsector*. Bij de kalibratie-onzekerheidsanalyse zijn tekortkomingen van het huidige model voor de

transportsector naar voren gekomen. Een nieuw model voor de transportsector, gebaseerd op fysieke indicatoren en de budgettering van tijd en geld, kan leiden tot meer inzicht en meer mogelijkheden voor regionale differentiatie.

c. *Expliciete modellering van infrastructuurontwikkeling*. Dit proefschrift gaat nauwelijks in op de ontwikkeling van infrastructuur, maar de beschikbaarheid van wegen, spoorwegen, elektriciteitsnetten en distributienetwerken voor LPG, kerosine of aardgas zijn van essentieel belang voor het energiegebruik. De nieuwe energievraagmodellen voor huishoudens en transport kunnen verder worden verbeterd door indicatoren voor infrastructuur te ontwikkelen en de relatie tussen infrastructuur en energiegebruik te kwantificeren.
d. *Uitgebreide analyse van kalibratie-onzekerheid*. Deze vorm van onzekerheid is van groot belang gebleken voor prognoses van het energiegebruik in de huishoudens- en transportsector. Daarom raden wij aan om kalibratie-onzekerheid ook te analyseren in de modellen voor andere sectoren en regio's.

Met betrekking tot mondiale energiemodellering in het algemeen:

a. *Expliciete modellering van de kenmerken van energiesystemen in ontwikkelingslanden*. Traditionele brandstoffen, elektrificatie, inkomensverdeling en verschillen tussen urbane en rurale gebieden zijn relevante kenmerken van energiesystemen in ontwikkelingslanden. Dit proefschrift biedt een methodologische basis om deze thema's op te nemen in mondiale energiemodellen. Als deze onderwerpen worden geïmplementeerd, zijn mondiale energiemodellen beter in staat tot het verkennen van interacties en synergie tussen ontwikkelingsbeleid en klimaatbeleid.
b. *Meer aandacht voor regionale verschillen en ontwikkelingen*. Er is een grote verscheidenheid tussen regio's met betrekking tot het ontwikkelingstempo, culturele voorkeuren en energiepatronen. Ook technologieën zijn niet homogeen mondiaal beschikbaar en variëren per regio. Een voorbeeld is het gebruik van compressed-air voertuigen, die wellicht meer kans maken in ontwikkelingsregio's. Ook het potentieel voor energietechnologieën, zoals geconcentreerde zonne-energie (CSP), is niet gelijkmatig verdeeld over de wereld. Regionaal relevante energieproblemen zijn van invloed op het energiebeleid, wat bepalend is voor toekomstige ontwikkelingen. Omdat mondiale projecties de som zijn van regionale modelresultaten, is het van belang dat mondiale energiemodellen representatief zijn op regionaal niveau.
c. *Meer aandacht voor onzekerheid van model kalibratie*. Kalibratie-onzekerheid is van grote invloed op prognoses en in dit proefschrift is een methode voor de identificatie van deze vorm van onzekerheid beschreven. Deze methode kan worden toegepast op andere modellen die geworteld zijn in de simulatie van historisch energiegebruik
d. *Gebruik meer informatie uit ontwikkelingslanden*. Lokale gegevens en inzichten zijn waardevol voor mondiale energiemodellen. Meer samenwerking tussen mondiale modelontwikkelaars en regionale instituten uit ontwikkelingslanden kan bijdragen aan het verbeteren van mondiale energiemodellen.
e. *Meer energiemodellering in ontwikkelingslanden*. Lokale deskundigen hebben beter inzicht in relevante energieproblemen en de dynamiek van energiesystemen. Ontwikkeling van nieuwe energiemodellen vanuit het perspectief van ontwikkelingslanden, of het gebruik van mondiale energiemodellen door lokale

onderzoeksgroepen zou een waardevolle aanvulling zijn op de bestaande energiemodellering. Het AIM-model (Kainuma et al., 2003) is een voorbeeld van dit soort samenwerking. Dit model wordt gecoördineerd door IGES in Japan en wordt ontwikkeld en toegepast door lokale onderzoeksgroepen in Aziatische ontwikkelingslanden.

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Curriculum Vitae

Bas van Ruijven was born on 3rd April 1978 in Amsterdam, the Netherlands. Between 1997 and 2003, he studied Music Education for two years, changed to a first year of physical geography and graduated in Environmental Sciences at Utrecht University. During his studies, Bas was teaching assistant and member of the education committees of Music Education and Environmental Sciences. He wrote his MSc thesis during an internship at the National Institute for Public Health and the Environment (RIVM) on modelling hydrogen energy in the global energy model TIMER. After his graduation, Bas was junior researcher at RIVM for six months. He joined the department of Science, Technology and Society of Utrecht University as PhD student in June 2004. During this research, Bas spend two months as visiting researcher at the department of Physical Resource Theory of Chalmers University in Gothenburg (Sweden) to develop a multi-agent implementation of the SUSCLIME model (Chapter 3 of this thesis). In 2007, he stayed two months in India as visiting researcher at IGIDR in Mumbai and IISc Bangalore. Bas is currently affiliated as energy analyst to the Netherlands Environmental Assessment Agency (PBL).