Sustainable energy for developing countries:

Modelling transitions to renewable and clean energy in rapidly developing countries

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Sustainable energy for developing countries:

Modelling transitions to renewable and clean energy in rapidly developing countries

Proefschrift

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“ We can’t solve problems by using the same kind of thinking
we used when we created them.”

Albert Einstein (1879-1955)

Preface

It all began in autumn 2000 when I started studying Geoecology at the University of Bayreuth in Germany. Besides a very good education in the Natural and Environmental Sciences, I learned to appreciate nature and the environment. A field-trip to Mexico sparked my interest in developing countries.

The foundation for this thesis was laid in 2003/04, when I studied Environmental Sustainability at the University of Edinburgh in Scotland, UK. I followed courses on sustainability, which included lessons on renewable energy. The topic renewable energy immediately attracted me and I decided to write my Master thesis about it. In 2004, I got into contact with CEA, the Consultants on Energy and the Environment in Rotterdam, The Netherlands. CEA was the project managing consultancy for the SIWERM-project on wind energy implementation in the European Community. I joined as a trainee on wind energy policy and conducted research for my M.Sc. thesis.

Working in the Netherlands, I was inspired by the Dutch interest in renewable energy and was happy to begin my Ph.D. in December 2004 at the Center for Energy and Environmental Studies IVEM at the University of Groningen. I received a scholarship funded by the Ubbo-Emmius-Foundation. Henk Moll became my promotor and René Benders my daily supervisor and co-promotor. Later on, Ton Schoot Uiterkamp became my second promotor. In my research project, I modelled the possibilities and constraints for sustainable energy transitions and their effects in rapidly developing countries with emphasis on China and India.

After thorough desk research, it was time to visit a rapidly developing country in practise. I therefore attended the ICORE Conference on renewable energy in Hyderabad, India in early 2006 and also took some time to travel around India. In late 2006, I attended the Young Scientists Conference YSC and the ESSP Global Environmental Change Conference in Beijing, China and also meet my Chinese colleagues Zhang Xiliang and Wang Yu. This collaboration turned into a research placement at the Institute for Nuclear and New Energy Technology INET at Tsinghua University in Beijing, China where I worked for three months in 2007. Living and working in China gave me a much deeper understanding of my research and the Chinese society than any desk research could ever have done.

Back at the IVEM, I finalised my research in autumn 2008. Inspired by work on developing countries and the link between energy and climate change, I got the chance to work for the Climate Change and Development Group at the Institute of Development Studies IDS at the University of Sussex in Brighton, UK as a research fellow as of October 2008.

For my time at the IVEM, I would particularly like to thank my (co)promotors Henk Moll, René Benders and Ton Schoot Uiterkamp who supported me and motivated me throughout my study, gave useful advice and enabled me to learn from their experience, knowledge and skills (especially on modelling, thank you, René). I will be very happy to continue our cooperation in the future. I am also grateful to other current and former IVEM staff members: Anne Jelle Schilstra, Annemarie Kerkhof, Annemiek Huizinga, Dick van den Berg, Emiel Elferink, Laurie Hendrickx, Michiel Berger, Michiel Hekkenberg, Nicole van Marle (many thanks for everything), Niels Schenk, Sander Lensink, Sanderine Nonhebel, Sandra Bellekom, Thomas Kastner, Winnie Gerbens-Leenes and special thanks to those who turned from colleagues into friends.

I would also like to thank Peter Ho for initiating research contacts in China. Thanks to Bas van Ruijven, Bert de Vries, Jeroen van der Sluijs and Detlef van Vuuren for the work on our joint article.

For my time in China, I would like to thank Zhang Xiliang and Wang Yu for making it possible for me to work in China and for our fruitful research cooperation and academic exchange which is still continuing today. I am also thankful to Viktoria Mainow, Ling Zheng, Claire Philippe and Daniel Rady without whom my stay in China would not have been as enjoyable as it was. Thanks also to Humaira Sultana from YSC.

Most of all, I would like to thank my husband Johan. Johan has been very supportive during the past four years, supporting my travelling between Oldenburg and Groningen, approving my leaves to China and India, reading and constructively criticising my articles and always believing in me and my capacities. Thank you also for coming to the UK with me. I would also like to thank my parents Eva and Reinhold and my brother Arne for always believing in me and for their great support.

Finally, I would like to express my special thanks to those organisations making it financially possible for me to conduct my PhD: the Ubbo-Emmius-Fund from the University of Groningen for my 4-year long scholarship which gave me the possibility to undertake this PhD, the Stichting Groningen Universiteitsfonds, the World Meteorological Organisation WMO and the Earth System Science Partnerships ESSP for enabling research and travelling in China.

A final thanks to those committed people around me who aim at living a sustainable low-carbon lifestyle – you are my inspiration.

Contents

1. General introduction

1.1 Introduction

Energy is a vital commodity and is closely intertwined with climate change and development. Energy is needed for basic human needs: for cooking, heating, lighting, boiling water and for other household-based activities. Energy is also required to sustain and expand economic processes like agriculture, electricity production, industries, services and transport. It is commonly suggested that access to energy is closely linked with development and economic well-being (e.g. DFID, 2002; IEA, 2002; WEC, 2000; WEC, 2001; WHO, 2006) and that alleviating energy poverty is a prerequisite to fulfill the Millennium Development Goals (DFID, 2002; WHO, 2006).

Fossil energy resources are limited and fossil energy use is associated with a number of negative environmental effects, therefore energy has become a major geo-political and socio-economic issue. This development puts pressure on all countries around the world. The pressure on developing countries may be even greater, because they are currently in the process of development which requires higher energy resources for achieving higher living standards. High population levels and high fossil fuel reliance increase this pressure even more. To meet energy security, reduce pressure on fossil energy resources and to ensure a higher environmental quality, the share of low-polluting renewable and clean energy should be enhanced.

1.2 Impacts of energy use

The Intergovernmental Panel on Climate Change IPCC (2007a:253) states that “Currently, energy-related [greenhouse gas] GHG emissions, mainly from fossil fuel combustion for heat supply, electricity generation and transport, account for around 70% of total emissions including carbon dioxide, methane and some traces of nitrous oxide”. It is well documented that these emissions may increase the global temperature. Energy use has potentially significant climate impacts, which are assumed to exceed the impacts from other sources like land-use and other industrial activities. It is considered crucial to implement greenhouse gas (GHG) emission reduction technologies for fossil fuel combustion processes, as they are considered the main contributors to global climate change. The IPCC states a wide range of global and regional effects of global climate change relevant for this research:

According to the IPCC (2007b), the global mean surface temperature has risen by 0.74°C ± 0.18°C between 1906 and 2005 as indicated in Figure 1. This increase has been particularly significant over the last 50 years. From a global perspective, the IPCC (2007b) reports that they found high increases in heavy precipitation events, while droughts have become more frequent since the 1970s, especially in the (sub)tropics. There are also documentations about changes in the large-scale atmospheric circulation and increases in tropical cyclone activity since the 1970s (IPCC, 2007b).

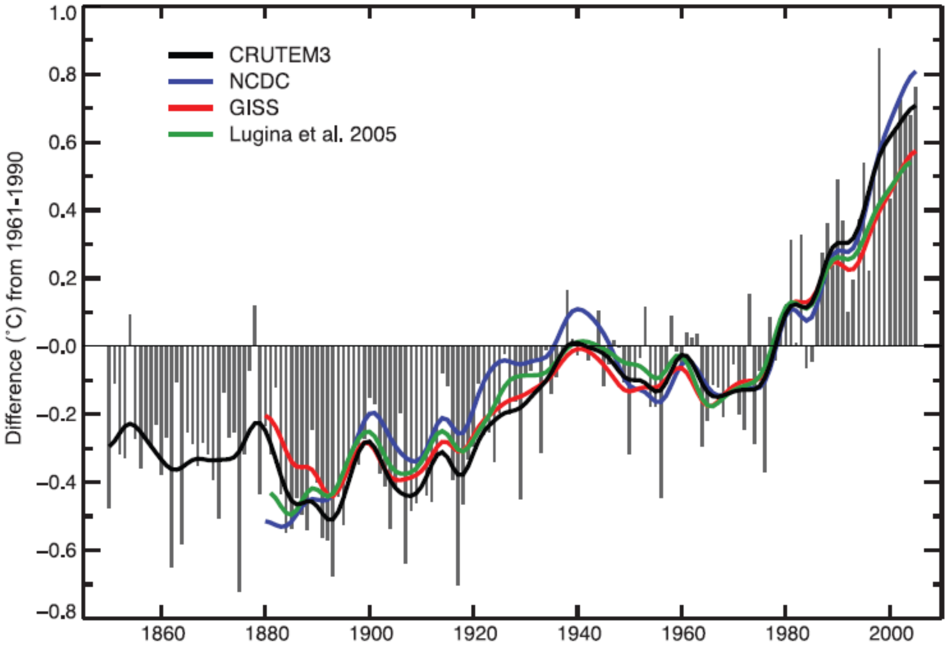

Figure 1: Annual anomalies of global land surface air temperature in °C from 1850 to 2005, relative to the 1961 to 1990 mean. Source: IPCC, 2007b.

Climate change is a serious threat for developing countries, such as for the world's most populous developing countries China and India in Asia. The IPCC (2007c) projects for Asia that most regions are likely to warm above the global mean. Only Southeast Asia is expected to warm similarly to the global mean. It is very likely that heat waves will be of longer duration, higher intensity, and more frequent in East Asia, while there might be less very cold days in East and South Asia. Precipitation is likely to increase in most regions in Asia, but is projected to decrease in Central Asia. It is very likely that there will be increases in the frequency of intense precipitation events in parts of South Asia and in East Asia (IPCC, 2007c). The IPCC (2007c) further assumes that there will be increases in extreme rainfall and extreme wind due to tropical cyclones in East, Southeast and South Asia. It is possible that Monsoon flows and large-scale tropical circulations might be weakened (IPCC, 2007c).

Global climate change is already an observed phenomenon today. Strategies for climate change mitigation, as under the Kyoto Protocol, are necessary on a global scale, particularly for high GHG emitters like the industrialised countries, countries in transition and rapidly developing countries. Strategies for climate change adaptation –strategies of how to live with and adapt to climate change- are of an equal global importance. These adaptation strategies are especially needed for the poorest developing countries, which suffer from the impacts of climate change without even significantly contributing to it. Especially developing countries are assumed to be vulnerable to climate change. Unlike industrialised countries, they do often not have the financial and infrastructural resources to adapt to and mitigate climate change (IPCC, 2007c). It should be a global priority to promote and support climate change mitigation and adaptation strategies in developing countries. Especially the industrialised Northern countries, which are historically considered responsible for the bulk of global climate change, should have the responsibility to assist their poorer neighbours in the South.

Energy use is not only likely to contribute to global climate change, but also gives rise to other negative impacts. One of the possible impacts of energy use is local air pollution, which has been a serious problem in the world's mega-cities for decades and which is linked to fossil fuel combustion. Health problems linked to local air pollution, such as lung cancer and chronic respiratory diseases, are a serious problem. These diseases also result in high cost burdens to the world's health systems (WHO, 2000 and WHO, 2005). Other possible impacts of energy use are the exploitation of finite resources, the destruction of nature, landscapes and biodiversity for energy resources, the need for energy imports and struggles for energy security which sometimes even result in geo-political conflicts and wars. Energy use further involves high externalities: the costs for environmental and health damages which institutions and governments have to pay as a consequence of energy consumption.

All these impacts demonstrate how meaningful sustainable energy transitions could be especially for developing countries.

1.3 Sustainable development, equity in the climate change debate and the role of technology leap-frogging

Sustainable development is defined by the Brundtland commission as development "meeting the needs of the present without compromising the ability of future generations to meet their own needs" (United Nations, 1987:1). The development of mankind dates back thousands of years. Even though humans have always exploited nature in some way or the other, this development only became excessively unsustainable during the last two centuries. Many of today's global climate change problems and other environmental problems are assumed to be due to the increased consumption and production of industrialised countries starting with the Industrial Revolution in the late 18th century and which is still continuing. Even now, many developed countries are characterised by industrialisation, high levels of consumption and production and unsustainable development patterns.

Developing countries have only recently begun to industrialise. Rapidly developing countries like China and India developed within a few decades from relatively modest users of energy to some of the world's major consumers of energy and natural resources. Recently, they also became significant emitters of GHG measured in absolute terms. The current per capita contribution of rapidly developing countries to climate change is however much lower than the per capita contribution of industrialised countries. In 2003, the average Indian emitted 16.6 times less CO_2 per capita than the average US citizen and the average Chinese citizen emitted 6.2 times less CO_2 than the average American (see Figure 2) (World Bank, 2008).

The same trend can be observed for energy use: per capita energy use and especially per capita electricity use remain low in rapidly developing countries compared to industrialised countries, despite increasing consumption. The electric power consumption per capita in India was 29.2 times lower and in China 8.4 times lower than the per capita consumption in the US in 2004 (World Bank, 2008).

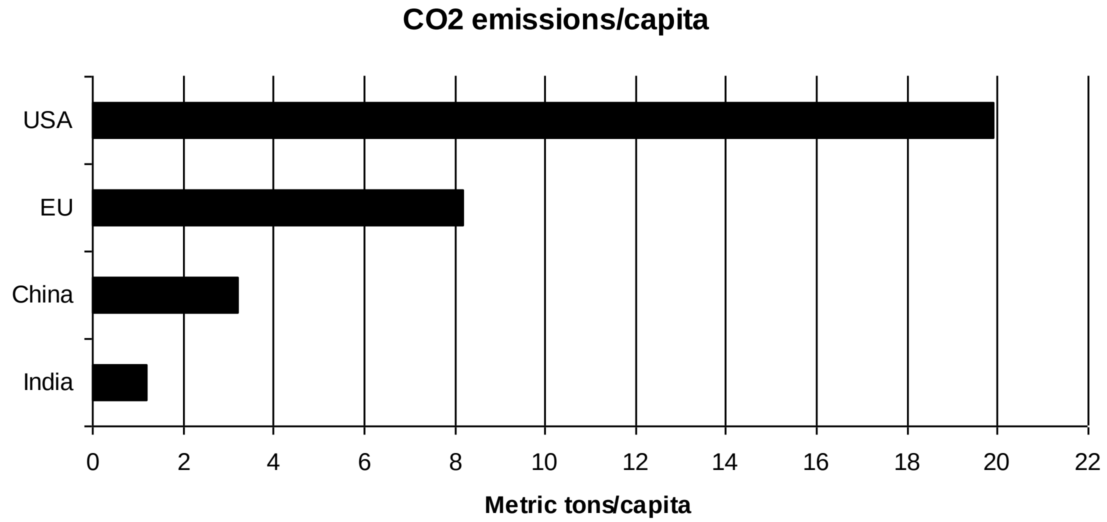

Figure 2: Per capita CO_2 emissions for the USA, the European Monetary Union, China and India in 2003. Source: World Bank, 2008.

The International Declaration of Human Rights of 1948 advocates global equity. According to these principles of equity and equality, it should be the incontestable right of developing countries to develop and to meet their growing needs, even though consumption levels and population levels increase rapidly in many developing countries. It also has to be considered, that a significant share of the industry in many developing countries is manufacturing low-cost goods which are exported and consumed in developed parts of the world like North America, Europe and Australia. The effects of this embedded energy, like the environmental damages and the emissions from this production, largely occur in developing countries, even though the goods are mostly not consumed within the country of production. 23% of China's total carbon emissions in 2004 are estimated to be due to net export (Wang and Watson, 2007). The craving for low-cost consumption in the Western World may be one of the reasons why total GHG emissions and total energy consumption is growing in some developing countries. In return, some agricultural and food products are produced in the Western World and are exported to developing countries. It has to be acknowledged that even though climate change is a global issue, there are "common but differentiated responsibilities" for different countries as stated in the Kyoto Protocol (United Nations, 1998: 9).

Though many developing countries have approved, accepted or ratified the Kyoto Protocol, thus far developing countries do not have binding commitments for emission reductions. It is suggested by many that developing countries should have binding targets to avoid ineffective global results and free-riding. Viguier (2004) proposes a "rent-sharing" approach in which climate change is linked to sustainable development assistance, international trade, technology research and development (R&D) and technology transfer. This approach suggests a strategy how rapidly developing countries like China and India could benefit from soft binding targets while at the same time allowing economic growth. Another option might be sectoral agreements and/or the integration of climate mitigation in development policies. Elzen et al. (2008) suggest a "staged sectoral approach" in which developing countries should be encouraged to participate in international climate policy by imposing incentives instead of penalties. It is indicated in a research on China that since China's economy is rapidly increasing it might be impossible to reliably project future GHG emissions on a national scale for the entire economy; therefore sectoral approaches might need more attention (Yamin, 2007). Other research suggests that from an economic perspective, national GHG reduction targets are not likely to pose an excessive burden on China (Zhang, 2000). International climate negotiations such as at the UNFCCC conference in Bali 2007 show the importance of increasing the participation of developing countries under the next climate agreement of the post-2012 era.

The very fact that developing countries develop should not be contestable. However, the way in which developing countries develop may be debated. There are a number of options to enable a more sustainable development, and renewable and clean energy are one of these options. There are thus means for developing countries to avoid the “dirty path” of development which today’s industrialised countries followed and instead to develop more sustainably by using the latest climate- and environment-friendly technologies. This process is often referred to as technological leapfrogging.

Technological leap-frogging is assumed to play an important role in the growth of today’s developing countries as it should give access to modern technologies and to innovation enabling a sustainable growth. The Kyoto Protocol incorporates this approach to equity in its Clean Development Mechanism (CDM) (United Nations, 1998), although developing countries recently criticised that the CDM does not meet these goals. The use of the CDM can in principle enable developing countries to receive modern technology for sustainable development from industrialised countries while industrialised countries in return receive certified emission reduction credits (CERs) to offset their emission reduction obligations. Innovation and technological leap-frogging might play a significant role in the coming decades and might change energy systems significantly and rapidly. Innovation and leap-frogging might also lead to “jumping over” potentially polluting periods, like the coal era during the Industrial Revolution which Europe and North America had to go through. Developing countries may have a chance to avoid such periods due to cleaner and more advanced technologies. Predicting the future of energy systems in rapidly developing countries involves risks, because of the uncertainty of the implementation of innovative technologies that could enable the leap-frogging process.

1.4 Energy transitions and the role of renewable and clean energy

Energy transitions can be defined as shifts from a country’s economic activities based on fossil fuels to an economy based partially on renewable and cleaner low-carbon energy. This means that substitutions take place from fossil fuel-based technologies to cleaner technologies. Such transitions can take place in every sector of a country’s or a region’s economy. Sustainable energy transitions are likely to open up new possibilities for developing countries to achieve higher development and higher living standards while at the same time safeguarding energy resources, the environment and human health.

The concept of the ‘Trias Energetica’ was developed in the Netherlands by Lysen (1996) as a three-step strategy to achieve such energy transitions: 1. by reducing energy use, 2. by introducing renewable energy, 3. by using fossil fuels efficiently. This thesis acknowledges the importance of all three options, but focuses on the introduction of renewable and clean energy.

Renewable energy comes from renewable resources, such as sun, water and wind, which are abundant and globally available. Renewable energy technologies are close to zero-carbon technologies. They are usually climate-friendly and environment-friendly. Unlike fossil fuels, renewable energy technologies do not emit GHG emissions during energy generation. If the complete life cycle of renewable energy technologies is taken into account, there will be GHG emissions from the production, transport and waste phases. These GHG emissions are substantially below the GHG emission of fossil fuels. Modern renewable energy sources are also not likely to contribute to local air pollution or to serious health problems.

Energy transitions can be achieved through the use of clean energy sources. Clean energy sources are defined as low-carbon energy sources which emit less GHG than conventional coal and oil, such as a.o. natural gas, compressed natural gas (CNG), liquid petroleum gas (LPG), and nuclear energy. It has to be noted that the term “clean” energy actually describes less polluting energy, keeping in mind that there is no completely clean energy. Renewable energy can negatively impact the environment too considering its complete lifecycle as mentioned earlier, though not to the same extent as other energy sources. Despite this fact, the term clean energy is commonly used in energy-related literature.

Renewable and clean energy can enhance energy security and reduce the exploitation of natural resources. Dependency on energy imports may decrease and natural resources can be safeguarded. Renewable and clean energy can also support energy security in rural areas. In contrast to most conventional fossil energy, renewable energy and some clean energy (e.g. LPG) can be used locally in areas where there is no grid connection and where people rely on traditional biofuels like fuel wood, dung and agricultural residues. The quality of life of the local population might be increased due to modern renewable and clean energy, as these energy sources may be used for lighting, cooking, heating, water boiling and for running electronic devices such as radios and irrigation pumps. The time spent for collecting traditional fuels or working with manpower can thereby be reduced; the efficiency of energy services usually increases and negative health impacts are likely to decline. The usage of traditional biofuels is considered to have high impacts on health. They are associated with pneumonia, chronic respiratory disease, lung cancer and adverse pregnancy outcomes due to exposure to indoor air pollution as well as body deformations due to the transport burden of fuel wood collection (WHO, 2000; WHO, 2005; WHO, 2006). The World Health Organisation WHO reports that 4.7% of all deaths in least developed countries could be due to traditional solid fuel use (WHO, 2000). According to the WHO (2005), 1.6 million people -mainly women and children- are likely to die every year, because of exposure to indoor air pollution from traditional biofuels. Introducing modern renewable and clean energy sources as a replacement for traditional biofuels is likely to increase the health of the population in developing countries.

There is a high potential for renewable energy world-wide (Hoogwijk, 2004). However, only a small percentage of this potential is exploited so far (Hoogwijk, 2004). The technologies for energy transitions are commercially available world-wide. The IPCC further reports that transitions to low-carbon economies have begun, also in developing countries (IPCC, 2007a).

There are however a number of main barriers which limit the growth of renewable energy: economic, political, social, environmental, technical and geographic barriers. Those considered the most relevant ones are briefly listed below:

- Economic barriers: There can be high investment costs and high generation costs for renewable energy which makes it difficult to compete with highly-subsidised fossil fuel costs. These high costs are considered to exist mainly due to insufficient financial policies and low penetration rates.
- Political barriers: These are likely to occur due to missing supportive governmental policies and the favouring of fossil fuels due to economic and/or geo-political reasons.
- Social barriers: Social conflicts may occur concerning the evacuation and relocation of the local population for large-hydropower dams, like at the Three-Gorges-Dam in China where 1.4 million people were relocated and another 4 million people might have to be evacuated

within the next decade according to Xinhua (2007a). There is the NIMBY-effect (Not In My BackYard) for wind energy; and there is social opposition to first-generation biofuels partly due to the competition of land for biofuel crops and food crops. The opposition against first-generation biofuels has been steadily growing and reached its most recent peak in April 2008 concerning the debates about a global food crisis. This debate is spurred by riots over increased food prices in some of the world's poorest countries like Haiti and Burkina Faso, but also in Egypt, Mexico and India. Other renewable energy sources such as small-hydropower, solar energy, geothermal energy and biogas from agricultural residues are likely to have lower social barriers.

- Environmental barriers: There might be a range of high environmental impacts for large-hydropower like the flooding of creeks and canyons, the decrease in water flow speeds, more frequent erosion, more frequent landslides and increased water pollution like at the Three-Gorges-Dam (Xinhua, 2007b). Fragmented development or degradation of the landscape is often associated with wind turbines. Conflicts arise concerning land-use for first-generation biofuels. Other renewable energy sources such as small-hydropower, solar energy, geothermal energy and biogas from agricultural residues are likely to have lower environmental barriers.
- Technical barriers: Possible barriers are low outputs and fluctuating outputs, need for back-up capacity and difficulty associated with the storage of power from renewable energy. Substantial research is currently going on into storage possibilities.
- Geographic barriers, both physical and spatial: Renewable energy sources depend on natural resources like wind, water, sun and land. The availability of these natural resources varies locally. Renewable energy technologies can not be used in places where these natural resources are not available or not sufficiently available. There may not be enough land for first-generation biofuel production or not enough wind for wind energy production in some areas.

Clean energy sources such as natural gas, CNG and LPG are mostly competitive compared to conventional fossil fuels and do not usually suffer from the above described barriers. Nuclear energy tends to be associated with concerns a.o. about safety, environmental risks, health risks, social resistance, nuclear proliferation and high costs (e.g. Lee et al., 2007; NEA, 2002). While it is suggested in the IEA World Outlook 2006 and the IEA World Energy Outlook 2007 that nuclear power might play an increased role in the future in mitigating climate change and increasing energy security (IEA, 2006; IEA, 2007), some environmental organisations like Greenpeace repeat the risks and costs of nuclear power (Greenpeace 2006a; 2006b).

Despite the discussed barriers, renewable energy is globally being implemented at a high growth rate. Due to its rapid implementation time, renewable energy may also avoid carbon lock-ins and path dependency. Implementing renewable energy technology today may provide sustainable energy quickly and may avoid lock-in effects, such as dependence on coal power plants for decades. Renewable and clean energy are therefore globally considered as viable options for sustainable energy transitions.

1.5 Energy modelling

Energy transitions can be analysed, planned and managed by the use of energy models. Energy models are planning tools for exploring the future of the global and regional energy setting and the effects of energy use on the human and natural environment (Chapter 3). Scenario-making is a method to simulate the consequences of energy use for regions and countries given different future pathways. Energy models were first developed in the 1970s as a result of the increasing availability of the personal computer and the increasing environmental awareness due to a.o. the Club of Rome and the first oil crises. Most of the energy models were built and used by industrialised countries, so that the assumptions about energy systems of developing countries were mainly based on experience from the energy systems of industrialised countries. It was therefore assumed that the energy systems of developing countries would behave like those of industrialised countries (Shukla, 1995; Chapter 3). It was further assumed, that the present-day development trajectories for developing countries would be similar to the historic development trajectories in industrialised countries, which in reality is not the case. Especially rapidly developing countries like China, India, Brazil and South Africa may defy in many ways the industrial countries´ perception of development, which tends to be largely based on their own industrialisation. Technological leap-frogging, ambiguity towards different trajectories of development, significant regional and income-related differences between consumption patterns in developing countries are issues which played no role or only marginal roles in the development of today's industrialised countries. For energy modelling, trends for developing regions were often derived from those of industrialised regions and extrapolated to low-income ranges. What seems to be a fair modelling technique may nevertheless result in models biased towards industrialised countries, potentially leading to incorrect interpretations of the energy systems of developing countries. Still today, many well-known models like those of the IPCC's Special Report on Emission Scenarios (SRES) tend to be built by and predominantly for industrialised countries and tend to be seldom specifically made for use in developing countries. There is thus a need to adapt energy models to properly describe the energy future of developing countries.

There is a great variety of energy models and energy modelling approaches for various purposes. Models can vary by their regional scope, their time perspective, research aim, methodology, modelling approach, mathematical approach and other factors. Energy models could be clustered according to their methodologies and modelling approaches. Based on an adapted simplified approach by Van Beeck (1999, 2003), these models could be clustered into four prevailing methodologies: scenario simulation, optimisation, economic equilibrium and toolbox modelling, though differentiation of methodology could be difficult sometimes due to overlaps. Energy models could also be clustered into three prevailing modelling approaches: top-down, bottom-up and hybrid approach (Chapter 3). It has to be kept in mind that all models have shortcomings and limitations by definition, since models are simplifications of the complex real-world (Schenk, 2006). Schenk (2006) indicates that some of the major weaknesses of energy models are that they may represent only one viewpoint about the future, that they may be used in a manipulative way to give the impression that subjective judgments are based on thorough analysis and calculation and that they should not be used to address problems they were not built for.

1.6 Aim and scope of the thesis

Energy use is quickly rising in rapidly developing countries like China and India. The majority of conventional energy sources used in rapidly developing countries come from polluting fossil fuels, while unconventional energy sources like traditional biomass are also used to a large extent, especially in rural areas (IEA, 2008). Fossil fuel use is associated with significant environmental impacts such as global climate change, air pollution and resource depletion. Since energy processes are considered the main contributors to environmental problems like global climate change, it is crucial to implement mitigation measures. An effective mitigation measure is to use low-carbon energy technologies like renewable and clean energy technologies which can spur sustainable energy transitions. Sustainable energy transitions are important for developing countries, because they can avoid carbon lock-ins, provide possibilities for sustainable development and leapfrogging while safeguarding energy resources, the environment and human health. Energy models are considered important tools for analysing and planning such energy transitions. Many present-day energy models are developed by and for industrialised countries. Their approach tends to be biased towards the energy systems of industrialised countries and may neglect that the situation is very different in developing countries. Developing countries usually differ from industrialised countries in terms of energy consumption, production and distribution, energy infrastructure and energy economy. There is a need for new energy modelling approaches which are especially suited for the energy systems in developing countries.

The main objective of this thesis is therefore first to adjust energy models for use in developing countries and second to model sustainable energy transitions and their effects in rapidly developing countries like China and India. This research can be relevant for energy experts and policy-makers, especially in developing countries. It could give an indication about the opportunities and implications of sustainable energy transitions and potential future energy pathways. This could increase the knowledge developing countries have concerning their own choices for energy planning and climate policy negotiations in the post-2012 era.

The focus of this research is three-fold: a) to identify the characteristics of developing countries´ energy systems and to elaborate the differences between energy systems in developing countries and in industrialised countries, b) to move away from energy models´ bias of industrialised countries´ energy systems and to adapt energy modelling approaches by means of scenario-making to increase their suitability for rapidly developing countries and c) to develop scenarios using these adapted models to simulate sustainable energy transitions for rapidly developing countries. The core of this research is to develop scenarios for sustainable energy transitions in China and India. Renewable energy sources which are taken into account for these energy transitions are first-generation biofuels (e.g. biodiesel, bioethanol), biogas, geothermal energy, hydrogen, hydropower (small and large-hydropower), solar energy (e.g. photovoltaic (PV) cells, solar water heaters, solar lamps), tidal energy and wind energy. Clean energy sources considered are CNG, LPG and natural gas. Nuclear energy is also considered with its implications.

The main research questions are:

1. How are energy systems of developing countries characterised, with a focus on developing Asia? What are the factors influencing these energy systems and how will they change in the process of development? How is this modelled in present-day energy models and how could the modelling be improved?
2. How could sustainable energy transitions take place in specific economic sectors of China and India?
3. What could be the effects of these energy transitions on emissions, the electricity system, energy resource use, costs and social issues (e.g. access to electricity, effects on the urban and rural population)? What policy recommendations would be useful?

These questions will be addressed using energy modelling and scenario-making as tools.

It has to be noted at this point that developing countries show a large variety in and among themselves. Rapidly developing countries like China, India, Brazil and South Africa differ greatly from less developed countries or even from the least developed countries as in Sub-Saharan Africa (e.g. Burkina Faso, Mali, Mozambique, Niger, Sierra Leone) and in Southeast Asia (e.g. Bhutan, Cambodia, Myanmar, Nepal). Rural and urban areas can also differ significantly within one country. In some countries like Brazil or South Africa, large differences exist between the poor and the rich and their energy consumption patterns. Significant differences between urban and rural areas prevail in many developing countries concerning access to energy infrastructure and energy consumption patterns. A limitation on specific countries and a case study approach for specific regions and sectors is therefore necessary.

The general aspects of the energy systems of developing countries and their representation in energy models are elaborated first to address research question 1. For addressing research questions 2 and 3, case studies are chosen. This thesis focuses on rapidly developing countries in Asia and more specifically on China and India. These countries have been chosen, because they are currently the most rapidly developing, most energy consuming, most climate change-relevant and one of the most economically-growing developing countries. Their development will have global impacts. Implementing renewable and clean energy sources in these countries is likely to mitigate climate change. Due to the high variety also within China and India, system boundaries have to be determined and three case studies are selected to assess energy transitions in specific sectors of China and India. The case studies are the following: 1. a study on a national level examining the energy supply-side perspective for the power sector of China, 2. a study on an urban regional level examining the energy demand-side perspective for Beijing and its economic sectors and 3. a study on a rural regional level examining the energy supply and demand for the non-electrified residential sector in India. These case studies are chosen to assess energy transitions both from the supply-side and the demand-side, from the national and regional perspective, from the urban and rural perspective and for various sectors. This variety aims to give a comprehensive picture of energy transitions in rapidly developing countries like China and India.

1.7 Structure of the thesis

Besides introduction and conclusion, the thesis comprises five main chapters.

Chapter 2 elaborates concepts on energy and development, their relevance for developing countries and their implementation in the IPCC´s Special Report on Emission Scenarios (SRES) for Asia. This chapter focuses particularly on the concepts of the Energy Ladder and the Environmental Kuznets Curve and suggests that improvements can be made in modelling the issues underlying these concepts.

Chapter 3 deals with characterising and modelling energy systems of developing countries with a focus on developing Asia. Factors influencing energy systems and possible changes due to development are elaborated. Since the energy systems of developing countries differ from those of industrialised countries, consequences for energy modelling are involved. New requirements should be met by energy models to adequately explore the future of developing countries' energy systems. This chapter therefore aims to assess if and how the main characteristics of developing countries are adequately incorporated in commonly used energy models. It indicates how to improve energy models for increasing their suitability for developing countries and elaborates possible modelling techniques and data requirements.

Chapter 4 elaborates on sustainable energy transitions as mitigation options of climate change for China's power sector. Sustainable energy transitions are modelled based on scenarios developed in PowerPlan, a bottom-up model simulating a countries' power sector and the emissions arising from it. China’s carbon-based electricity production system of today is simulated as well as possible sustainable energy transitions for the future. Some of the improvements suggested for energy modelling in chapters 2 and 3 are incorporated in this chapter.

Chapter 5 presents scenarios for transitions to renewable energy for China’s capital Beijing. This chapter aims to elaborate alternative futures of the energy demand of Beijing using the Long-range Energy Alternatives Planning System LEAP. The scenarios are based on Beijing’s fossil fuel-dependent economy of today and the government’s targets for a future economy relying more on renewable energy. Some of the improvements for energy modelling addressed in chapters 2 and 3 are incorporated in this chapter.

While Chapters 4 and 5 aim at modelling the grid-related energy supply and demand of rapidly developing countries, Chapter 6 presents a different approach. The residential energy supply and demand of rural India is modelled using the Regional Energy Model REM. This approach focuses on non grid-connected households and compares possibilities for rural electrification with grid-extensions, decentral renewable energy systems and decentral diesel systems. Issues like electrification, energy poverty and fuel-switching play a role in this chapter. Chapter 6 is a contrast to the modelling of mainly urban energy systems in Chapter 5 and also includes some of the improvements suggested for energy modelling in Chapters 2 and 3. In Chapter 7, the conclusion is elaborated.

2. Modelling energy and development: an evaluation of models and concepts[1]

Abstract

Most global energy models are developed by institutes from developed countries, focusing primarily on issues that are important in industrialised countries. 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 all these aspects of energy and development.

2.1 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. Industrialisation, 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 is developed in industrialised countries, they mainly focus on issues that 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 (Shukla, 1995; Pandey, 2002).

In 2000, the IPCC published a set of scenarios in the Special Report on Emission Scenarios (SRES) (IPCC, 2000a; IPCC, 2000b). 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 this analysis, the focus is especially on

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[1] This chapter is a slightly adapted version of Van Ruijven, B.*, Urban, F.*, Benders, R.M.J., Moll, H.C, Van der Sluijs, J., De Vries, B. and Van Vuuren, D.P., 2008. Modeling Energy and Development: an Evaluation of Models and Concepts. *World Development,* Vol. 36(12): 2801-2821.

* Both F. Urban and B. Van Ruijven are the main authors and have contributed equally much to the article.

the Asian region. It is first evaluated whether two broad concepts of energy and development, the *Energy Ladder* and the *Environmental Kuznets Curve*, can be found in the SRES model results (Chapter 2.2). Next, several key issues of energy systems in developing countries are identified that are relevant for global energy models. Chapter 2.3 discusses these issues, focusing on the trends and stylised facts and the relevance for global energy models. Chapter 2.4 discusses the methods and gives the conclusions.

Some notes on this study have to be made beforehand. First, completeness of the key issues is not claimed; the focus is on what is considered the most relevant changes in energy systems in developing countries with respect to global energy modelling, based on this own analysis and observation. Second, the focus is 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, developing countries are defined 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). The terms developing country and developing region are used interchangeably.

2.1.1 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-called 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; van Vuuren and Alfsen, 2006; Nordhaus, 2007). 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 (van Vuuren and Alfsen, 2006). 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, MER values are used in the discussion of the SRES results (Chapter 2.2) and PPP values for the analysis of data (Chapter 2.3), as PPP is more suitable for the comparison of welfare levels between different developing countries. The different use of metrics in these two chapters is irrelevant for the type of comparisons that are made.

2.2 Developing countries in global energy models

One of the few consistent databases with scenario results from global energy models is the IPCC/SRES (IPCC, 2000b). Due to differences in regional definitions and levels of detail of the models, the reporting of model results in this database is rather rough and at a high level of aggregation. For example, results are published for only four world regions (of which the focus is 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, the focus is 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; IPCC, 2000b). 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 globalisation 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; IPCC, 2000b). Per scenario one model is the marker model, which is illustrative of a particular storyline. On several key-variables, the results of other models are harmonised with the marker model.

In this analysis, all data 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, the source-codes and technical documentation of the models should have analysed with respect to specific development issues. However, documentation of many of these models is incomplete and source codes are hard to obtain. Therefore, it was decided to use the results of the models and the available model documentation. By limiting this evaluation to these models, there is awareness that a range of specific energy models are excluded, 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 it is presumed that little has changed on the issues discussed in Chapter 2.3. Finally, it should be noted that data in the chapters are often presented as function of per capita income, an indicator used as a proxy of development level[4].

2.2.1 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

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[2] Due to different regional aggregations of the SRES models, the final report used only four regions: REF (economic reforming countries), OECD90, 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), it was chosen to limit the graphs to 12,000 US$/capita, which is the maximum average Asian income level in the A2 scenario.

Smith, 2000). The Energy Ladder is a generic concept that postulates that household energy use often shows transitions 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) (Smith et al., 1994; Barnes and Floor, 1996; Martins, 2005). 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 transitionsal theory, for instance, because the pattern is not observed as a sequence and it is driven by more factors than increasing income (Masera et al., 2000; Martins, 2005). 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 (Hosier and Dowd, 1987; Kituyi et al., 2001; Brouwer and Falcao, 2004; Top et al., 2004).

To compare the Energy Ladder hypothesis and the results of the SRES models, the fraction of non-commercial fuels and electricity in secondary energy use is used. According to the concept, energy use should move from traditional fuels towards kerosene and electricity. Figure 3 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 6). 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 6,000-10,000 US$/capita, while the IMAGE model still shows a share of about 10% at 12,000 US$/capita. Figure 4 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.

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

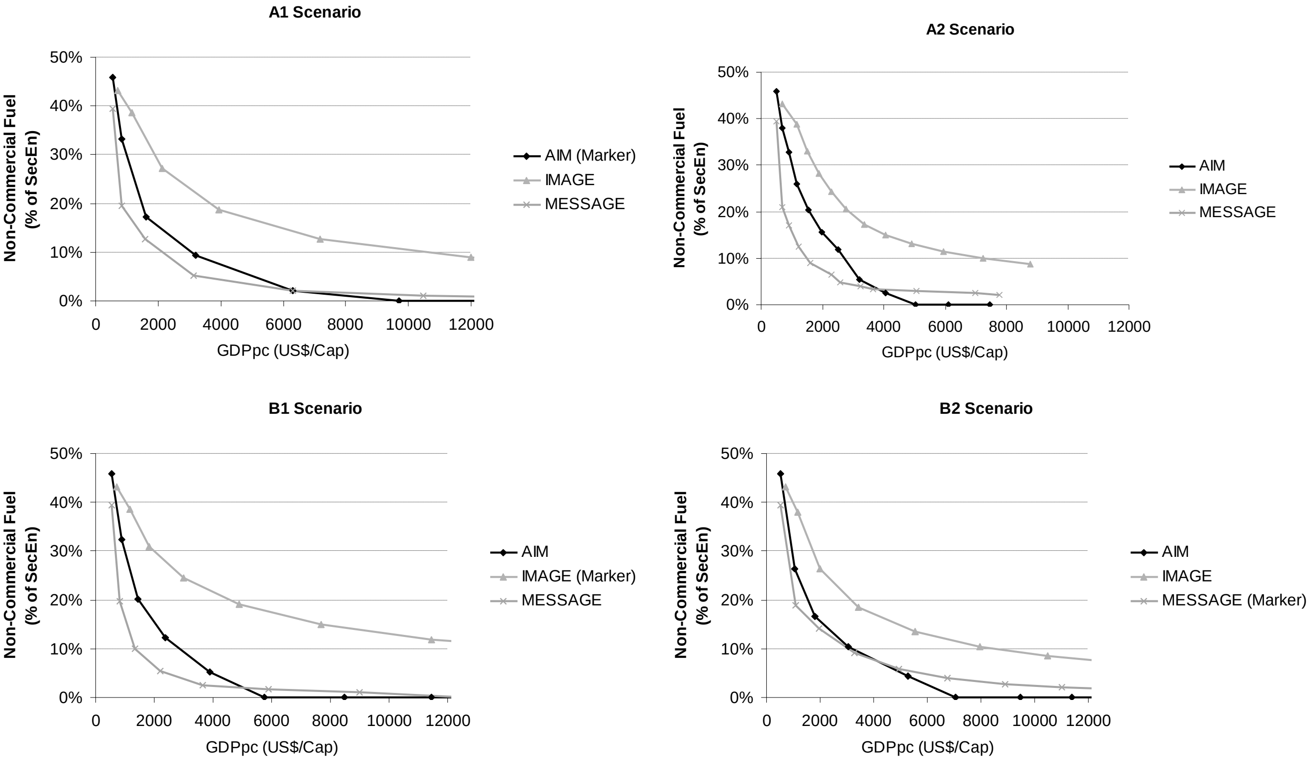

Figure 3: Fraction of non-commercial fuels in secondary energy use use vs. GDP/capita in MER for the region of ASIA from the SRES models.

The results of all IPCC/SRES models for Asia 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 transitions 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. These issues, especially traditional fuels and electrification, are often not explicitly incorporated in the global energy models (see Table 1).

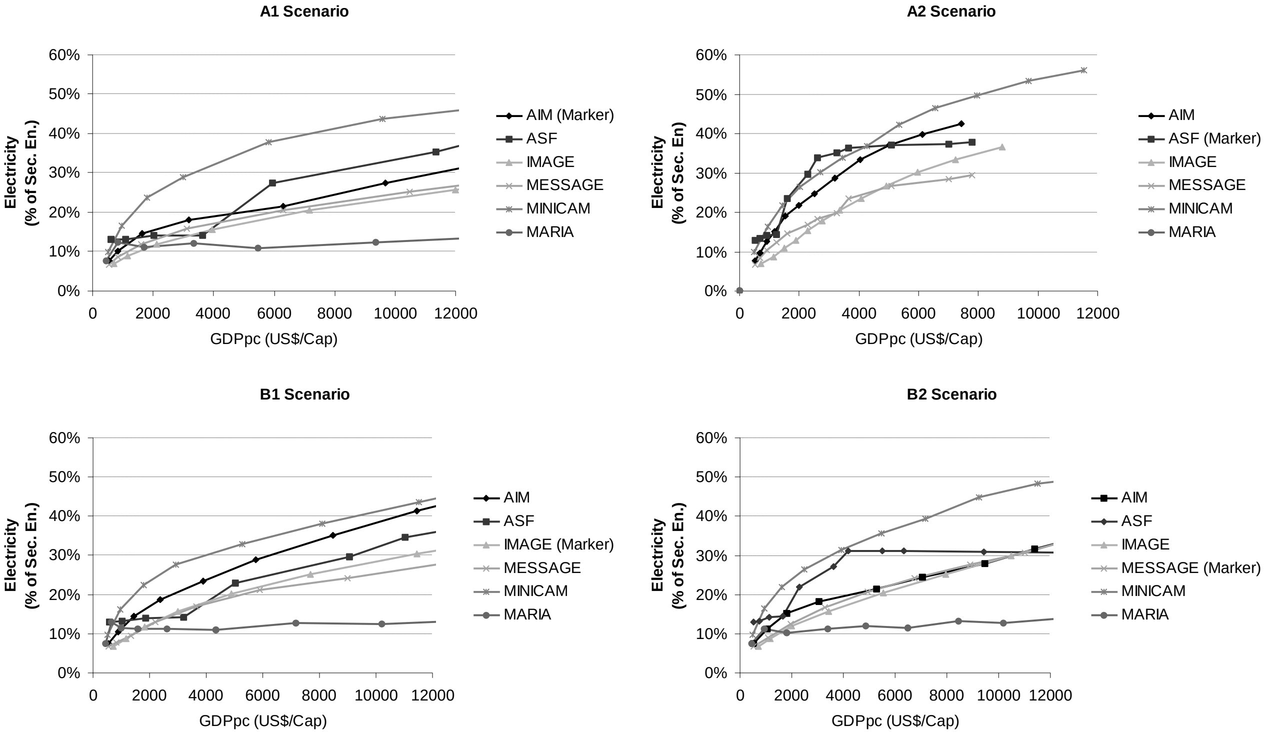

Figure 4: Fraction of electricity in secondary energy use vs. GDP/capita in MER for the region of ASIA from the SRES models.

2.2.2 The Environmental Kuznets Curve in the SRES models

The concept of the Environmental Kuznets Curve (EKC) generalises empirical observations of environmental pressure with economic development as an inverted U-shaped-curve, analogous to the income inequality curve described by Kuznets (Kuznets, 1955). Based on the concept of the EKC, it is often agued that environmental pressure will decrease once developing countries become more prosperous (Stern, 2004). Beside the observation that the statistical basis for the EKC is weak and many definitions are used to indicate environmental pressure (absolute (kg), per capita (kg/cap) or intensity (kg/$)) critics question its value for projections of developing countries and urge to focus on a decomposition of the underlying processes that drive this generic concept (Stern, 2004; Focacci, 2005). For instance, Focacci (2005) found that the EKC does not hold for developing regions and explained this from the heterogeneous income distribution, large presence of poor regions, prevailing rural lifestyle and economic and social barriers to the widespread adaptation of technologies.

Two environmental pressure indicators are used to analyse the EKC in the results of the IPCC/SRES models: 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 5). The wide variations 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 correspondingly high SOx emissions. The sulfur emissions of the IMAGE and MESSAGE models show wide variations between scenarios.

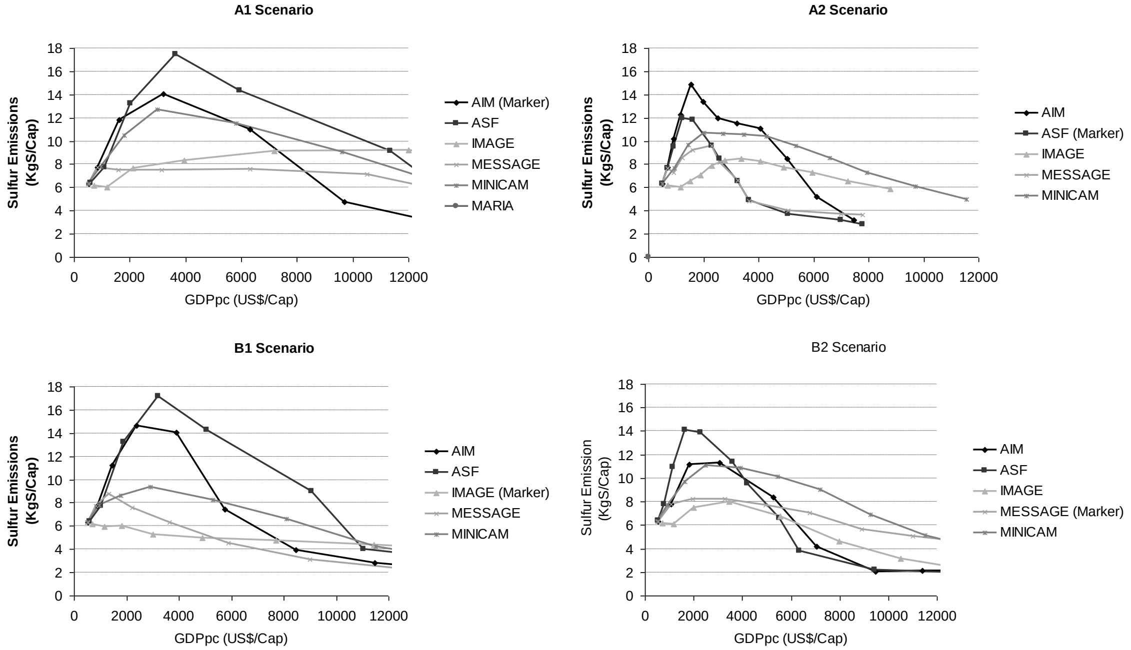

Figure 5: Sulfur emission projections vs. GDP/capita in MER for ASIA from the IPCC/SRES models.

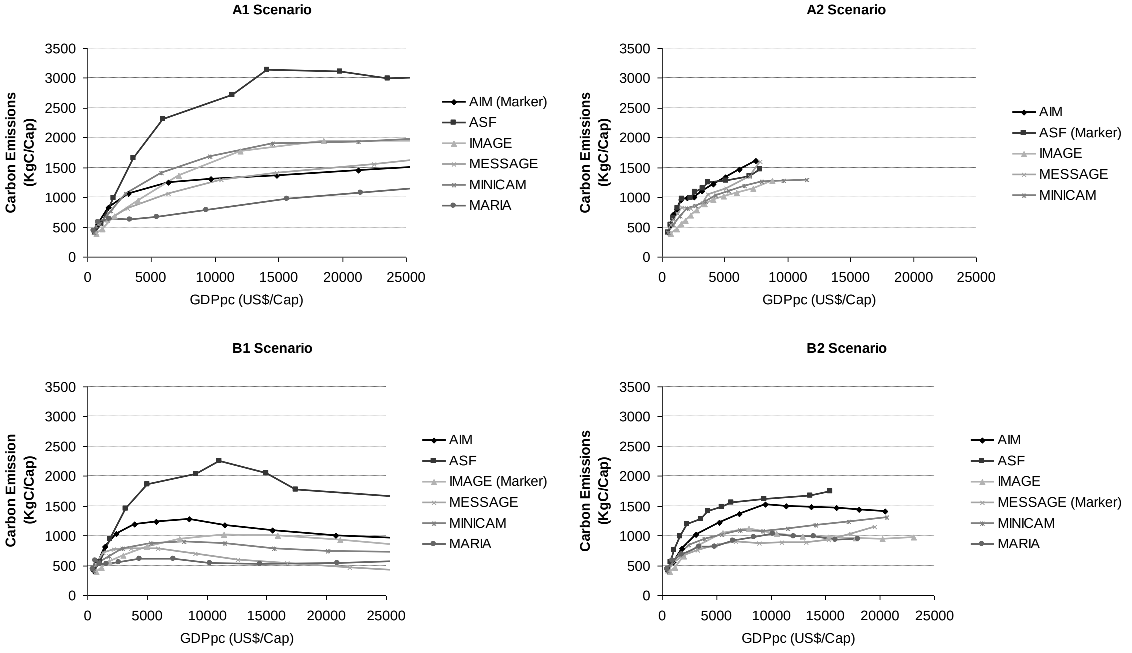

Figure 6: Carbon emission projections vs. GDP/capita in MER for ASIA from the IPCC/SRES models.

Figure 6 shows the carbon emissions results of the SRES models. In this figure, the upper limit of the income axis was increased, because the results seem to suggest that carbon emission projections could be following an EKC-type of trajectory in the model projections, although with a higher turning point than SO_2. Also for carbon emissions, wide variations exist between models and scenarios. In the A2 scenario, the top of the EKC is not reached in the 21st century, in the B1 scenario the turning point of the EKC is well below 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 regionalising 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).

Generally, all model results show the inverted U-shape of the EKC in the A1 and B1 scenarios. 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). The SRES results of the A1 and B1 scenarios show an EKC pattern for CO_2 emissions, although carbon mitigation policies were explicitly excluded from the scenarios. 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).

Also for the EKC, 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), are not explicitly modelled in global energy models (see Table 1).

2.3 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, three groups of key issues can be distinguished 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, this is discussed together with the key issues below.

	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 (optimisation)	Simulation model / Dynamic, non-linear	Optimisation model / Dynamic, non-linear	Simulation, Optimisation, Dynamic linear	Economic equilibrium model
KEY ISSUES	**Traditional Fuels**	Included, method unknown	Not included	Included, related to income, urbanisation 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 [5]	Implicitly included via demand elasticity [5]
	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 Nakicenovic et al. 1998 (fossil), assumptions for other resources. No impact on economic development	Rogner 1997 (fossil) World Energy Assessment (renewables). No impact on economic development	Rogner 1997 (fossil), Fuiji 1993 (renew-ables), Dusses et al. 1992 (biomass), OECD/NEA 1995 (uranium). 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

Table 1: Overview of issues of Energy and Development in the SRES models (Based on IPCC, 2000a; IPCC, 2000b; Mori, 2000; van der Sluijs et al., 2001). Note that only the SRES versions of the models were analysed.

Are these key issues incorporated in the IPCC/SRES models? This question was assessed qualitatively, based on the IPCC/SRES report (IPCC, 2000a; IPCC, 2000b), the available model documentation from the time of the SRES (Mori, 2000; de Vries et al., 2001; Kainuma et al., 2003) and an overview of the SRES models structure (van der Sluijs et al., 2001) (see Table 1). Below, it is elaborated on the key issues, evaluate whether and how they are incorporated in the SRES models and discuss their relevance for global energy models.

2.3.1 Developments in the energy system

2.3.1.1 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, 2002). Traditional biomass combustion causes indoor air pollution which triggers various adverse health effects and an estimated 1.6 million deaths per year (WHO, 2006). Another issue is the availability of fuel wood and its impact on deforestation (Arnold et al., 2006).

Data and stylised 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 7 and Figure 8, 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 7 and Figure 8, 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.

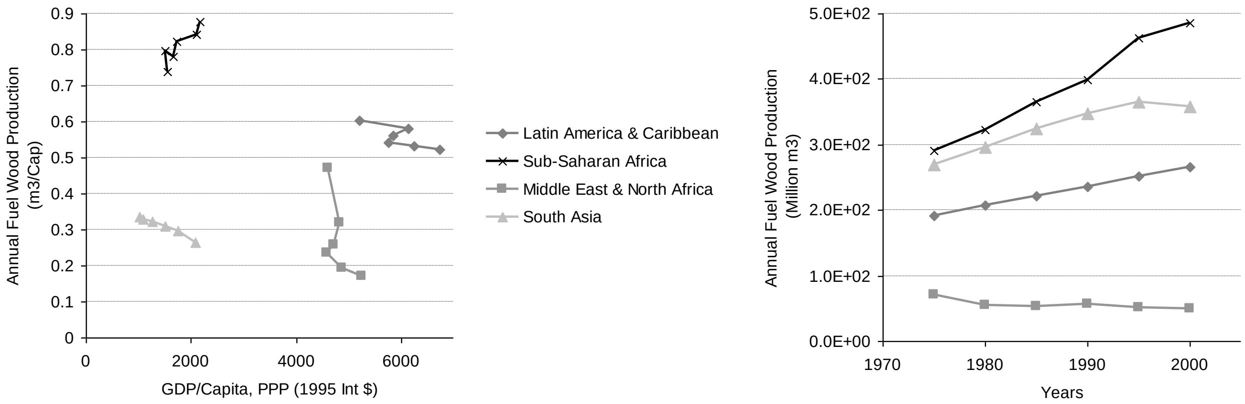

Figure 7: Left: Fuel wood production per capita vs. GDP/capita (PPP) for several developing world regions, data from 1975 to 2000. Right: Absolute annual fuel wood production for several developing world regions. Data from FAO (FAOSTAT) and World Bank WDI, 2004.

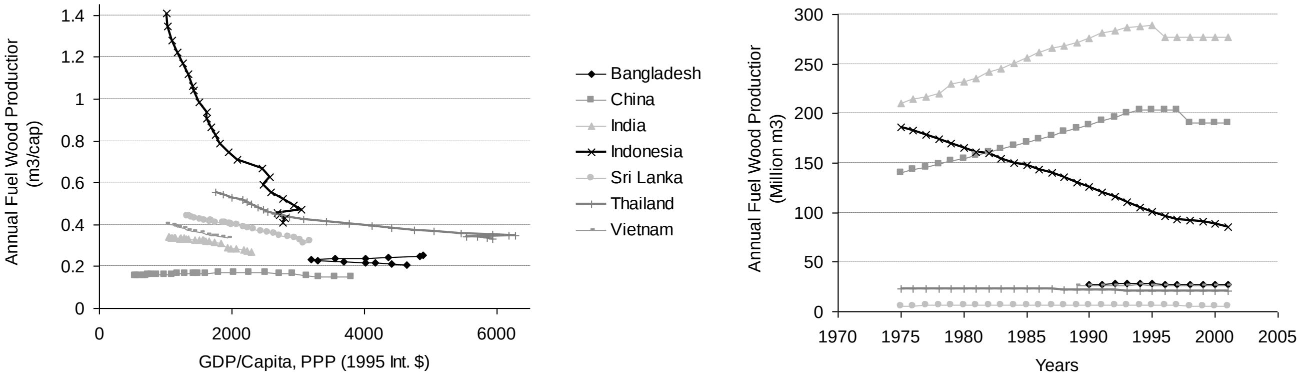

Figure 8: Left: Fuel wood production per capita vs. GDP/capita (PPP) for several Asian countries for the period 1975-2000. Right: Absolute annual fuel wood production for several Asian countries. Data from FAO (FAOSTAT) and World Bank WDI, 2004.

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 (2000). They found that declining fuel wood use can statistically mainly be explained from several factors: changes in income, differences in availability, degree of urbanisation and industrialisation. Besides 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).

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 1). This means that the models ignore an essential element of the energy system, potentially underestimating the demand for energy. 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 relates to pressure on forests, feedbacks from shortages and a 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. Finally, the importance of traditional energy use for health issues and climate change is another reason to include this fuel type in the models.

2.3.1.2 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, 2002). 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 9 and (Goldemberg, 2000; Reddy, 2000)). Many remote villages, especially those in mountainous areas, are not connected to a central electricity grid.

Data and stylised facts

Data on electrification are scarce and their usefulness is limited as definitions for ‘access to electricity’ differ per country (IEA, 2002). The data from the World Energy Outlook (2002) was used to analyse stylised 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 9 and 10).

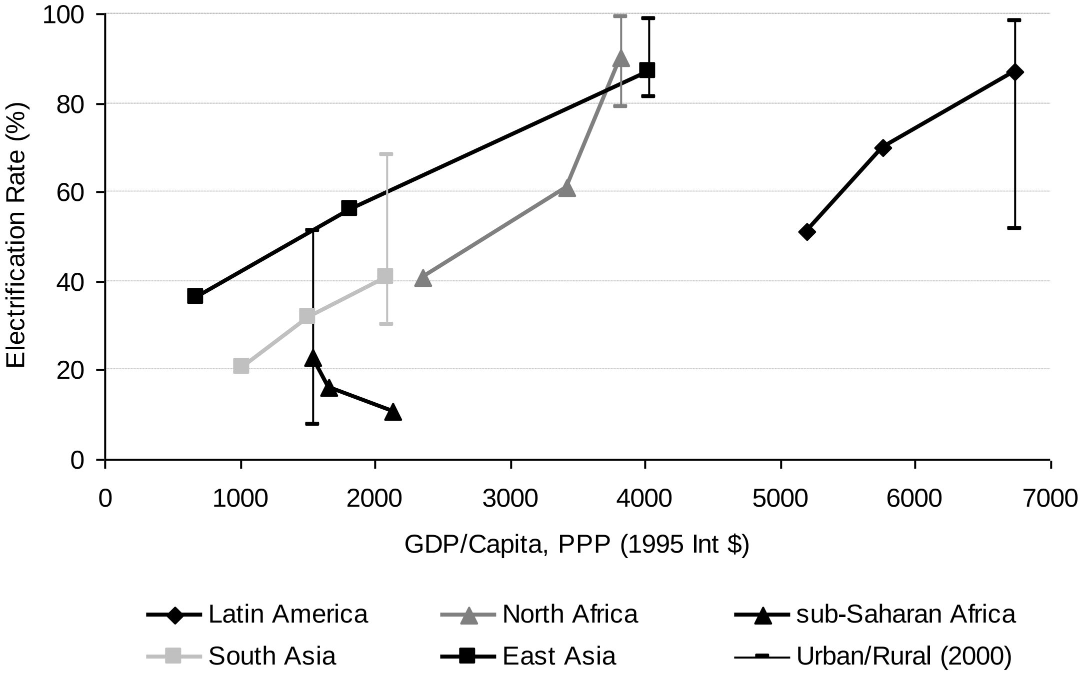

Figure 9: Electrification rates in several developing regions vs. GDP/capita (PPP). Data points are for 1975, 1990 and 2000. For the year 2000 information on urban and rural electrification is added, in all regions urban electrification rates are higher than rural. Note that sub-Saharan Africa faced a declining GDP/capita over the described period. Data from IEA, 2002 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 do not 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).

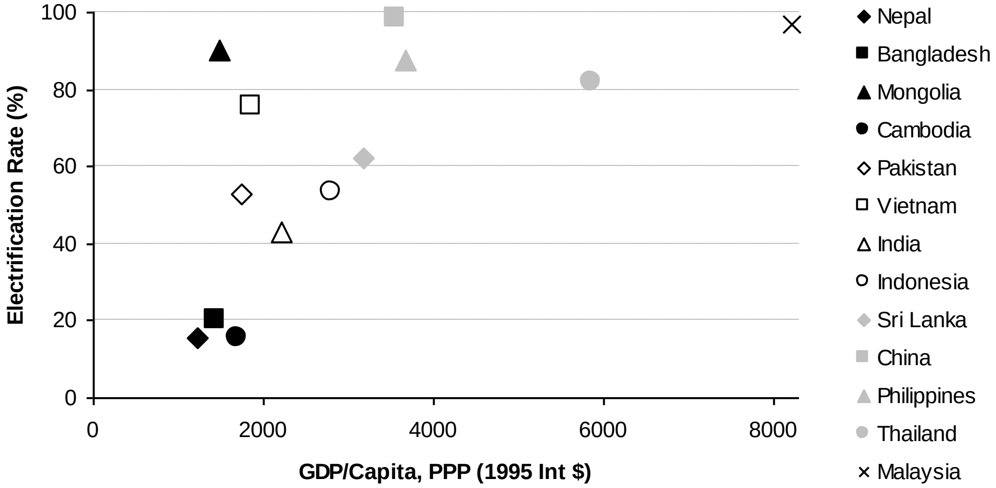

Figure 10: Electrification rates in several Asian developing countries vs. GDP/capita (PPP) for the year 2000. Data source: IEA, 2002 and World Bank WDI 2004.

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 1)[6]. 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

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[6] Research on more recent technical documentation and a questionnaire addressed by the model developers indicates that in MESSAGE and MiniCAM electrification is modelled explicitly (chapter 3).

and the implicit way of describing electrification in these models may not capture the possible limitations posed by access to capital and economic viability.

2.3.2 From economic development to energy use

2.3.2.1 Economic structural change and dematerialisation

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 11, left graph). Historically, developing countries that changed into an industrial economy did this by increasing the production of labour 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 stylised, 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 noteably high share of services (see Figure 12; Vries et al., 2007), which influences the prospects for scenario development. Another reason why developing country development might be different is that the decline in the industrial sector in developed countries is partly caused by a replacement of (heavy) industry from high to low income countries. Such "outsourcing" of industry can obviously not be reproduced by countries that currently have the lowest income levels.

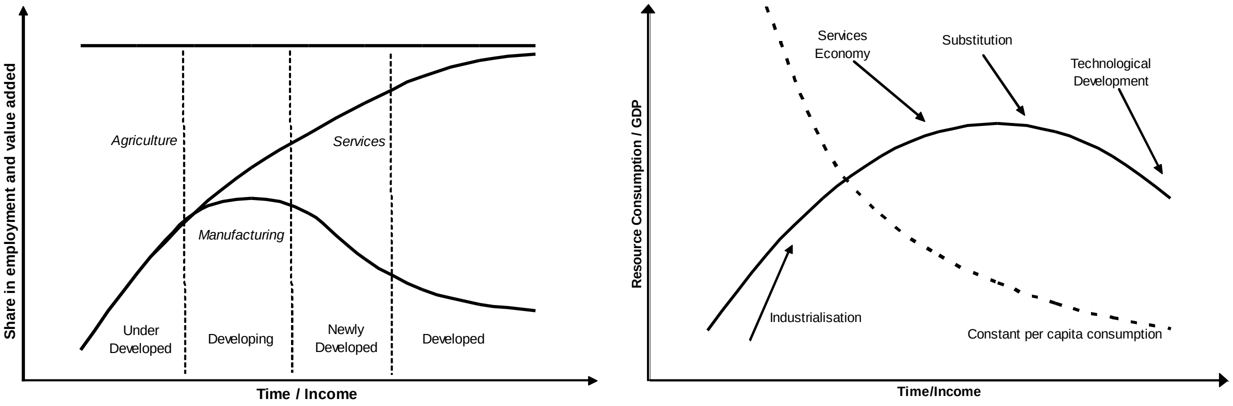

Figure 11: Left: typical stages in the share of employment or value added of agriculture, manufacturing and services, based on Jung et al. (2000). Right: the typical intensity of use curve of resources with economic development, based on van Vuuren et al. (1999).

A concept that can be related to economic structural change is the long-term trend of dematerialisation. The theory of dematerialisation can be summarised in two elements: 1) the intensity of use (in kg/\$) of a given material follows a similar pattern for all economies, first increasing with per capita GDP, reaching a maximum and than declining (see Figure 11, right graph); 2) the maximum intensity of use declines the later in time it is attained by a given economy (Bernardini and Galli, 1993). 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).

The question is whether these patterns hold true 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 stylised 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 12, 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.

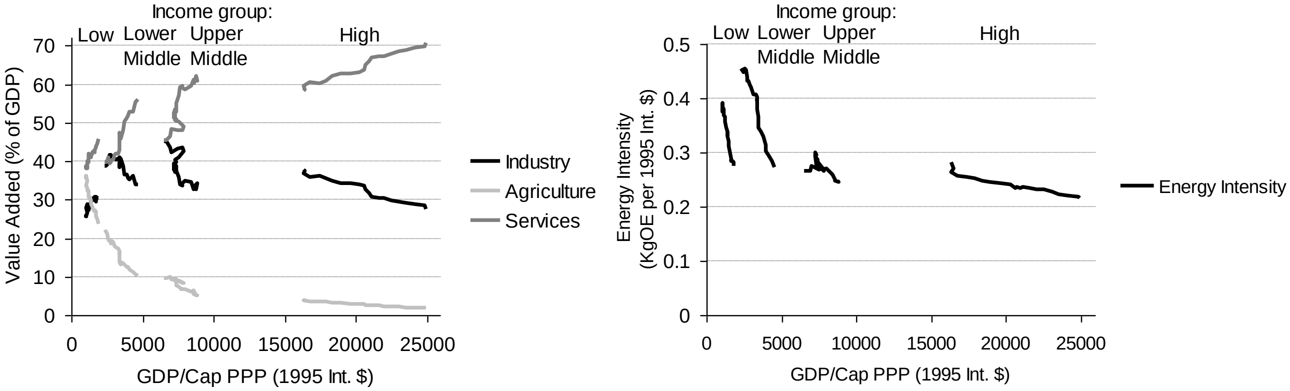

Figure 12: Value added (left) and primary commercial energy intensity (right) vs. GDP/capita (PPP) for low income, lower middle income, upper middle income and high income countries (1975-2000, data from World Bank (2004).

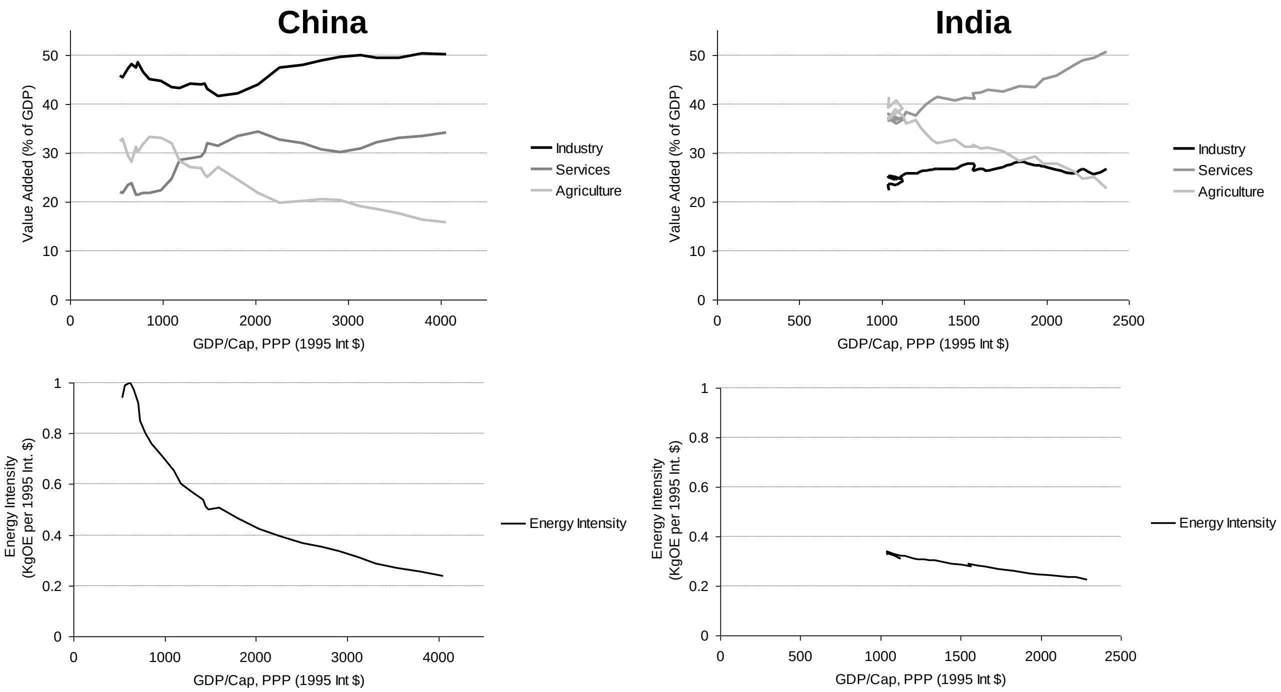

Figure 13: value added (upper) and primary commercial energy intensity (lower) vs. GDP/capita for India and China from 1975-2002, data from World Bank (2004).

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 13). 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 12). Differences in the energy intensity of the total economy can not only be explained from different economic structures; because for instance the applied technologies, policies, climate differences and population density play also 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 1). However, the agriculture sector, which is dominant in economic terms in most developing regions and uses electricity for irrigation, is seldom explicitly modelled. 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).

2.3.2.2 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 stylised fact of increasing and decreasing income inequality (see e.g. Saith, 1983; Glomm, 1997).

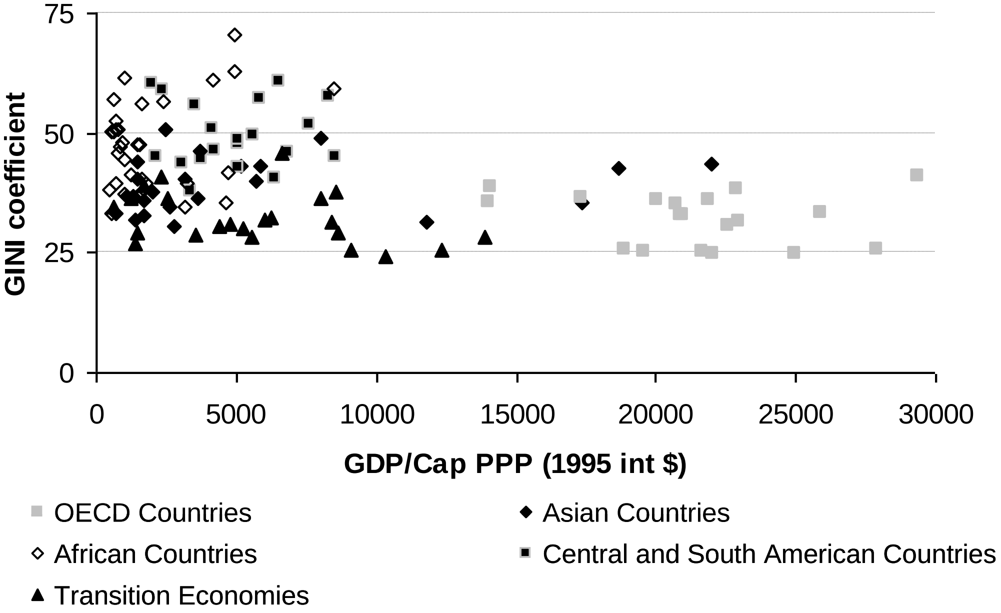

Figure 14: Gini coefficients vs. GDP/capita (PPP) for 121 countries. A higher Gini coefficient indicates a more unequal income distribution. Data for different years between 1990 and 2001, from World Bank (2004).

Data and stylised facts

Data on income inequality are scarce. The Gini coefficient was used in the World Bank WDI (World Bank, 2004) as a numerical measure for the degree of inequality of income[7]. It appears that income distribution generally tends to become more equal with increasing GDP/capita (Figure 14). However, a stylised function for this development, like a 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 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

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[7] 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).

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 realise that independent modelling of high and low income groups may result in very different dynamic behavior than suggested by the averages (see Van Vuuren et al., 1999 for 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 behavior that is typically related to low- or high income groups, e.g. the use of traditional energy or the electricity and transport behavior 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 urbanisation and decreasing household size. However, it could be worthwhile to attempt as 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.

2.3.2.3 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), 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 (Kahn and Pfaff, 2000; Chaudhuri et al., 2006): on average in 1999-2000 41% of the total official GDP, against an average of 17% in OECD-countries (Schneider, 2005).

Data and stylised 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.

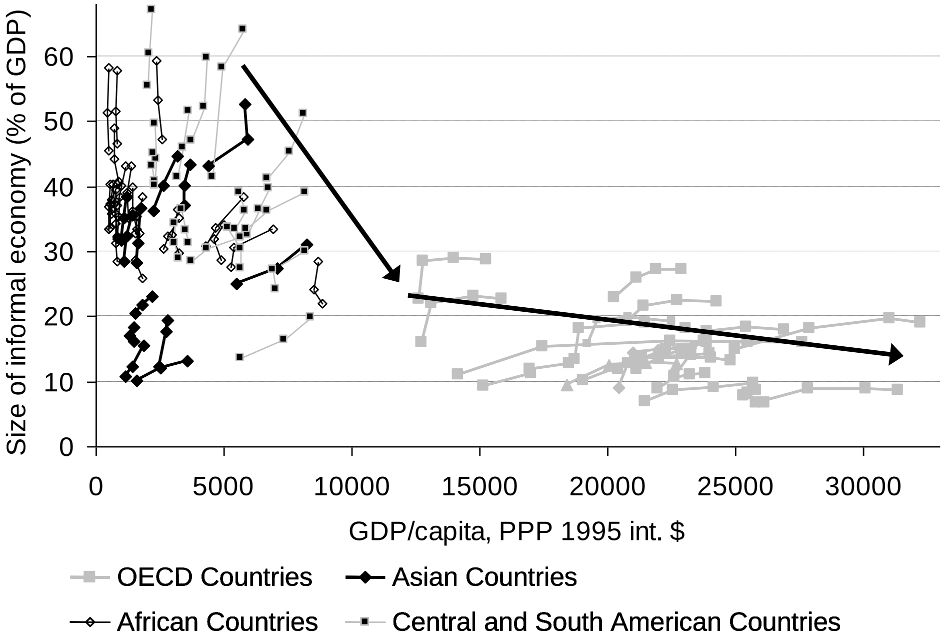

Figure 15: Estimations of the size of the shadow economy for several countries vs. GDP/capita (PPP). Data from World Bank WDI, 2004 and Schneider, 2005; data points for developing regions: 1990/1991, 1994/1995 and 1999/2000, for OECD regions: 1989/1990, 1994/1995, 1997/1998 and 1999/2000.

Figure 15 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; Schneider, 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 15) indicates a process of 'formalising' 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 13, in which China and India show rapidly declining energy intensities; this might also be explained from formalisation (or monetisation) 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 6). 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 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 exist (Van Vuuren and Alfsen, 2006).

2.3.3 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, some characteristics of energy systems and socio-economic developments are discussed 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 before (see Table 1).

2.3.3.1 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 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.

2.3.3.2 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 (O'Brien et al., 2004; Halsnæs et al., 2007), 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.

2.3.3.3 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 sulfur 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., 2006) 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 favored, 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).

2.4 Discussion and conclusion

This article 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. The need of focus meant that this paper 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 as 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. Of course the choice of models influences the results, but to this experience most discussed issues are not well captured in other global energy models either. 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, it was 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 can give more insight in the impact of different lifestyles. Establishing a relation between different income groups, their behavior 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.

2.5 Acknowledgements

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3. Modelling energy systems for developing countries[8]

Abstract

Developing countries' energy use is rapidly increasing, which affects global climate change and global and regional energy settings. Energy models are helpful for exploring the future of developing and industrialised countries. However, energy systems of developing countries differ from those of industrialised countries, which has consequences for energy modelling. New requirements should be met by present-day energy models to adequately explore the future of developing countries' energy systems. This paper aims to assess if the main characteristics of developing countries are adequately incorporated in present-day energy models. These main characteristics will first be discussed; focusing particularly on developing Asia, and then a model comparison will be presented consisting of 12 selected energy models to test their suitability for developing countries. It is concluded that many models tend to be biased towards industrialised countries, neglecting main characteristics of developing countries, e.g. the informal economy, supply shortages, poor performance of the power sector, structural economic change, electrification, traditional biofuels and the urban–rural divide. To more adequately address the energy systems of developing countries, energy models should be adapted and new models should be build. It is therefore indicated how to improve energy models for increasing their suitability for developing countries and it is given advice on modelling techniques and data requirements.

3.1 Introduction

The energy use in developing countries is rapidly growing and affects global climate change and the world's energy resource stocks. Mankind has to acknowledge the increasing influence of developing countries on the global energy setting. One way to do this is through energy models, which explore the future of the global and regional energy setting and the effects of energy use on the human and natural environment.

Most present-day energy models were built and used by industrialised countries, so that the assumptions about energy systems of developing countries were mainly based on experience from the energy systems of industrialised countries. It was therefore assumed that the energy systems of developing countries would behave like those of industrialised countries (Shukla, 1995). It was further assumed, that the present-day development trajectories for developing countries would be similar to the historic development trajectories in industrialised countries, which in reality is not the case. For energy modelling, trends for developing regions were derived from those of industrialised regions and extrapolated to low-income ranges. What seems to be a fair modelling technique may nevertheless result in models biased towards industrialised countries, possibly leading to incorrect interpretations of the energy systems of developing countries. The use of these biased models is therefore questionable for developing countries.

In line with this reasoning, this chapter of the thesis aims to assess to what extent present-day energy models used in developing countries adequately address main characteristics of developing countries' energy systems and economies. Chapter 3.2 first describes briefly these main characteristics: poor performance of the power sector and traditional fuels which implies supply shortages, lack of access to electricity and the predominance of traditional biofuels.

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[8] This chapter is a slightly adapted version of Urban, F., Benders, R.M.J., Moll, H.C., 2007. Modelling energy systems for developing countries. *Energy Policy*, Volume 35(6): 3473-3482.

Afterwards, it is elaborated on the transitions from traditional to modern economies which include the informal economy, non-monetary transactions and structural economic change. Finally, there is a discussion about structural deficiencies in society, economy and energy systems by which is meant the urban-rural divide, inadequate investment decisions and misdirected subsidies. For evaluating these characteristics in Chapter 3.3, secondly 12 present-day energy models are compared to assess their suitability for developing countries' energy systems and their economies. In Chapter 3.4, the results of the energy model comparison are presented and discussed in Chapter 3.5. In Chapter 3.5, it is also indicated how to improve energy models for increasing their suitability for developing countries. In Chapter 3.6, the findings are concluded and recommendations for future research are indicated.

For the description of the energy systems and the model comparison, wide disparities are acknowledged between "developing countries", particularly between smaller and larger, poorer and wealthier countries and the differing modelling approaches required for each individual country. For this study, developing countries are defined as countries with an average income of below \$10,065 GNI per capita (representing the lower and middle income countries of the World Development Indicators, World Bank, 2006), an under-developed infrastructure and a poor human development index. Recognising the wide cross-country disparities, the focus is only on developing Asia in this study, because it is the world's largest developing region, hosting the world's largest population, having the highest economic and industrial growth rate and contributing the most to global climate change in absolute terms compared to the contributions of other developing regions. The focus is especially on rapidly developing countries such as China and India.

3.2 Characteristics of the energy systems and economies of developing countries

The energy systems of industrialised countries are characterised by a constant match of supply and demand, low losses of transmission and distribution, universal access to electricity, predominance of modern energy carriers, similar structural premises in urban and rural areas, adequate financing and investment decisions, adequate subsidies and profit-making utility companies in developed economies with a low extent of informal economies. To the contrary, the energy systems of developing countries differ from those of industrialised countries and among each other. A number of issues will be elaborated which are described in scientific literature as the main characteristics of developing countries' energy systems and economies (e.g. Van der Werff and Benders, 1987; Schramm, 1990; IEA, 2002a b; Xu Yi-chong, 2002, Xu Yi-chong, 2005; Urban et al., 2006). These characteristics are also the most important issues for energy modelling. It is therefore evaluated in Chapter 3.4, whether these characteristics have been adequately addressed in present-day energy models. For the description of the main characteristics of developing countries' energy systems and economies, specific examples for Asia are given.

3.2.1 Poor performance of the power sector and traditional fuels

Many Asian developing countries suffer from a poor performance of the power sector for various supply-side, demand-side and economic reasons.

First, from a supply-side perspective, the power system configurations are often sub-optimal: these systems are often not meeting the demand, even though a substantial excess capacity may exist (Schramm, 1990). The reasons for the excess capacity are faulty planning and poorly performed operational and maintenance tasks leading to frequent plant breakdown, outages and voltage fluctuations, resulting in unreliable service causing economic losses (Schramm, 1990).

For the functioning of modern economies, meeting the electricity demand is crucial. Supply shortages are unfortunately characteristic for many Asian developing countries and regions. They are caused by (a) a poor performance of the power sector such as poor conditions of generation and distribution equipment, inadequate operational and maintenance performance and a high level of technical and nontechnical losses. Other reasons are (b) a rapidly growing demand for electricity (c) a low number of power plants (d) technical constraints (e) organisational problems (f) underfinanced power companies (g) restriction on capital available for investments (h) a dependence on import of plants and equipment for power supply and (i) too low consumer prices (Schramm, 1990; Van der Werff and Benders, 1987; IEA, 2002b). A reliable electricity supply can in some situations also be threatened by high electricity losses, such as in India where they account for 27%, ranking world second just after Nigeria (IEA, 2002a). The Philippines have also high losses of about 14% and Indonesia has 12%, compared to an OECD average of about 6% (IEA, 2002a).

Second, a demand-side problem is access to electricity, which is in general rather low in developing Asia, particularly in poorer rural areas. Only 64% of the Asian population had access to electricity in 2000, leaving about one billion inhabitants in the dark (IEA, 2002a). A good example for increased access to electricity is, however, China which managed to achieve an electrification rate of about 99% in the last years, because of wide-spread electrification schemes. The lowest electrification rates in Asia in 2000 were in Afghanistan with only 2% and Myanmar with only 5% (IEA, 2002a). Despite some very low electrification rates, the IEA (2002a) expects that with rising per capita income access to electricity will reach 81% in developing Asia by 2030, thus an increase of 0.57% per year. Critically assessed, however, it appears to be too simplistic to assume a direct link between income and access to electricity for a number of reasons: income is not equally distributed, governments can refuse to invest in electricity infrastructure, also structural problems may occur as described earlier, and technical and geographical limitations exist for grid connections. Further, population growth will also lead to an increase of at least one billion inhabitants in developing Asia until 2030. Consequently, the additional one billion inhabitants need to be provided with electricity, which will decrease the annual rise of electrification rates. Further, stand-alone renewable options or mini-grids are also possibilities to electrify households, but these options are often not included in the national statistics of electrification. Finally, some studies advocate that electrification in developing Asia can only be successful if long-term strategies comprise micro-loans or other forms of financial support for investments for electric equipments (Kanoria, 2006) or create opportunities for a higher income generation (Bhattacharyya, 2005), as experience from India has shown.

Third, concerning the demand side, even though electricity consumption is at the rise, the predominant fuels in developing Asia are still traditional biofuels: fuel wood, fuel roots, dung, agricultural waste, crop residues, and fuel sticks. Traditional biofuels are primarily used domestically for cooking and heating, particularly in poorer rural areas, as indicated by 1.7 billion poor inhabitants in Asia who relied on traditional biofuels in 2000, which is about 53% of the total Asian population (IEA, 2002a; IEA, 2004). The number of people relying on traditional biofuels is expected to increase to 2.6 billion by 2030, mainly because of population growth and unavailability of alternative fuels (IEA, 2002a). Besides population growth and the unavailability of alternative fuels, increased consumption of traditional biofuels is mainly due to three factors: changes in income, the degree of urbanisation and the degree of industrialisation. The share of traditional biofuels declines in general with rising GDP, although differences exist between countries and regions (Victor and Victor, 2002). When income distribution and geographic distribution is taken into account, the relation between income and traditional bio-fuel use, particularly fuel wood use, can be different (Victor and Victor, 2002), because traditional biofuels are mainly used by lower income households and in poorer rural areas.

Fourth, from an economic perspective, poor sector financing is common with tariffs below long-term marginal costs of production or even below average operating costs and a poor revenue collection performance by the utilities where a large share of the non-paid bills will never be collected (Schramm, 1990; Van der Werff and Benders, 1987). This is mainly because governmental departments and government-owned companies are under government protection and do therefore frequently not pay their electricity bills or because customers are simply to poor to pay their bills (Schramm, 1990). Another reason for the financial deficiencies is that theft of electricity is common. India’s power sector, for instance, is facing a serious risk of bankruptcy, mainly because of unpaid bills and high transmission and distribution losses (IEA, 2002b). For such cases, installing a theft-proof system would be helpful, as experience has shown in Haiti (Schramm, 1990).

3.2.2 Transitions from traditional to modern economies

There are currently transitions ongoing in many Asian countries from a traditional mainly rural-based economy to a modern mainly industry- or service-based economy. One important part of these economic transitions is the concept of the informal economy and non-monetary transactions. The informal economy (also often referred to as the shadow-economy) and non-monetary transactions take into account the unofficial transactions which occur in reality, but which are not accounted for in official economic descriptions, like GDP or value added (Chapter 2). The informal economy is a broad concept based on varying definitions associated with illegal activities, tax evasion or avoidance and (non-)monetary transactions (Schneider, 2005; Chapter 2). The main drivers for the informal economy are estimated to be the burdens from tax and social security contributions, the intensity of regulations, social transfer systems, overregulation and high costs on the official labour market (Schneider and Enste, 2000; Chapter 2). All around the world, informal economies and non-monetary transactions occur, but it has been observed that they are usually larger in developing countries (Kahn and Pfaff, 2000; Chapter 2). The informal economy had the size of 41% of the total official GDP in developing countries in 1999–2000 in average. Although OECD countries also show a share of 17%, the issue is clearly more present in developing countries (Schneider, 2005; Chapter 2). A major problem with the informal economy and non-monetary transactions is that data are rare which causes difficulties for representing developing countries’ economies and their energy systems.

Besides the informal economy, the economies in developing Asia are characterised by different structural economic changes than in industrialised countries. For developing countries, it is often assumed that they will follow the same development trajectory as today’s industrialised countries did in the past: first a decline of the agricultural sector, then a heavily growing industry and later a shift towards the service sector (Jung et al., 2000). It has been observed, however, that structural economic change in many Asian developing countries takes place as an early shift towards energy-extensive services in the economy of a country, which results in low energy intensity. The trends for India, for example, indicate that the country first developed a modest industrial sector, but then shifted towards the service sector which is flourishing nowadays (Urban et al., 2006; Chapter 2). There are large differences between countries in Asia, such as between the mainly service-based India and the mainly industry-based China. These differences can partially be explained by differences in culture (e.g. it is often stated by Indians that “India’s biggest asset is people” which can most cost-effectively be employed in the service sector) and politics (as a communist country China needed a large industry for producing raw materials, such as steel, for being independent from Western imports and for competing in the global arms race).

3.2.3 Structural deficiencies in society, economy and energy systems

Many Asian countries suffer from structural problems which affect society, economy and energy systems. One of these structural problems is the urban–rural divide which describes differences between urban and rural areas affecting access to energy, fuel use, access to education, safe drinking water, health services and sanitation. The urban–rural divide is more common in the developing world than in the industrialised world, usually with rural areas being worse off than urban areas (WEC, 2005). China, as an example, is expected to have to deal with rural poverty for another decade as Yao et al. (2004) report, mainly because of the growing inequality between urban and rural areas as a consequence of policy-makers who tend to favour urban areas. On the other hand, it has to be noted that national and international policy-makers regularly stress the importance of increasing basic human needs, infrastructure and economy in rural areas. Many Asian countries therefore have rural development schemes and/or rural electrification schemes in place since years or even decades, such as Bangladesh, China, India, Nepal, the Philippines and Sri Lanka. The existence of rural development schemes is an indication that the situation might become better in the coming decades.

Another major structural problem of developing Asia’s power sector is inadequate planning which results in inadequate investment decisions. In developing countries, actual investment costs often turn out to be much higher than the initial appraisal estimate, because forecasting techniques are poor and/or uncertainty ranges were neglected (Schramm, 1990). This often results in exceeded private and governmental funds, difficulties to attract foreign investors and incomplete or sub-standard power projects.

Another structural problem can be the abuse or inadequate use of subsidies. Subsidies were a way of ensuring state regulation of the power industry in many Asian countries in which the power industry was formerly often dominated by state regulation, monopolies and inefficient legislative and policy frameworks (IEA, 2002a; Xu Yichong, 2002; Xu Yi-chong, 2005). Subsidies which are purpose-bound, such as subsidies for rural development and irrigation, e.g. providing free electricity to farmers, may be helpful for the individual consumer and are a way to reduce poverty and enhance rural development, but may lead to market distortion, discarded prices, limited competition between utility companies, and the favouring of government-owned utility companies.

Conclusively, the energy systems of developing countries are complex and face serious challenges. To solve these challenges, good energy planning is required. Good energy planning can, however, only take place when good energy models are used. The issue of energy modelling is discussed in the following chapter.

3.3 Energy model comparison

The above discussed characteristics of the energy systems of developing countries need to be addressed in energy models to ensure an adequate representation of developing countries. This is crucial for an adequate modelling and scenario-making of the regional and global energy future which adequately tackles issues such as climate change, energy security, local air pollution and energy resource use. Due to technical limitations and possibly also due to biases from industrialised countries, these characteristics may be missing in present-day energy models. In this chapter, present-day energy models are compared for their use in developing countries, to assess to what extent these models adequately address the discussed main characteristics.

Energy models have been used to analyse a wide range of issues, serving different purposes and employing a variety of different techniques. Because of the complexity of energy models it is helpful to make a model comparison to analyse their purposes and performances. In line of this reasoning, Beaujean et al. (1977) developed the first survey of global and international energy models based on earlier reviews of energy models by Charpentier (1974–1976), followed by Meier (1984) who compared energy models for developing countries and developed a classification typology describing a variety of modelling techniques and their usefulness for developing regions. Shukla (1995) compared greenhouse gas models for developing nations and assessed the advantages and disadvantages of top-down and bottom-up models for this purpose, whereas Bhattacharyya (1996) compared applied general equilibrium models for energy studies.

Today, a wide range of present-day energy models exist which has not been evaluated for use in developing countries. An energy model comparison is performed here to assess to what extent present-day energy models used in developing countries adequately address main characteristics of developing countries' energy systems and their economies. The models are evaluated according to the main characteristics discussed in Chapter 3.2: performance of the power sector, supply shortages, electrification, traditional biofuels, urban–rural divide, informal economy, structural economic change, investment decisions and subsidies.

First, for the energy model comparison a pre-study was done to select the models on the basis of three criteria: (a) the model specifically takes into account developing countries; (b) the model is widely used by institutions in developing regions or widely used by institutions cooperating with developing regions; (c) the model is cited in scientific literature. The models had to fulfill all three criteria for being selected. For the selection process, 40 present-day energy models were identified, which are all the well-known or medium-well-known models currently used at institutions in developing countries and the OECD. These 40 models were then scrutinized according to the selection criteria, which lead to a selection of 12 models. The selection was restraint to energy and electricity models only and excluded models which entirely focused on climate change, carbon management and its impacts or addressed economic issues such as energy markets, investments and regulation.

Second, after the pre-study to select the energy models, the model comparison was done, which was based on a methodology composed of three steps: (1) literature review of model documentation: analysed material were model documentation guides, user manuals, articles in scientific journals, research reports, technical reports, websites, press releases etc.; (2) model runs: analysed material were input data, output data and model structure; (3) expert questionnaire: analysed material were answers by model developers. For each step, it was assessed to what extent the main characteristics of developing countries' energy systems were addressed. For the evaluation, a difference was made between explicitly and implicitly modelled characteristics. Explicitly means that the characteristics were adequately modelled e.g. that electrification is an input parameter, whereas implicitly means that the characteristics were partially modelled, e.g. electrification is embedded in the energy equation. Implicit modelling is problematic, because even after thorough scrutinisation it often remains unclear how certain characteristics have exactly been modelled. The model codes were not analysed, because of restricted access. The selection of models and applied methods can be seen in Table 2.

Third, for reasons of comparability, the selected models were classified by using a typology, because the models differ widely among each other in terms of modelling techniques and purposes. For this purpose, an adapted version of Van Beeck's classification typology (1999, 2003) was used, which was specifically meant for use in developing countries. Van Beeck classifies a few present-day energy models, but does not assess the suitability of the models for developing countries. Therefore, this is done in this paper. Van Beeck classifies energy models according to their purposes, model structure, analytical approach, underlying methodology, mathematical approach, geographical coverage, time horizon and data requirements. This typology was restricted to those classification criteria in which models differed the most: the underlying methodology: simulation, optimisation, economic equilibrium and toolbox models; the analytical approach: top-down, bottom-up, hybrid and the purpose. A hybrid approach combines top-down and bottom-up approaches.

Model abbreviation and full name	**Method**		
	Documentation	Model run	Questionnaire
AIM (Asian-Pacific Integrated Model)	X	X	
ASF (Atmospheric Stabilization Framework)	X		X
IMAGE/TIMER (TARGETS-IMAGE Energy Regional model)	X	X	X
LEAP (Long-range Energy Alternatives Planning System)	X	X	X
MARIA (Multiregional Approach for Resources & Industry Allocation model)	X		
MARKAL (MARKet ALlocation model)	X		X
MESSAGE (Model for Energy Supply Strategy Alternatives & their General Environmental impact)	X		X
MiniCAM (Mini Climate Assessment Model)	X		X
PowerPlan	X	X	X
RETScreen (Renewable Energy Technology Screening model)	X	X	X
SGM (Second Generation Model)	X	X	X
WEM (World Energy Model)	X		X

Table 2: Selection of models and applied methods. Applied methods are indicated by a X.
General information about the models can be found at: Kainuma et al. (2005 and 2003) for AIM; EPA (1990) and SEDAC (1996a) for ASF; De Vries et al. (2001) and RIVM (2001) for IMAGE/TIMER; SEIB (2006a and 2006b) for LEAP; Mori (2000) and IPCC (2005) for MARIA; Seebregts et al. (2001) and ETSAP (2002) for MARKAL; IIASA (2005) and Nakicenovic and Riahi (2003) for MESSAGE; SEDAC (1996b) and Edmonds et al. (1997) for MiniCAM; Benders (1996) and IVEM (2006) for PowerPlan; RETScreen International (2005a and 2005b) for RETScreen; JGCRI (2006) and Edmonds et al. (2004) for SGM; IEA (2004 and 2005) for WEM.

3.4 Results of the energy model comparison

For the energy model comparison, the models were evaluated according to the main characteristics of developing countries' energy systems and economies mentioned earlier. As a result, the model comparison of the main characteristics of developing countries can be seen in Table 3. Table 3 shows that only few of the main characteristics are addressed by the compared energy models.

Table 3 also shows that characteristics which have been addressed by the majority of models are electrification, traditional biofuels and the urban–rural divide. A range of models however modelled electrification, the urban–rural divide and traditional biofuels only implicitly, and despite substantial efforts it often remains unclear what exactly has been/what has not been modelled and what purposes the implicit modelling serves. All models further incorporate other features such as greenhouse gas emission trading and the Clean Development Mechanism which are rather popular, whereas individual modelling input assumptions per country, a wide assessment of renewable energy, off-grid renewable energy, rural energy programmes and a special focus on energy and poverty are rare.

Despite some characteristics being often addressed, other important characteristics have not received much attention, such as supply shortages, performance of the power sector, structural economic change, investment decisions, subsidies and especially the informal economy and non-monetary transactions. This is also due to the purposes of the models, since many models are specifically build for certain tasks and are not made for dealing with issues out of their scope.

Model	**Main characteristics of developing country´s energy systems and economies**										
	Performance of power sector	Supply shortages	Electrification	Traditional biofuels	Urban-rural divide / urbanisation	Informal economy	Structural economic change	Investment decisions	Subsidies	Others features*	* Specification of other features
AIM			(X)	X	X					X	Individual assumptions per country, emission trading (ET)
ASF			(X)							X	Clean Development Mechanism (CDM)
IMAGE/TIMER			(X)	X	(X)					X	CDM, ET, wide assessment of renewable energies (RE)
LEAP	(X)		X	X	X				(X)	X	Indiv. ass. p.country, ET, CDM, RE, rural energy programmes
MARIA			(X)				X			X	CDM
MARKAL			X	X	X				(X)	X	ET, CDM, RE
MESSAGE			X	X	(X)		X		(X)	X	ET, CDM, RE
MiniCAM			X	(X)	(X)				(X)	X	ET, CDM, RE
PowerPlan	X	X	(X)							X	CDM, RE
RETScreen			X	X	X			(X)	(X)	X	ET, CDM, RE, off-grid RE systems
SGM			X	X					(X)	X	ET, CDM, RE
WEM			X	X	X			(X)	(X)	X	Indiv. ass. p. country, ET, CDM, RE, focus on energy & poverty

Table 3: Comparison of the main characteristics of developing countries' energy systems and their economies per energy model.
X: explicitly modelled characteristics, (X): implicitly modelled characteristics.

There are also wide differences between how many main characteristics of developing countries are addressed per model. Models which address a large number of characteristics are LEAP, MESSAGE, RETScreen and WEM. Models which address a medium number of characteristics are MARKAL, MiniCAM, AIM, IMAGE/TIMER, PowerPlan and SGM. Models which address a small number of characteristics are MARIA and ASF.

Reasons for these different results are mainly the model structure, as indicated in Table 4 which evaluates the models according to Van Beeck's (1999, 2003) adapted classification typology, and also the different purposes of the models which are specialised for solving certain tasks.

Table 4 shows that models which address larger numbers of main characteristics like LEAP, MESSAGE, RETScreen and WEM are bottom-up or hybrid models, whereas models which address smaller numbers of main characteristics like ASF and MARIA are top-down optimisation models.

Model	**Method**				**Approach**			**Type of model / purpose**
	Simulation	Optimis.*	Eco. Equi.*	Toolbox	Top-down	Bottom-up	Hybrid	
AIM	X						X	Energy-economy-climate
ASF		X			X			Energy-economy-climate
IMAGE/TIMER	X						X	Energy-economy-climate
LEAP	X					X		Energy-economy-environment tool
MARIA		X			X			Energy-economy-climate
MARKAL		X				X		Energy-economy-climate
MESSAGE		X					X	Energy supply-economy-climate
MiniCAM			X				X	Energy-economy-climate
PowerPlan	X				X			Electricity-supply-environment
RETScreen				X		X		Renewable energy-climate decision support
SGM			X		X			Energy-economy-climate
WEM			X				X	Energy-economy-climate, poverty & development

Table 4: Typology of selected energy models, specifying the underlying methodology, analytical approach and purpose. Adapted from Van Beeck´s energy model classification (1999; 2003).
*: Optimisation and Economic Equilibrium Model.

3.5 Discussion

3.5.1 Discussion of model comparison and model groups

In Chapter 3.2, the main characteristics of the energy systems and economies of developing countries are first discussed. Modelling these main characteristics is crucial for an adequate representation of developing countries and therewith also crucial for an adequate modelling and scenario-making of the energy future and environmental problems. In line of this reasoning, present-day energy models were compared to assess whether the main characteristics of the energy systems and economies of developing countries are incorporated in the models.

Differing results were found, both positive and negative, which can mainly be explained by the differing underlying methodology, analytical approach and purpose of the models. These model classification differences will be discussed in detail at this point referring to top-down, bottom-up and hybrid models as well as to simulation, optimisation, economic equilibrium and toolbox models.

Top-down models use aggregated data for predicting purposes, they do not explicitly represent technologies and the most efficient technologies are given by the production frontier, which is set by market behaviour. Top-down models also determine energy demand through aggregate economic indices like GNP and price elasticities, but vary in addressing energy supply. They endogenise behavioural relationships and assume there are no discontinuities in historical trends (Van Beeck, 1999). One reason why a top- down approach is not realistic for developing countries is that market behaviour is only a limited driver of energy consumption and production frontiers are less clear defined than in industrialised countries (e.g. the production frontier of fuel wood). Also, a large part of the economy is non-monetary and aggregate economic indices are not in relation to income distribution, living standards, energy supply and demand. Technologies can further not be determined by market behaviour, because predominant technologies are often based on traditional biofuels, which are not part of the commercial market. Also, assuming no discontinuities in historical trends is not realistic, because rapid population and economic growth affect energy use much more today than a few decades ago, as can be observed in China and India. Another weakness is that top-down models externalise major structural changes such as lifestyles, urbanisation in developing countries and technological changes. The strengths of the top-down approach are its consistency, its links to historic references and economic frameworks, equilibrating prices and quantities and its data availability. Especially data availability is a crucial issue for energy modelling in developing countries.

Bottom-up models use disaggregated data for exploring purposes; include a detailed description of technologies where efficient technologies can lie beyond the economic production frontier suggested by market behaviour. They represent supply technologies in detail, but vary in addressing energy demand. They assess costs of technological options directly and assume interactions between the energy sector and other sectors as negligible (Van Beeck, 1999). A bottom-up approach for developing countries can be useful, mainly because the model is independent of market behaviour and production frontiers and because technologies are explicitly modelled. The weaknesses of bottom-up models are that main drivers remain exogenous such as demand, technology change and resources. Also, quality does not matter e.g. the quality of a given policy.

Hybrid models combine the advantages (and disadvantages) of both bottom-up and top-down approaches. Top-down and bottom-up models can be combined in a tailor-made hybrid approach, depending on purpose, data requirements and desired output. The tailor-made approach leads to flexible models, as needed especially for developing countries. For example, IMAGE/TIMER uses a top-down approach for its energy demand model and a bottom-up approach for its energy supply model.

Optimisation models are used to optimise energy investment decisions by finding best solutions. Optimisation models assume perfect markets and optimal consumer behaviour which do not exist in real life. The use of optimisation models for developing countries might be limited, first because the attempt to optimise investments, which can also be inadequate investments, can lead to suboptimal instead of best solutions. Second, the assumption of perfect markets and optimal consumer behaviour is only of limited use in developing countries where large parts of the economy are non-market-based and where consumer behaviour accounts only for a (small) part of the population. Another (large) part of the population in developing countries consists of inhabitants who do not reflect consumer behaviour such as those without access to modern energy, subsistence farmers, slum dwellers etc.

Economic equilibrium models, on the other hand, either assume partial or general market equilibriums. Shukla (1995) criticises that economic equilibrium models are of limited use in developing countries, because developing countries suffer from constant disequilibrium of markets and because excessive non-market influences determine the situation.

Another option are toolbox models which are mainly bottom-up accounting type models, having the advantage that they are easy to use even by untrained users, which increases their usefulness for developing countries where users do often not have the same financial and training possibilities as in industrialised countries. The main disadvantage of toolbox models is that many important variables are indicated exogenously as parameters in future scenarios.

Finally, simulation models are mostly bottom-up or hybrid descriptive models which aim at reproducing a simplified task of a system. They tend to be rather useful for developing countries, because they do neither assume perfect markets nor optimal consumer behaviour, but allow scenario analysis for future pathways. The disadvantage of simulation models is their complexity, because they may require excessive data inputs and advanced user skills.

Despite certain flaws, present-day energy models can be improved to make them more suitable for the energy systems of developing countries. Table 5 indicates how certain groups of models can be improved for use in developing countries by incorporating suitable characteristics.

Applicable characteristic	**Method**				**Approach**		
	Simulation	Optimis.*	Eco. Equi.*	Toolbox	Top-down	Bottom-up	Hybrid
Performance of power sector	(X)			(X)		X	(X)
Supply shortages	(X)			(X)		X	(X)
Electrification	X	(X)	(X)	(X)	(X)	X	(X)
Traditional bio-fuels	(X)	(X)	(X)	(X)	(X)	(X)	(X)
Urban-rural divide / urbanisation	(X)	(X)	(X)	(X)	(X)	(X)	(X)
Informal economy		**	**		**		**
Structural economic change	(X)	X	X	(X)	X	(X)	(X)
Investment decisions		X	X	(X)	X		(X)
Subsidies		X	X	(X)	X		(X)

Table 5: Applicable characteristics of developing countries' energy systems and their economies per model group. X: Modelling this characteristic is applicable regarding model structure and purpose. (X): Modelling this characteristic is applicable regarding model structure, if the purpose allows. *: Optimisation and Economic Equilibrium Model. **: Modelling this characteristic would improve the model, but currently the modelling methods and data are insufficient.

Table 6 gives an indication of modelling methods and data requirements for the described characteristcs.

Applicable characteristics	**Modelling method**	**Data**
Performance of power sector	Explicitely (loss-of-load-probability)	Available for some dev. countries
Supply shortages	Explicitely (capacity required/installed)	Available for some dev. countries
Electrification	Explicitely * / Implicitely (energy equation)	Available for all dev. countries (IEA)
Traditional bio-fuels	Explicitely (fuel choices)**	Estimates for all dev. countries
Urban-rural divide / urbanis.	Explicitely (urban/rural energy consumers)	Available for most dev. countries
Informal economy	Unknown	No official data, only rough estimates
Structural economic change	Explicitely (changing value-added/sector)	Available for most dev. countries
Investment decisions	Explicitely / Implicitely	Available for most dev. countries
Subsidies	Explicitely / Implicitely	Available for most dev. countries

Table 6: Modelling methods and data requirements for the applicable characteristics of developing countries' energy systems and economies.
*: Increasing number of people having access to electricity, can be linked to decreasing traditional bio-fuel use over time. **: Can be linked to electrification over time.

3.5.2 Discussion of methodology

The method was composed of three parts, thus three different kinds of sources were examined (documentation, model runs, and questionnaire). Problems with the method were that quality and quantity of the sources differed for each model, because not every model was documented in the same way or to the same extent, not every model developer gave us access to the model, not every developer answered the questionnaire.

There is full awareness that the results of the questionnaire tend to be subjective as they tend to reflect the personal opinion of each more or less biased model developer. It was checked whether the results of the questionnaires were consistent with the results of other methods, which was the case for all models. Finally, there could not be found any correlation between differing results and the availability or unavailability of certain method parts.

A wide range of models were tested, from economic models like MARKAL and MiniCAM to user-support modelling tools such as LEAP and RETScreen. The differences in modelling approaches are acknowledged and there is full awareness that these differences lead to different outcomes, just as much as different scenario inputs lead to different scenario outputs. These results are therefore not standardised, but can still be considered relevant, because they indicate for each model in specific to what extent the main characteristics of developing countries' energy systems are addressed, as discussed in Chapter 3.4.

3.6 Conclusions

In conclusion, this results show that present-day energy models tend to be biased towards experience from the energy systems and economies of industrialised countries as experience from these systems has a long and successful tradition. However, the energy systems and economies of developing countries are different and therefore also need to be modelled differently. None of the present-day energy models fulfills all requirements for adequately addressing the energy systems and economies of developing countries. A "universal" model which will solve all tasks equally well and which will represent all main characteristics of developing countries is also illusory, because of technical restrictions, data inconsistencies, limited purposes of the models and the complexity of the system.

Nevertheless, a poor characterisation of the energy systems and economies of developing countries can lead to incorrect modelling of the future energy and climate settings. This could affect the results of optimisation models, meaning that their modelled best solutions might be only sub-optimal, because the economy and energy systems of developing countries might not have been modelled correctly. There could be similar effects for economic equilibrium models, which might neglect the disequilibrium of markets and overestimate market influences which might lead to distorted results. The consequences of a poor characterisation of developing countries' features for simulation models could be that unreliable scenarios might be developed based on inconsistent or incomplete data and assumptions computing unrealistic results for the global and regional energy future. Toolbox models could be affected by using incomplete or incorrect data and relationships in their accounting scheme which might lead to distorted results. Similarly, bottom-up models could primarily be affected by incomplete or incorrect technological data which might result in incorrect outputs while top-down models could primarily be affected by their link to incorrect or incomplete economic frameworks, which might result in incorrect computed outputs. The effects of a poor characterisation of developing countries' features in hybrid models could lead to distorted results due to incorrect economic and technological data. As indicated before, present-day energy models can be improved to make them more suitable for the energy systems of developing countries. It is suggested that models take more into account those characteristics of developing countries, which are the most relevant for the purpose and scope of the models (as indicated in Table 5).

For further research, new or improved existing energy models need to be developed which adequately address the characteristics of developing countries' energy systems and economies such as indicated in Tables 5 and 6. Particularly those characteristics need to be modelled for which reliable data are available and where the system dynamics are understood, e.g. for the performance of the power sector, electrification, investment decisions and subsidies. For a better representation of developing countries, these new or improved models should preferably follow a bottom-up or hybrid approach and be simulation or toolbox models.

Such research is performed for this thesis by developing an improved version of the electricity model PowerPlan for China in specific, which, besides the performance of the power sector and supply shortages, explicitly models electrification and the urban–rural divide (see Chapters 4). It is also intended to develop a new version of one of the simulation energy models discussed earlier to assess a.o. the use of traditional biofuels and the urban–rural divide for specific developing countries (see Chapter 5 and 6).

3.7 Acknowledgements

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4. Renewable and low-carbon energy as mitigation options of climate change for China's power sector[9]

Abstract

This article discusses how renewable and low-carbon energy can serve as mitigation options of climate change in China's power sector. This study is based on scenarios developed in PowerPlan, a bottom-up model simulating a countries' power sector and its emissions. First, the model was adapted to China's present-day economy and power sector. Different scenarios were then developed based on story lines for possible future developments in China. China's carbon-based electricity production system of today was simulated and possible future transitions to a low-carbon system relying on renewable and low-carbon energy. In this analysis, the business-as-usual scenarios are compared with more sustainable energy scenarios. It was found that by increasing the share of renewable and nuclear energy to different levels, between 17-57% of all CO_2 emissions from the power sector could be avoided by 2030 compared to the business-as-usual scenario. It was also found that electricity generation costs increase when more sustainable power plants are installed. As a conclusion, China has two options: choosing for high climate change mitigation and high costs or choosing for moderate climate change mitigation and moderate costs. In case high climate change mitigation will be chosen, development assistance is likely to be needed to cover the costs.

4.1 Introduction

Diminishing the share of fossil fuel energy and increasing the share of renewable and low-carbon energy sources in the energy portfolio is essential to mitigate climate change. For a highly populous and vast country like China, which produces more than 2,000 TWh of mainly coal-produced electricity annually and emitted 5,126.84 Mt of CO_2 in total from all sectors in 2005 (IEA, 2008; according to reference approach), the use of renewable and low-carbon energy sources offers important options to mitigate climate change, reduce air pollution and limit natural resource use.

In this article, the possibilities and limitations of implementing renewable and low-carbon energy sources as mitigation options in the Chinese power sector are therefore studied by using the bottom-up simulation model PowerPlan.

Energy planning models are means for exploring "the future of the global and regional energy settings and the effects of energy use on the human and natural environment" (Chapter 3). The PowerPlan model simulates the electricity supply of a country or region for the coming decades while assessing the effects of energy choices on a.o. emissions, costs, fossil fuel dependency and system stability.

The objective of this study therefore is to explore how renewable and low-carbon energy can partially replace fossil fuels in the Chinese power sector and thereby serve as mitigation options. It is aimed to assess the implications of this energy transitions on climate change, costs and effects on the electricity system and to assess the possibilities for a more sustainable development. This study is a scenario study based on 'what if'-simulations, not a policy

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[9] This chapter is a slightly adapted version of Urban, F., Benders, R.M.J., Moll, H.C., 2009. Renewable and low-carbon energies as mitigation options of climate change for China. *Climatic Change*, in press.

projection. Trends in current policies are however used to ensure the feasibility of the simulations.

In September 2007, the National Development and Reform Commission of China (NDRC) set the objective to raise the share of renewable energy among the total primary energy consumption to 10% in 2010 and to 15% in 2020 including large-hydro power. This equals an installed electric capacity of about 10% renewable energy in 2010 and about 20% in 2020, excluding large-hydro power (NDRC, 2007; Philippe, 2007). The NDRC reports that modern biomass - including biogas, biofuels and biopellets -, geothermal energy, hydro power, solar power - including solar thermal, solar PV and solar heating systems -, tidal energy and wind energy will be promoted. According to Nature (2008), energy officials announced the increase of nuclear power plants leading to at least a contribution of 5% among the total primary energy consumption in 2020. Nuclear and renewable energy are expected to account for at least half of China's energy mix by 2050 (Nature, 2008).

China's Renewable Energy Law which is effective since 1st January 2006 and China's 11th Five-Year Plan, covering the years 2006 to 2010, both aim at promoting renewable energy. The 11th Five-Year Plan further indicates the objective to close down 50 GW of inefficient and small-capacity coal power plants (Philippe, 2007), to decrease the share of energy produced from coal and oil and to promote hydro power, nuclear power and natural gas (Wang, 2007). The modelling and scenarios developed for this study partially simulate the effects of these policies and will be explained below.

4.2 Method

The tool used for this research is the PowerPlan model which is explained below. The research method is composed of three parts: first, modelling the Chinese power sector and its specific economic, demographic and energy-related settings. Second, story-lines were developed for the future development of China. Third, scenarios for future transitions to sustainable energy were made.

4.2.1 Description of PowerPlan

PowerPlan is a dynamic and interactive simulation model that can address 'what if' questions quickly.

The model is built from the perspective of a central electricity board, in control of the central demand/supply balance in a country or region. Starting from a reference year, the electric power system is simulated. At each planning interval (which can be one or more years), investments in new power plants can be made. At the end of each simulation step, the results such as costs, reliability, fuel use, and environment can be examined and used as an aid for the input of the next planning round. The core of the PowerPlan model simulates the electric power generation in a given year. A complete one-period-calculation-cycle is calculated as follows: The annual demand for electricity is calculated from the Load Duration Curve (LDC) or a year pattern and the Simultaneous Maximum Demand (SMD) or so-called peak demand. The LDC is an electric load curve describing the typical demand for electric energy at each time of a given year. The LDC represents the relationship between capacity utilisation and generating capacity requirements. The SMD or peak demand is the maximum demand for electric energy which is required at a certain point in time. For example, in the morning and evening the SMD is usually higher than during the day, because more electricity is needed for lighting, for heating shower and bathing water, for electric devices for cooking, making coffee and similar. More electricity is thus needed during these peak times.

The electricity supply needs to cover the demand during all times. Often small and flexible gas turbines are used for peak loads, while base and middle loads are covered by larger and less flexible power plants such as coal, oil or hydro. Renewable energy does typically cover base loads. In PowerPlan, the means of production are the electricity generating equipment installed. Using the merit-order approach, annual fuel inputs are calculated from the electricity generated per plant. In combination with exogenous fuel-price time-series, investment costs and interest rates, kWhe-generating costs are calculated. The emissions are calculated from the fuel use, fuel and power plant characteristics. Then, in turn, the growth of the electricity demand for the next period is calculated from the exogenously given economic growth and the price elasticity time-series, or is directly available as a SMD-growth time-series. After each calculation step the user can make his/her decisions: what type of power plant and how many should be build, should the fuel quality be adapted, is a retrofitting of existing power plants needed etc. Besides centrally steered capacity planning, investments in decentralised capacity and conservation options are possible. Decentralised electricity and conservation options are treated as a negative demand and thus subtracted from the total electricity demand to remain the central demand.

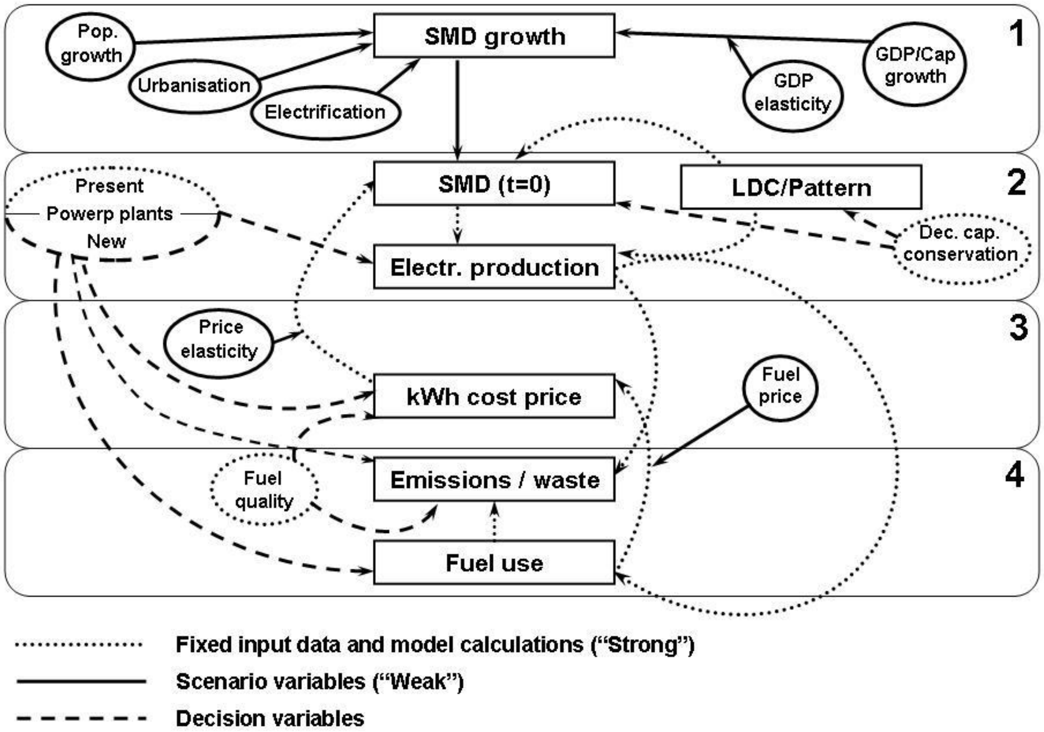

Figure 16: Schematic overview of the PowerPlan model and its four modules, including input data, scenario variables and decision variables.

The PowerPlan model consists of four modules (see Figure 16):

1. A macro-economic forecasting module from which the growth in electricity demand is determined by:
    - the growth rate of the population which is assumed to be linear with the growth rate of the electricity demand
    - the economic growth (GDP growth per capita) coupled by an elasticity (GDP elasticity)
    - the urbanisation and the electrification which will increase the growth of the demand. Urbanisation is determined by the urbanisation growth rate which changes per year based on historic data and assumptions derived from World Bank data (World Bank, 2007).

Electrification is calculated separately for urban and rural regions considering the urban-rural divide in China. Electrification rates are calculated individually for each year subject to changes in electricity investment growth, urbanisation/ruralisation growth rates and population growth rates. Electrification rates are also based on historic data and assumptions derived from IEA data (IEA, 2002).

2. The production simulation module in which the electricity production (Electr. production) is calculated from the LDC or year pattern and the SMD, and in which the supply reliability of the generating system (Power plants) is calculated. The SMD and LDC/Pattern can be influenced by the installation of decentralised capacity and conservation options (Dec. cap & conservation).
3. A costs module in which the kWh cost-price is calculated using fixed (investments, power plant characteristics), variable (fuel costs = fuel use * fuel price) and Transmission & Distribution (T&D) costs data. Changes in the kWhe cost-price influence the SMD through price elasticity's for the next planning round.
4. The fuel and environment module in which fuel use and associated emissions as well as other solid waste products are calculated, which depend on the electricity generated, power plant characteristics and fuel quality.

The system simulates results in form of scenarios concerning installed capacity, generated electricity, reliability, emissions, solid waste, fuel use and costs. Most of the output can be made available in tables as well as in graphs.

For a more detailed description of the PowerPlan model see Benders (1989, 1996, 1998) and Vries (1990, 1991, 1994).

4.2.2 Modelling the Chinese power sector

The PowerPlan model has mainly been used for developed countries, such as the Netherlands and other EU countries (Benders, 1996). Some earlier studies were undertaken for Maharashtra, India (Werff and Benders, 1987) and Taiwan (Vries, 1990). Since the energy systems and economies of developing and developed countries differ greatly (Chapters 2 and 3; Urban et al. 2006), PowerPlan was adapted for modelling the Chinese power sector and its specific economic, demographic and energy-related settings. Some key starting variables for the base year 2005 are listed in Table 7. Data on the Chinese power sector (e.g. power plants installed, emissions, costs, production, consumption, imports etc.) mainly comes from the Energy Statistics Data Service of the IEA (2008) and the China Energy Databook from the Lawrence Berkeley National Laboratory (LBNL 2004), which is mainly based on the National Bureau of Statistics of China and their China Statistical Yearbooks.

Key starting variable	**Value in 2005**	**Reference**
GDP/capita (2007 CNY)	13,322	World Bank, 2007
GDP/capita growth rate (%)	6.5	Amended from ERI, 2003; Larson et al., 2003; Kainuma et al., 2003
Population (million)	1,304.5	World Bank, 2007
Population growth rate (%)	1	World Bank, 2007
Urbanisation rate (%)	39.15	World Bank, 2007
Electrification urban (%)	99.7	Calculated from IEA, 2002
Electrification rural (%)	96.6	Calculated from IEA, 2002

Table 7: Key starting variables for 2005 for modelling the Chinese energy setting and data sources.

In 2005, China's central electricity production was about 2500 TWh with an average growth rate of 5.5% in the last five years. This electricity is mainly produced by coal fired power plants (74%) and large-hydro plants (15%). According to PowerPlan, the most important yearly emissions are about 16 Mton of SO_2, 0.7 Mton NO_x, 2,050 Mton CO_2 and 0.3 Mton of aerosols. During the last decade, China made a significant leap forward in terms of economic, industrial and energy-related output. The power sector alone contributes to about 35-45% of the total national CO_2 emissions (IEA, 2008). Low-carbon technologies in the power sector, such as renewable energy, nuclear energy, natural gas, coal liquidation and coal gasification technologies with CO_2 storage are thus of growing importance. In the past, renewable energy only played a minor role, but since the Renewable Energy Law came into force in 2006, the Chinese government aims at augmenting the share of renewables on the total electricity production (Buruku, 2005). The goal of the Renewable Energy Law is "… to promote the development and utilization of renewable energy, improve the energy structure, diversify energy supplies, safeguard energy security, protect the environment, and realise the sustainable development of the economy and society" (National People's Congress of China, 2005 (article 1)). More specific goals are removing market barriers to renewable energy development, establishing a financing system to ensure renewable energy development, establishing a self-sufficient and non-import dependant renewable energy industry system and building knowledge and awareness around renewable energy (Baker and McKenzie, 2007). The Renewable Energy Law does not name any specific targets, but provides the legislative framework for other policies, which include e.g. the renewable energy targets determined by the NDRC (NDRC, 2007), obligatory grid connections for renewable energy systems, cost-sharing agreements between utilities and end-users, pricing agreements like feed-in tariffs, surcharges and concessions to guarantee the market (Baker and McKenzie, 2007).

In line with recent developments, the types of power plants modelled in PowerPlan for the Chinese setting are coal-fired power plants, conventional oil-fired power plants, combined-cycle-gas-turbines (CCGT), peak gas turbines (GT peak), combined heat and power (CHP), large-hydro plants, biogas plants, geothermal plants, small-hydro plants (SHP), solar photovoltaic panels (PV), tidal plants and wind turbines. The renewable energy modelled in this study are those promoted by the NDRC's Medium and Long-Term Development Plan for Renewable Energy in which the NDRC sets its renewable energy targets; the development of these renewables is thus likely to increase (NDRC, 2007). Electricity imports to China are also considered, which came in 2001 from Hong Kong, Russia and North Korea (LBNL, 2004).

4.2.3 Story-lines and scenario-making

After adapting the model to the specific settings of China, qualitative story-lines were developed. These story-lines explore the 'stories' of the future taking into account a.o. possible economic, demographic, technical and energy-related developments for China.

Three story-lines were developed: business-as-usual (BAU), renewable energy future (RE) and nuclear future (NUC). Other low-carbon energy, like natural gas and coal gasification/liquidation with CO_2 storage, are also important mitigation options of climate change, but have not been assessed in this study. Natural gas has not been considered, because it does not play a major role in China's power sector and its use requires imports -mainly from Russia- and costly infrastructure, thus decreasing China's energy security and increasing costs. Coal gasification/liquidation with CO_2 storage has not been considered, because world-wide it is not yet commercially employed. The simulation of its use would thus be based on speculations.

The main drivers in the story-lines are economy, population, technological change (e.g. energy efficiency improvements, costs, emission factors) and policy. The policies taken into account are the objectives in the 11th Five-Year Plan, the Renewable Energy Law of China and the NDRC's Medium and Long-Term Development Plan for Renewable Energy (see Table 8). There are three BAU scenarios: BAU, BAUhigh and BAUlow. The BAU scenario simulates medium economic and population growth, the BAUhigh scenario simulates high economic and population growth and the BAUlow scenario simulates low economic and population growth. The BAU scenarios do not follow any renewable energy policies; the share of renewable energy does not increase in the future. There are four RE scenarios: RE30%, RE20%, RE20%(PVwind) and RE30%(SHPbiogas). All RE scenarios have a medium economic and population growth, which makes them comparable to the BAU scenario. The RE30% and RE20% scenarios focus on a mixed portfolio of renewable energy (biogas, geothermal, SHP, solar PV, tidal, wind), while the RE(PVwind) and RE(SHPbiogas) scenarios focus mainly on two types of renewable energy. Wind and solar energy contribute to the major share of renewables in the RE20%(PVwind) scenario, while biogas and small-hydro power (SHP) contribute to the major share of renewables in the RE30%(SHPbiogas) scenario. RE20% and RE20%(PVwind) further aim at an implementation of 20% renewable energy among the total installed capacity in 2030 as indicated by the policy goals which the NDRC foresees for 2020, while RE30% and RE30%(SHPbiogas) aim at an implementation of 30% renewable energy among the total installed capacity in 2030 (NDRC 2007). The NUC scenario has a medium economic and population growth, which makes it comparable to the BAU scenario. The NUC scenario aims at the implementation of 20% nuclear energy among the total installed capacity. This surpasses China's nuclear policy goal which targets at least 5% of total primary energy consumption from nuclear energy in 2020. Since this modelling approach is a simulation study only and not a policy prediction study, the same share for nuclear and renewable energy are modelled for reasons of comparability. 'What if' questions can thus be addressed and the potential effects of energy choices on greenhouse gas (GHG) emissions, energy use and costs can be compared.

After developing qualitative story-lines about possible future developments of China, it was assessed how to quantitatively model these 'stories'. The qualitative input was translated into 'measurable' quantitative input data and there from developed a variety of different quantitative scenarios. Scenarios can be defined as "… self-consistent story-lines of how a future energy system might evolve over time in a particular socioeconomic setting and under a particular set of policy conditions" (SEI, 2006a:67). In the line of this reasoning, three BAU scenarios were developed, four RE scenarios and one NUC scenario as indicated in Table 8.

Scenario	**Economic growth**	**Population growth**	**Renewable energy policy goals**	**Demand**
BAU	Medium	Medium	Not reached	Medium
BAUlow	Low	Low	Not reached	Low
BAUhigh	High	High	Not reached	High
NUC	Medium	Medium	Not reached	Medium
RE30% (mixed REs)	Medium	Medium	Reached +	Medium
RE20% (mixed REs)	Medium	Medium	Reached	Medium
RE20%(PVwind) (wind/solar)	Medium	Medium	Reached	Medium
RE30%(SHPbiogas) (biogas/SHP)	Medium	Medium	Reached +	Medium

Table 8: Overview of the developed scenarios and their underlying assumptions on economic and population growth, policy goals and electricity demand.

Note: The higher/lower economic and population growth result in higher/lower electricity demand. Concerning polices, "reached" means that the goal of 20% renewable energy among the total installed capacity in 2020 is reached and the share is kept equal until 2030. "Reached +" means that the goal is surpassed and 30% renewable energy among the total installed capacity is installed in 2030. These goals are based on the 11th Five-Year Plan, the Renewable Energy Law and the NDRC's Medium and Long-Term Development Plan for Renewable Energy and the NDRC´s renewable energy targets. The RE, RE(PVwind) and RE(SHPbiogas) scenarios differ in the renewable energy technologies used (see also chapter 4.2.3).

4.3 Results

4.3.1 Results of the business-as-usual scenarios

The developed scenarios have a simulation length of 25 years. The results for the BAU scenario are as follows: The 3 BAU scenarios (BAU, BAUhigh, BAUlow) simulate what happens if China will continue its current pathway of mainly coal-based fossil fuel consumption without any substantial technological or policy-related changes. In the BAU scenarios, the energy efficiency of existing technologies increases steadily over time, while no new energy technologies are introduced into the market.

Table 9 shows that the fossil fuel share among the total installed capacity increases for BAUhigh and BAU between 2005 and 2030. The fossil fuel share decreases slightly for BAUlow between 2005 and 2030. Coal accounts for 96-99% of the fossil fuel share. Table 9 also indicates that the share of large-hydro power increases for BAUlow and BAU over the simulation period, while it deceases for BAUhigh. This is due to approaching the limit of the estimated economically and technically feasible potential for large-hydropower, which is currently estimated at 290 GW by the World Energy Council (WEC, 2004). For all three scenarios, the share of renewable energy among the total installed capacity does not exceed 5%. The share of nuclear power installed stays stable at around 1% to 2%.

Share (%)	Fossil fuels				Large-hydro power				Nuclear power				Other renewable energy			
Scenario / Year	2005	2010	2020	2030	2005	2010	2020	2030	2005	2010	2020	2030	2005	2010	2020	2030
BAU	78.2	80.1	78.3	80.9	15.6	14.6	17.0	15.9	1.6	1.6	1.3	0.9	4.2	3.6	3.4	2.4
BAUhigh	78.2	81.9	83.7	85.6	15.6	13.3	12.8	12.0	1.6	1.5	1.0	0.7	4.2	3.3	2.5	1.6
BAUlow	78.2	78.6	73.9	73.7	15.6	15.8	20.5	21.9	1.6	1.7	1.6	1.2	4.2	3.9	4.1	3.2

Table 9: Share of different types of energy among the total installed capacity for the BAU scenarios.

Table 10 indicates the estimated effects of the business-as-usual approach on the installed capacity, electricity generated, generation costs and CO_2 emissions for the future.

	Capacity (GW)				Electricity (TWh)				Costs (kWh/CNY)				CO2 emissions (Mton)			
Scenario / Year	2005	2010	2020	2030	2005	2010	2020	2030	2005	2010	2020	2030	2005	2010	2020	2030
BAU	550	761	1121	1546	2479	3140	4621	6628	0.38	0.41	0.44	0.47	2034	2413	3117	4082
BAUhigh	550	836	1491	2051	2479	3403	5796	8699	0.38	0.41	0.45	0.47	2034	2649	4081	5718
BAUlow	550	705	933	1119	2479	2956	3793	4675	0.38	0.41	0.45	0.48	2034	2259	2416	2581

Table 10: Installed capacity, electricity generated, generation costs and CO_2 emissions for the BAU, BAUhigh, BAUlow scenarios.

Figure 17 shows the different types of power plants contributing to power generation in the BAU scenario (mainly coal-fired and large-hydro power plants). Several types of power plants are grouped to keep the graph readable. It can be seen that between 2005 and 2030, the peak demand is likely to increase by factor 2.7.

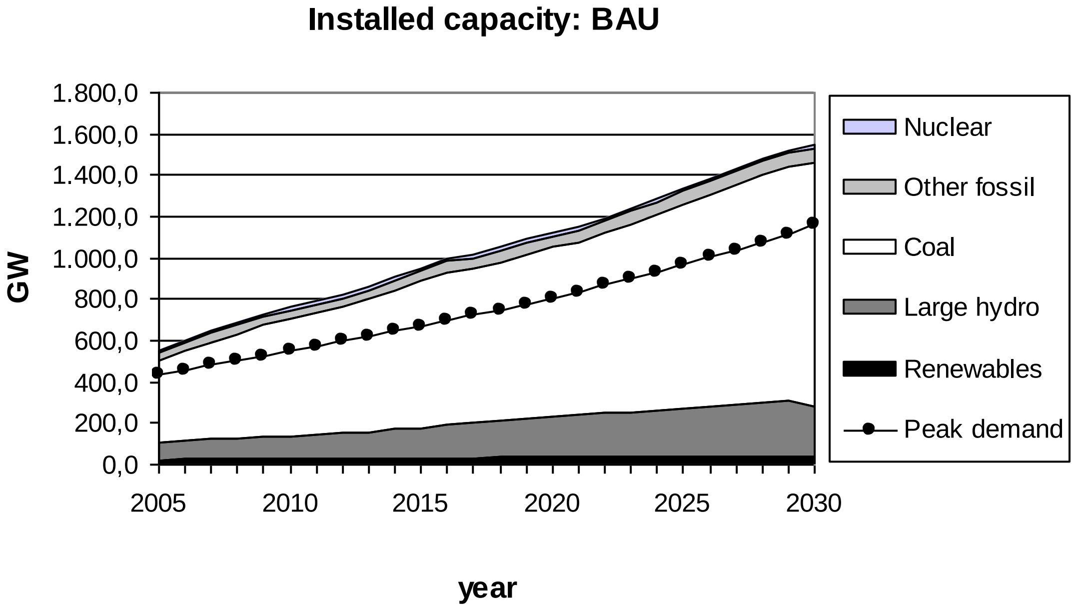

Figure 17: Increase of power supply between 2005 and 2030 in the BAU scenario: contribution of different power plants to installed capacity.

4.3.2 Results of the renewable and low-carbon energy scenarios

The RE and NUC scenarios simulate what happens if China will undergo transitions to renewable or nuclear energy sources within the next 25 years. Such transitions require stringent policy targets and technological improvement. In the RE and NUC scenarios, the costs for renewable and nuclear energy decrease due to technological learning, optimisation of technological processes and material use and increased market penetration. Energy efficiency of existing technologies increases steadily over time. New technologies such as tidal energy are introduced into the market after 2010.

As can be seen in Table 11, for the NUC scenario, 20% of the total capacity installed comes from nuclear energy by 2030. For the RE20% and RE20%(PVwind) scenario, 20% of the total capacity installed is renewable energy, while for the RE30% and RE30%(SHPbiogas) scenario, 30% of the total capacity installed is renewable energy in 2030. It can be seen from Table 11, that the share of fossil fuels and large-hydro power decreases for all five scenarios.

Share (%)	Fossil fuels				Large-hydro power				Nuclear power				Other renewable energy			
Scenario / Year	2005	2010	2020	2030	2005	2010	2020	2030	2005	2010	2020	2030	2005	2010	2020	2030
BAU	78.2	80.1	78.3	80.9	15.6	14.6	17.0	15.9	1.6	1.6	1.3	0.9	4.2	3.6	3.4	2.4
NUC	78.2	76.3	64.7	61.7	15.6	14.7	17.0	15.8	1.6	5.3	14.9	20.2	4.2	3.6	3.3	2.3
RE30%	78.2	75.7	65.1	57.8	15.6	13.4	13.7	12.0	1.6	1.3	0.7	0.2	4.2	9.4	20.6	29.9
RE20%	78.2	79.5	70.1	66.5	15.6	14.2	13.8	12.7	1.6	1.4	0.7	0.2	4.2	4.9	15.4	20.5
RE20%(PVwind)	78.2	77.9	71.0	67.5	15.6	13.9	13.4	12.6	1.6	1.3	0.7	0.2	4.2	6.8	14.9	19.8
RE30%(SHPbiogas)	78.2	75.7	65.7	57.8	15.6	13.6	13.9	12.1	1.6	1.3	0.7	0.2	4.2	9.5	19.8	29.9

Table 11: Share of different types of energy among the total installed capacity for the renewable energy and nuclear scenarios.

Figure 18 indicates the different types of power plants contributing to power generation in the RE30% scenario (30% renewables). It can be seen that –as in the BAU scenarios- between 2005 and 2030, the peak demand is likely to increase by factor 2.7.

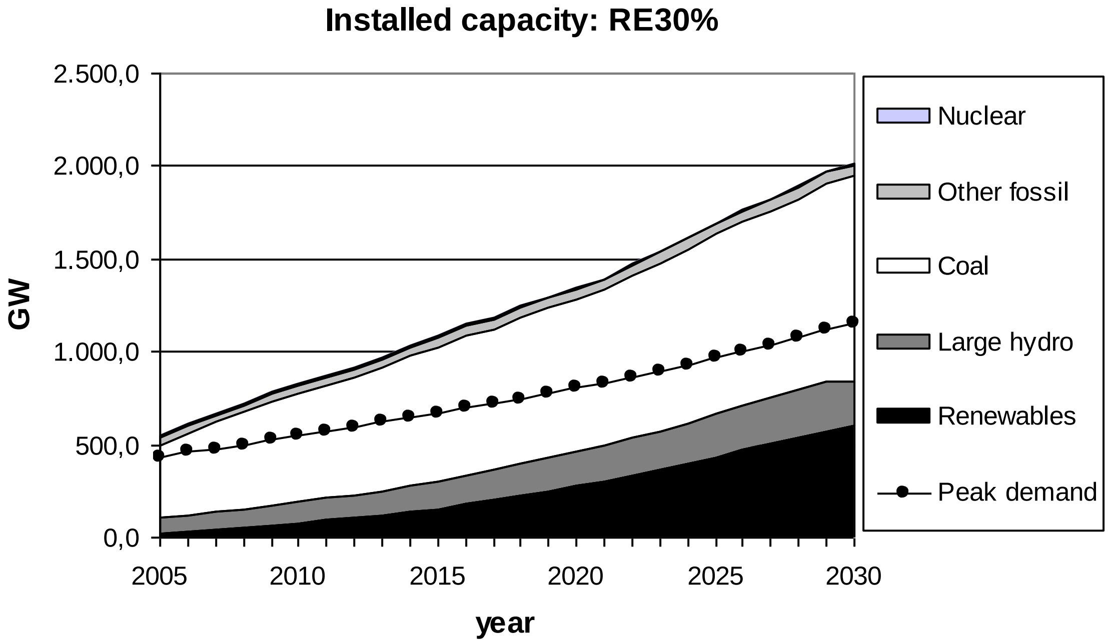

Figure 18: Increase of power supply between 2005 and 2030 in the RE30% scenario: contribution of different power plants to installed capacity.

Table 12 shows the estimated effects of the transitions to renewable and nuclear energy on the installed capacity, electricity generated, generation costs and CO_2 emissions for the future.

	Capacity (GW)				Electricity (TWh)				kWh costs (CNY)				CO_2 emissions (Mton)			
Scenario / Year	2005	2010	2020	2030	2005	2010	2020	2030	2005	2010	2020	2030	2005	2010	2020	2030
BAU	550	761	1121	1546	2479	3140	4621	6628	0.38	0.41	0.44	0.47	2034	2413	3117	4082
NUC	550	759	1124	1556	2479	3138	4617	6627	0.38	0.47	0.68	0.80	2034	2234	2233	2536
RE30%	550	829	1347	2014	2479	3142	4628	6650	0.38	0.55	0.78	0.96	2034	2185	2231	2309
RE20%	550	808	1342	1902	2479	3140	4628	6648	0.38	0.49	0.74	0.86	2034	2342	2475	2980
RE20%(PVwind)	550	824	1326	1864	2479	3141	4627	6643	0.38	0.46	0.54	0.64	2034	2316	2742	3385
RE30%(SHPbiogas)	550	837	1344	2017	2479	3147	4635	6662	0.38	0.65	1.06	1.42	2034	2112	1995	1738

Table 12: Installed capacity, electricity generated, generation costs and CO_2 emissions for the BAU, NUC, RE30%, RE20%, RE20%(PVwind), RE30%(SHPbiogas) scenarios.

4.3.3 Comparison of the scenarios

In all of the scenarios, China's electricity demand increases significantly. The electricity generated could increase between 2005 and 2030 by factor 2.7 for the BAU, NUC and RE scenarios. It could increase by factor 3.5 for the BAUhigh and by factor 1.9 for the BAUlow scenario. The RE and NUC scenarios follow the same trend as the BAU scenario. The electricity generation increases to a similar extent as the increase in maximum demand. The installed capacity is also expected to increase significantly between 2005 and 2030: by factor 2.8 for the BAU scenario, by factor 3.7 for BAUhigh, factor 2.0 for BAUlow, factor 2.8 for NUC and 3.5 in average for the RE scenarios. The capacity increase of 3.5 is needed for the RE scenarios, because the load factor of renewable energy systems is lower than for fossil and nuclear power stations, so extra capacity is needed. Figure 19 indicates the increase in installed capacity in China between 2005 and 2030 for all scenarios.

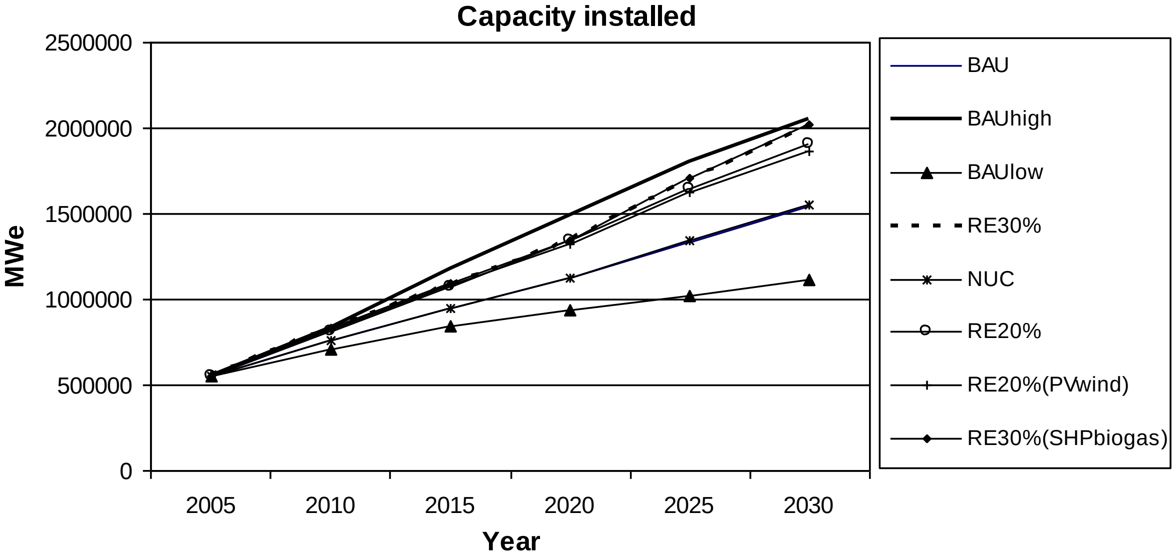

Figure 19: Capacities installed in MWe in China between 2005 and 2030 for all scenarios.

For all scenarios, the loss-of-load-probability (LOLP) decreases from a moderate LOLP in 2005 to a low LOLP afterwards. The loss-of-load-probability is a measure of the reliability of an electric system. The lower it is the more stable is the electric system. The LOLP for the RE scenarios is slightly lower than that of the BAU and NUC scenarios.

One of the most important results concerning transitions to sustainable energy is the possibility to mitigate CO_2 emissions. These results show that the CO_2 emissions from the power sector vary significantly between scenarios as indicated in Figure 20.

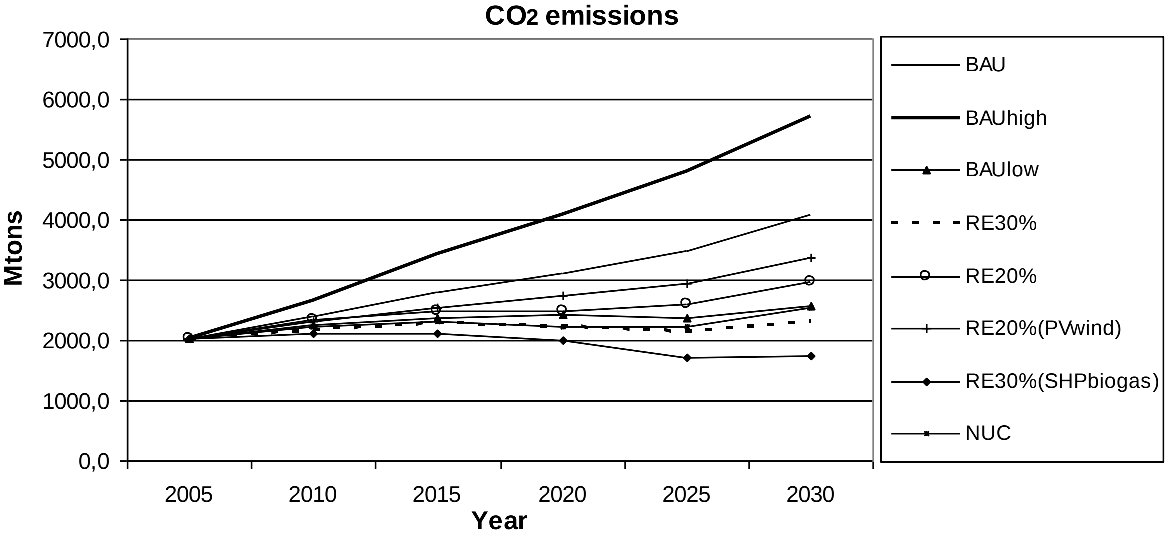

Figure 20: CO_2 emissions in Mtons/year from the Chinese power sector between 2005 and 2030 for all scenarios.

CO_2 emissions might increase up to 5,718 Mtons/year in 2030 in the BAUhigh scenario, while they might reach 4,082 Mtons/year in the BAU scenario and 2,581 Mtons/year in the BAUlow scenario. In the RE and NUC scenario, the CO_2 emissions might remain lower with 3,392 Mtons/year for the RE20%(PVwind) scenario, 2,988 Mtons/year for the RE20% scenario, 2,315 Mtons/year for the RE30% scenario and 1,777 Mtons/year for the RE30%(SHPbiogas) scenario in 2030. Conclusively, a share of 30% renewable energy among the total installed capacity in 2030 might reduce CO_2 emissions to up to 43-57 % for the RE30% and RE30%(SHPbiogas) scenarios, respectively, compared to the BAU scenario. A share of 20% renewable energy among the total installed capacity in 2030 might reduce CO_2 emissions to up to 17-27% for the RE20%(PVwind) and RE20% scenarios, respectively, compared to the BAU scenario. Implementing a share of 20% nuclear energy among the total installed capacity in 2030 might reduce CO_2 emissions to up to 38% compared to the BAU scenario, but a high amount of nuclear waste is likely to be produced by the reactors. In 2030, about 80,000 m^3 highly radioactive waste and 32,000 m^3 medium radioactive wastes are likely to be produced per year compared to 632 m^3 highly radioactive waste and 253 m^3 medium radioactive wastes in 2005, which is a 126-fold increase.

The effects on other environmental indicators are as follows: for the RE and NUC scenarios, the NO_X emissions are expected to be 37% lower in average by 2030 than in the BAU scenarios, while the SO_2 emissions are expected to decrease by 8% by 2030. Also, about 97,700 ktons coal waste could be saved in 2030 in average in the RE and NUC scenarios compared to the BAU scenarios, which equals a saving of 28%. The savings in NO_X and SO_2 emissions mean a decrease of local air pollution.

Concerning the cost factor, in average electricity costs are expected to rise until 2030 as indicated in Figure 21, although electricity costs vary greatly per region and per end-use, so high regional differences are very likely. Costs might increase from 2005's average national price of about 0.38 CNY/kWhe to between 0.47-1.42 CNY/kWhe. The highest electricity costs are expected to arise from the RE30%(SHPbiogas) scenario, followed by the RE30%, RE20% and NUC scenario. The lowest prices are likely to be found in the BAU, BAUlow, BAUhigh and RE20%(PVwind) scenario. See Figure 21.

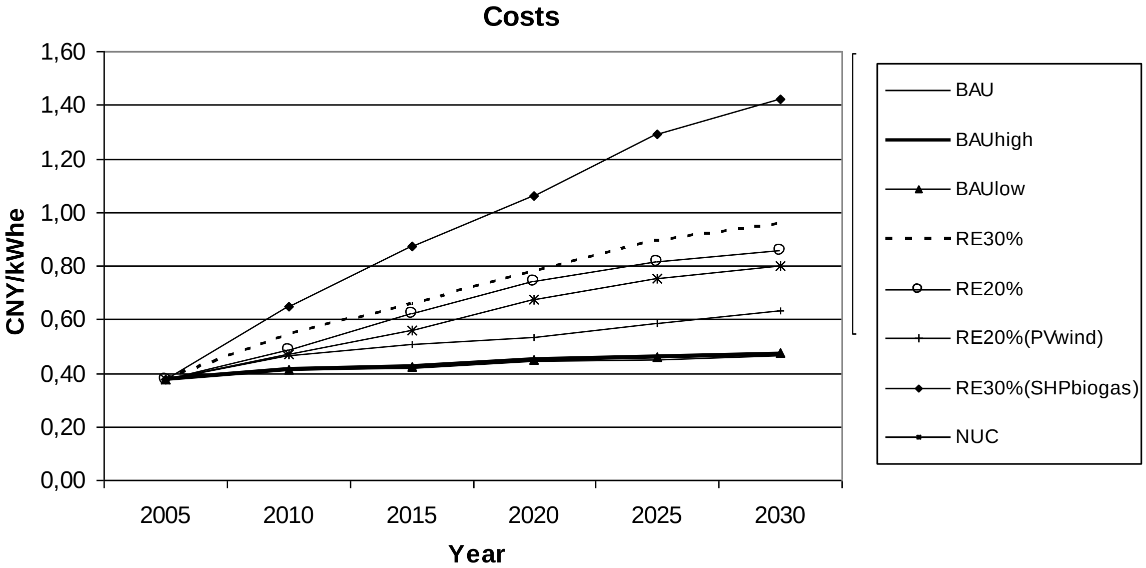

Figure 21: Electricity generation costs in CNY/kWhe in average for China between 2005 and 2030 for all scenarios.

4.4 Discussion

4.4.1 Discussion of the method

The output results are based on three important inputs: the modelling method and the model itself, the scenario assumptions and the input data. First, the modelling method determines how to approach the problems of meeting energy demand and mitigating climate change. The model used for this research is the bottom-up simulation model PowerPlan. Because PowerPlan is successfully calibrated with historical data and validated with another model (Benders, 1996), using a different model or a different modelling method would result in only slightly different outputs. Second, the scenario assumptions determine the results of the modelling. Other scenario assumptions would result in different outputs (e.g. a clean-coal scenario). The scenarios were oriented on earlier studies on the Chinese power sector, but it is assumed that some of the projections might be too low, due to a very high increase in electricity consumption during the last few years. Third, data availability and data reliability is an important issue for China. Reliable data are hard to obtain, as often data from international organisations such as the IEA or the WEC differ from the data published in China e.g. in the Statistical Yearbooks. To decrease the bias for one source of data, data from both sources were compared (mainly based on LBNL, 2004; IEA, 2008; IEA, 2007) and data was used which were the same or similar.

4.4.2 Discussion of the results and implications

For sustaining a country's economic development, energy is needed. The impact of energy on economic growth has been discussed controversially in the scientific community. Some argue that energy is a vital requirement for economic growth, and can thus be a restricting factor to economic growth, others argue that the costs for energy do only represent a marginal proportion of GDP and thus do have a neutral impact (Ghali and El-Sakka, 2004). Chontanawat et al. (2008) analysed causalities between energy and GDP from over 100 countries and draw the conclusion that there is an impact of energy on economic growth; however this impact is more prevalent in industrialised countries than in developing countries. In this study, economic growth is represented as GDP growth/capita and GDP elastcicity, which are two factors determining the energy consumption. Other factors like population growth, urbanisation and electrification are also important inputs which determine energy consumption.

It is also under discussion whether economic growth should be treated exogenously or endogenously in energy models. While electrification is modelled endogenously, economic growth, population growth and urbanisation are modelled exogenously. Exogenously and endogenously modelled economic growth appears to have the same external dynamics, but different internal dynamics and therewith different restrictions. This means that calculations can change depending on exogenously and endogenously modelled economic growth. An endogenously modelled economic growth, having a causal relationship with other factors, could for example affect and be affected by technological change, fuel prices or electrification. In PowerPlan, costs and economic growth are exogenously modelled and are thus independent factors. The aim of PowerPlan is to simulate the future electricity supply of a country. Detailed economic assessments of the energy system are not the focus of the model.

In all scenarios, China’s electricity demand increases significantly. This is due to basic drivers influencing energy consumption such as a high population level and a steeply growing economy, but also due to more complex factors such as higher per capita consumption levels, increased access to electric devices, growing electrification rates, increased investments in the power sector and fuel switching. If China's economy and related factors, like consumption levels and access to electric devices, will continue to grow as fast as they currently do for another few years or even for a few decades, the BAU or BAUhigh scenarios are likely. If China's economy and related factors will stabilise or slow down, the BAUlow scenario is likely. In any case, the increase in electricity demand will be high, leading to high impacts on CO_2 emissions, local air pollution, resource use and struggles for energy security. Alternatives to a mainly coal-dominated power sector should therefore be implemented. This research shows that it may be possible for China to install up to 30% renewable energy among the total capacity by 2030. As this share is very high, the geographic, technical and economically feasible potentials of some renewables could be reached e.g. for wind. Also, the location of resources could become a problem, as most regions having splendid renewable energy resources are located far from the regions with the highest electricity demand, so transport and storage would become an issue. This could be a problem, since there are several independent grids in China instead of one national grid, even though there are plans for building a national grid in the future. Implementing a lower share of about 20% renewables among the total installed capacity would reduce the stress on land-use and resources and might increase the geographical, technical and economic feasibility while also reducing a significant amount of CO_2 emissions.

Another drawback of renewable energy is that it tends to fluctuate. Therefore back-up capacity is needed, so more capacity has to be installed (see Figure 19). This can increase the costs as indicated in Figure 21. However, the effects on the electricity system's reliability are positive, as the LOLP (Loss-of-load-probability) for the RE scenarios is likely to decrease compared to the BAU and NUC scenarios.

The feasibility of installing a 20% or 30% share of renewable energy amongst the total installed capacity in 2030 is high, as Chinese policies developed by the NDRC aim at a share of 20% in 2020. For the 20%-scenarios, the installed capacity for renewable energy would thus need to grow at the same rate as the total increase in installed capacity between 2020 and 2030. For the 30%-scenarios, the installed capacity for renewable energy would need to grow at a higher rate than the total increase in installed capacity between 2020 and 2030. Martinot (2008) indicates that between 2006 and 2020, the installed capacity of hydro power is expected to more than double, to increase 12 times for wind energy, 15 times for biogas and 23 times for solar PV. The feasibility of a 20% or 30% share of renewable energy in 2030 is thus likely according to recent trends and policy goals. It also has to be noted that 20% and 30% renewable energy shares among the total installed capacity are simulated and not 20% and 30% renewable energy shares among the total electricity generated. Due to the lower load factor of renewable energy compared to fossil energy, a higher share of renewable energy needs to be installed, but a lower share of electricity from renewable energy is finally generated.

In this study, installing a share of 20% nuclear energy among the total installed capacity in 2030 is a simulation with the goal to address 'what if' questions and to enable a comparison with an installed capacity of 20% renewable energy. This simulation is not a policy scenario, even though nuclear energy is on the rise in China. The World Nuclear Association (2008:1) reports that currently "China has eleven nuclear power reactors in commercial operation, six under construction, and several more about to start construction. Additional reactors are planned, including some of the world's most advanced, to give a sixfold increase in nuclear capacity to at least 50 GWe by 2020 and then a further three to fourfold increase to 120-160 GWe by 2030." There are however a few restrictions to nuclear energy implementation: The construction time of a nuclear power plant is estimated at 8 years in average with an economic life time of 20 years.

Before a high share of nuclear energy will be implemented, a few years would thus pass due to construction. High investment costs are also involved for the construction of nuclear power plants. If nuclear energy will be implemented to a larger extent, nuclear waste is likely to increase rapidly. This is likely to raise concerns about nuclear waste treatment and disposal. Storage and recycling of the radioactive waste could therefore become an important issue. Finally, uranium is not a renewable resource, but a finite resource. China will depend mainly on imported uranium. Once easily accessible uranium will be depleted, the prices for uranium will increase rapidly. New nuclear technologies, such as fusion, might be a solution to this problem, but so far they do not exist.

Concerning China's future, there are two major possibilities how to mitigate climate change by reducing CO_2 emissions in the power sector: A CO_2 emission reduction can either be achieved by reducing economic growth, population growth and total electricity consumption (as in the BAUlow scenario) or by implementing ambitious policies which increase e.g. the share of low- or zero-carbon technologies, such as renewable energy and to introduce policies which increase energy efficiency. Other useful measures could be energy-saving programmes and installing more energy-efficient technologies etc.

The results of this study concerning costs give an indication of the relative costs between all scenarios. Technological learning curves have been incorporated in the RE and NUC scenarios, which makes costs decrease after time. However, the electricity prices for the RE and NUC scenarios remain between 22% higher for the RE20%(PVwind) scenario compared to the BAU scenario, 74% higher for the NUC scenario and 178% more expensive for the RE30%(SHPbiogas) scenario in 2030. This raises the following question: who will pay for the investments necessary for sustainable energy transitions?

Finally, urban and rural differences in China have to be acknowledged concerning the electricity supply. Many urban areas in China are rather developed and economically well-off, while many rural areas remain rather undeveloped and impoverished. The power systems differ between the urban and the rural areas, but China's government is striving for a country-wide modernisation in the power sector. The future of China's power sector will therefore also depend on how China will deal with equity issues in its energy supply and overall economy.

Security of supply is another important issue in the Chinese power sector. The IEA (2007) assumes that China might not be able to meet its growing demand for oil and gas by own reserves in the future. Either more oil and gas imports will be needed, or energy demand has to be curbed, or alternatives energy will have to be used. Alternatives are renewable energy and clean coal technologies. Clean coal technologies and CO_2 storage are however still in the research and development phase and are not being used commercially. The IEA (2007) also mentions options for hydrogen, which however is also not yet commercially used. Since China is endowed with rich renewable resources like hydro-power, wind, biomass and solar, these seem to be feasible alternatives.

4.5 Conclusion

The Chinese electricity demand is expected to increase significantly until 2030. This will have major impacts on resource use, energy security, the electricity system, local air pollution, and most important on climate change issues. In the business-as-usual case, the CO_2 emissions from the power sector might increase to about 2,600 Mtons/year (BAUlow), 4,100 Mtons/year (BAU) and 5,700 Mtons/year (BAUhigh) until 2030. Low- and zero-carbon energy, such as renewable and nuclear energy, is therefore essential for mitigating the CO_2 emissions of the growing giant economy of China. Various technology combinations were tested in the sustainable energy scenarios (biogas-SHP, wind-solar PV, mixed renewables, nuclear) and all contributed to climate change mitigation. Effects on the electricity system and the LOLP were positive, but costs increased to a larger extent than in the business-as-usual scenarios. It was found that implementing a share of 30% renewable energy among the total installed capacity in 2030 could reduce CO_2 emissions to up to 43-57% for the RE30% and RE30%(SHPbiogas) scenarios, respectively, compared to the BAU scenario. It was also found that implementing a share of 20% renewable energy among the total installed capacity in 2030 could reduce CO_2 emissions to up to 17-27% for the RE20%(PVwind) and RE20% scenarios, respectively, compared to the BAU scenario. The RE30%(SHPbiogas) scenario with a focus on biogas and SHP systems has the highest climate change mitigation potential, but is also the most expensive option. The RE20%(PVwind) scenario with a focus on wind energy and solar PV has the lowest climate change mitigation potential, but is also the most cost-effective option. Both options, the 20% and 30% share of renewable energy among the total installed capacity, seem feasible regarding China’s current renewable energy policies, programs and latest installation trends. Implementing a share of 20% nuclear energy among the total installed capacity in 2030 is currently not a policy goal in China, although the share of nuclear energy is targeted to increase significantly in the future. 20% nuclear energy among the total installed capacity could reduce CO_2 emissions to up to 38% compared to the BAU scenario, but the quantity of high and medium radioactive waste might increase more than a 120 times. An increase of nuclear power plants could further raise justified concerns regarding safety, human health, the environment and costs. Finally, uranium is not endlessly abundant, but a finite resource. In contrary, renewable energy are abundant in China and do not raise any safety or human health-related concerns. This study suggests that renewable energy is the most feasible option of climate change mitigation in the Chinese power sector.

There are thus several possibilities and several cost options for transitions to a more sustainable power sector in China. China may be faced with two main options: choosing for high climate change mitigation and high costs or choosing for moderate climate change mitigation and moderate costs. In case high climate change mitigation options will be chosen, costs are expected to increase significantly. Development assistance is likely to be needed to cover these costs. Even though China itself will have to choose which pathway it will follow, it is of global importance to assist the world’s most populous country in achieving a sustainable development. Industrialised countries should feel responsible to contribute to climate change mitigation in China considering their financial means, technological advancement and their own current and historic contributions to climate change.

4.6 Acknowledgements

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5. Scenarios for renewable energy transitions in Beijing[10]

Abstract

Beijing is facing severe energy and climate challenges. This article therefore aims to elaborate the energy future of Beijing and assesses the impacts on energy resources, greenhouse gas (GHG) emissions, costs and technology choices. LEAP was used to model a business-as-usual approach and transitions to renewable energy. The renewable energy scenario simulates the government's renewable energy targets. This research indicates that the energy demand is likely to increase by 80% between 2005 and 2020 in the business-as-usual scenario. The fossil fuel saving is expected to be 16% in the renewable energy scenario. The GHG emissions could increase by 60% until 2020 in the business-as-usual scenario, while transitions to renewable energy could save 23% of GHG emissions in 2020. Costs for fuels and energy investments will increase rapidly in the coming decades, but costs will be higher when transitions to renewable energy will be pursued. This study also indicates which renewable energy technologies could be used in each of Beijing's economic sectors and which policy choices are necessary. The research emphasises the need to implement renewable energy to reduce the effects on climate change, local air pollution, resource use and to increase energy security.

5.1 Introduction

Global climate change, local air pollution, increased pressure on energy resources and the struggle for energy security are challenges which the world is facing today. Renewable and other low-carbon fuels can therefore be of great value for mega-cities such as Beijing.

With more than 15 million inhabitants (Beijing Municipal Bureau of Statistics BMBS, 2007), Beijing is the political and cultural capital of China and also one of the country's most important economic motors. This entails not only increasing income, welfare and consumption of the population, but also a rapidly growing energy demand and a rapid increase in greenhouse gas (GHG) emissions. In 1996, Beijing's energy consumption was 37.4 million tonnes coal equivalent (tce) and rose to 55.2 mio tce in 2005 (BMBS, 2007). Since China is endowed with rich coal reserves, the majority of fuels used in Beijing is coal which has to be transported from coal-rich provinces such as Shanxi, Inner Mongolia and Hebei. The major energy-consuming sector is industry, which in Beijing is mainly based on energy-intensive manufacturing. However, since income is rising, the transport sector and the household sector, particularly heating, are expanding rapidly. The commercial sector is also prospering in Beijing, making high tech services, tourism and research flourishing industries (BMBS, 2007). The emissions from these commercial activities provoke both the concern of the international public regarding the 2008 Olympics and the awareness of tourists and local residents. Therefore, it is evident that measures have to be taken for the future to avoid adverse effects and to enhance the quality of life of Beijing's residents. One possibility which is under serious consideration and negotiation by government officials, policy-makers and researchers is to implement a greater share of renewable energy in Beijing.

This article therefore intends to give advice on this issue by elaborating the future of Beijing's energy demand and assessing the impacts on energy resources, greenhouse gas

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[10] This chapter is a slightly adapted version of Urban, F., Wang, Y., Zhang, X., Benders, R.M.J., Moll, H.C., 2009. Scenarios for a renewable energy transition in Beijing. *Energy Policy*, invited paper to the Special Issue "Renewable Energy in China", submitted.

emissions, costs and technology choices. The Long-range Energy Alternatives Planning System LEAP was used to model a business-as-usual approach and transitions to renewable energy. The renewable energy scenario simulates the government’s targets to implement 4% of renewable energy in 2010 and 6% in 2020.

Earlier research on renewable energy focused mainly on national level, such as Zhang and Martinot (2007) which elaborate the context of renewable energy development in China and discuss recent renewable energy policies and legislation. China’s Energy Outlook 2004 (INET, 2004) gives an overview of the renewable energy supply outlook and an overview of its production. Chang et al. (2003) also assess the production, consumption and prospect of Chinese renewable energy while Li et al. (2005) analyse the potential of renewable energy in China. In chapter 4, the possibilities and impacts of implementing renewable energy in the Chinese power sector are modelled. Even though there is much research on renewable energy in China, research on Beijing is rare. The World Bank (2007) project “Beijing Renewable Energy Development Study” is one of the first large-scale research projects on Beijing’s renewable energy present and future. An associated research by Philippe (2007) indicates the potential and implications for three renewable energy technologies in Beijing: solar water heaters, geothermal heating and municipal solid waste. This research stresses the possibilities and opportunities which Beijing faces concerning renewable energy and concludes that a substantial share of coal equivalents could be saved by employing these three technologies alone. This research is one of the first studies on local level which takes into account in detail the present energy demand of Beijing. The research follows a bottom-up approach to simulate Beijing’s energy developments over the next few decades and to assess a wide range of technologies under the business-as-usual and renewable energy transitions scenarios.

In chapter 5.2 the methodology is described giving special attention to the modelling with LEAP, in chapter 5.3 the results are explored, in chapter 5.4 the method and results are discussed and the conclusions are elaborated in chapter 5.5.

5.2 Methodology

5.2.1 Modelling with LEAP

The LEAP model was developed in 1980 by Paul Raskin from the Beijer Institute for the purpose of the Kenya Fuelwood Project. It was one of the first energy models to assess environmental impacts such as GHG emissions. The model was extended in the following decades and at the end of the 90s Charles Heaps from the Stockholm Environment Institute created a Windows-based version of LEAP. The first version of the model was available to the public in 2001 (SEI, 2007a).

LEAP is a bottom-up simulation tool with a flexible model structure which can be adapted to the user’s needs. It can incorporate a high level of technological detail allowing the user to model even as detailed as end-use appliances. LEAP is based on physical accounting and can be used as simulation, forecasting, scenario analysis and policy analysis tool. It is used world-wide in over 130 countries as of 2006 (SEI, 2007a).

Earlier studies with LEAP for China include among others the APEC Energy Demand and Supply Outlook 2006 and 2002, a study on national energy intensity reduction planning on end-use level by Lin et al. (2006), China’s Sustainable Energy Future by ERI (2003) and the East Asia Energy Futures (EAEF)/Asia Energy Security Project by Guo et al. (2003).

This research is however the first to model the energy demand of Beijing with LEAP. The study focuses on the energy demand only, due to restricted data availability for the energy supply. The research in chapter 5.4 however covers the energy supply and the possibilities for renewable energy on national level.

5.2.1.1 Final energy demand analysis

Main inputs of LEAP are the total activity level per fuel and end-use, the energy intensity per activity, the demand costs and the environmental loadings or emissions. The end-use could be for example the share of rural households using electricity for lighting. The energy intensity per activity could be e.g. 100 kWh electricity per household. The demand costs could be e.g. 555 CNY per household and the environmental loadings or emissions could be e.g. 140 kg/GJ of non-biogenic CO_2. The final energy demand is then calculated for the base year and for each future year in each scenario as follows (SEI, 2006a):

$$ED_{b,s,t} = TA_{b,s,t} * EI_{b,s,t}$$

ED = energy demand
TA = total activity level
EI = energy intensity
b = technology branch
s = scenario
t = year

For every technology branch, the energy demand is calculated separately, thus determining a specific fuel for every branch. When all technology branches are calculated, the total final energy demand is computed for each fuel. The total activity level for a fuel is calculated as the product of all activity levels in all branches (SEI, 2006a).

5.2.1.2 Activity levels, energy intensity, emissions and demand costs

Activity levels are defined by SEI (2006a:77) as "…a measure of the social or economic activity for which energy is consumed". It describes the share of usage of each technology and fuel in each sector and year. For the scenario-making assumptions on technological change, fuel switching and policy development were the main drivers of changes in activity levels. These drivers are explained in detail in chapter 2.2.

Energy intensity is defined as the energy use per unit of activity (SEI, 2006a). In this study, energy intensities are calculated individually for each technology in each scenario and each year. The energy intensities are based on data on consumption and energy use from the Statistical Yearbooks of the BMBS and China's National Bureau of Statistics NBS (2007).

CO_2 emissions are calculated using standard emission factors from the IPCC (2006) and estimates from Chinese governmental agencies. For renewable energy, it is assumed that CO_2 emissions equal zero, because only energy production is assessed and not the complete life cycle. Emissions would be higher if the complete life cycle was to be considered, due to the processing/production, transport and waste phase. Also, emissions for other energy would be much higher if the complete life cycle was taken into account.

CO_2 emissions account for about a 95% share of the total GHG emissions. Other GHG emissions such as methane, non methane volatile organic compounds, nitrogen oxides, nitrous oxide and sulfur dioxide come from the IPCC´s Revised Guidelines for National Greenhouse

Gas Inventories (1996) as incorporated in LEAP´s Technology and Environmental Database TED.

Energy costs are calculated as the total expenditures for satisfying the energy demand in a certain year.

In the household sector, costs are composed of the supply costs of energy e.g. costs per kWh electricity, the investment cost of the device e.g. the costs of a light bulb or a radio, and where applicable the installation and maintenance costs e.g. costs for installing and maintaining a PV panel. The costs are calculated per year taking into account the life time of the device and differentiating between regular costs, such as energy costs, and unique costs, such as investment costs. The costs are calculated for each technology and each fuel individually as indicated:

$$CH_{b,s,t} = ((IC_{b,s,t} / L_{b,s,t}) + SC_{b,s,t} + OMC_{b,s,t}) * ND$$

CH = Costs per household
IC = Investment costs per device
L = Life time of device
SC = Supply costs
OMC = Operation and maintenance costs (where applicable, otherwise 0)
ND = Number of devices per household
b = technology branch
s = scenario
t = year

Total costs in the household sector are the sum of all individual costs in each given year and scenario. Costs for the agricultural, commercial, construction, industrial, transport sectors and heating are calculated as activity costs. The activity costs are calculated as follows (SEI, 2006a):

$$C_{b,s,t} = CA_{b,s,t} * AL_{b,s,t}$$

C = Costs
CA = Costs per activity
AL = Activity Level
b = technology branch
s = scenario
t = year

The total costs are the sum of all individual costs per sector and per technology for each given year and scenario. Costs for externalities such as costs for environmental pollution are not considered. Costs are not discounted and no inflation rate is taken into account, because of lack of data.

5.2.2 Modelling framework for Beijing

5.2.2.1 Beijing

When referring to Beijing, the municipality of Beijing is meant. Of the total population, 83.6% were urban residents and 16.4% were rural residents in 2005 according to official numbers. Beijing has 18 districts, of which 8 are urban and 10 are rural (BMBS, 2007). Beijing covers an area of 16,411 km² comparable to the size of half of the Netherlands (BMBS, 2007). 6,000 km² are flat while the remaining area is hilly or mountainous. The central area of the city of Beijing covers 1,300km². Despite strict population regulation policies on child-bearing and immigration, the population of Beijing is growing by 2% annually since the 90s. Urbanisation levels are also on the rise. In 2005, Beijing's population surpassed the 15 million mark (BMBS, 2007).

Beijing is the political and cultural capital of China. Beijing experiences a rapid development since the 80s in all sectors and GDP growth rates rose to over 10% in recent years. Purchasing power parity is constantly rising and official incomes are reported to increase in average about 10% annually since 1992 (Philippe, 2007).

Beijing's economy is flourishing, particularly due to structural changes. The service sector increases rapidly since the 80s resulting in numerous research centres, universities and high-tech zones such as the Zhongguancun Science and Technology Park (BMBS, 2007). Today, the service sector is the main income motor of Beijing accounting for 63% of Beijing's GDP in 2005, but consuming only 24.5% of its total energy. The industrial sector remains however large, both in terms of GDP and in terms of energy consumption. In 2005, the industrial sector, including construction, consumed 49% of Beijing's total energy and accounted for 29% of its GDP. Particularly manufacturing and construction are responsible for a large share of both income and energy use. With a total energy use of 1.6% and a 1.4% share of Beijing's GDP in 2005 the agricultural sector plays only a negligible role. The remaining GDP is generated by the transport sector, which played a relatively small role so far in comparison to other countries, but projections indicate a rise in transport demand associated with higher consumption levels and car ownership (Zhang, 2007). The transport sector accounted for 10.2% of Beijing's energy use in 2005. The remaining 14.7% of Beijing's energy were consumed by the household sector in 2005 which is also subject to rising consumption levels (BMBS, 2007). Figure 22 shows the energy consumption per sector in 2005. Energy consumption increases steadily since the last decades, despite governmental reduction efforts. It is assumed that Beijingers consume in average at least double as much energy as the average Chinese citizen (Philippe, 2007). Due to China's abundant coal reserves, Beijing mainly relies on coal. Most industrial processes are coal-driven, commercial and household activities such as heating and cooking partially rely on coal as well as many agricultural processes. The majority of electricity and heat is generated from coal. Still, there is a change ongoing. As a consequence of the energy efficiency goals of the 11th Five-Year plan, smaller inefficient coal power stations are being shut down and replaced by more modern power plants. New natural gas power plants are being built and investments into renewable energy are increasing (Philippe, 2007).

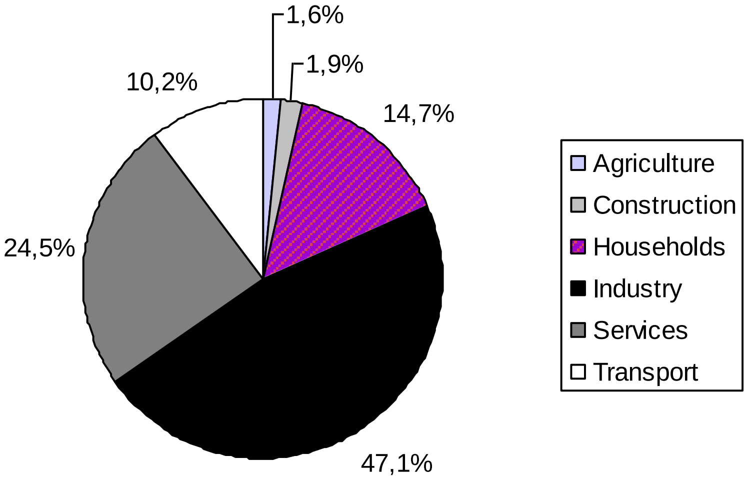

Figure 22: Energy consumption in Beijing per sector in 2005.

Table 13 indicates the key assumptions for the modelling which remain the same for both scenarios to ensure comparability.

Key assumptions	2005	2020
Total population	15.38 million	21.4 million
Urban population	12.86 million	19.3 million
Rural population	2.52 million	2.1 million
Urbanisation	83.6%	90%
Nr. of households	5.7 million	9.11 million
Household size	2.7 people	2.35 people
GDP	557,450 billion CNY	2,133,200 billion CNY
GDP/capita	36,245 CNY	99,682 CNY

Table 13: Key assumptions for the scenario-making

5.2.2.2 Modelling the system

In this research, the future energy demand of Beijing and the socio-economic, environmental and energy-related impacts of transitions to renewable energy are modelled.

All economic sectors of Beijing are modelled, thus the residential sector, which is divided into urban and rural, the commercial, agricultural and industrial sector, which is divided into construction and other industries, namely manufacturing, metal smelting, mining and resource supply, the transport sector and heating. Transport includes private transport, public and freight transport, thus cars, motorcycles, taxis, lorries, buses, coaches, subways, light railways, trains and airplanes. Heating is modelled separately, because it is a major energy consuming activity which deserves special attention. Urban households and services are major contributors to the category heating. Rural residential heating is included in the category rural households.

In Chapters 2, 3 and 4, the importance for energy modelling is stressed to assess urban-rural differences. Therefore differences are modelled in this study between urban and rural, such as different growth rates in energy demand, technology use and access to infrastructure and consumption pattern. For the household sector, a detailed analysis was performed on end-use level assessing technologies such as lighting, air conditioning, water heating, cooking, refrigeration and other uses for appliances such as TVs, radios, computers as well as the fuels used to run these technologies. There are differences in consumption pattern between urban and rural households, such as that in urban households natural gas is used for cooking and heating, but not in rural households.

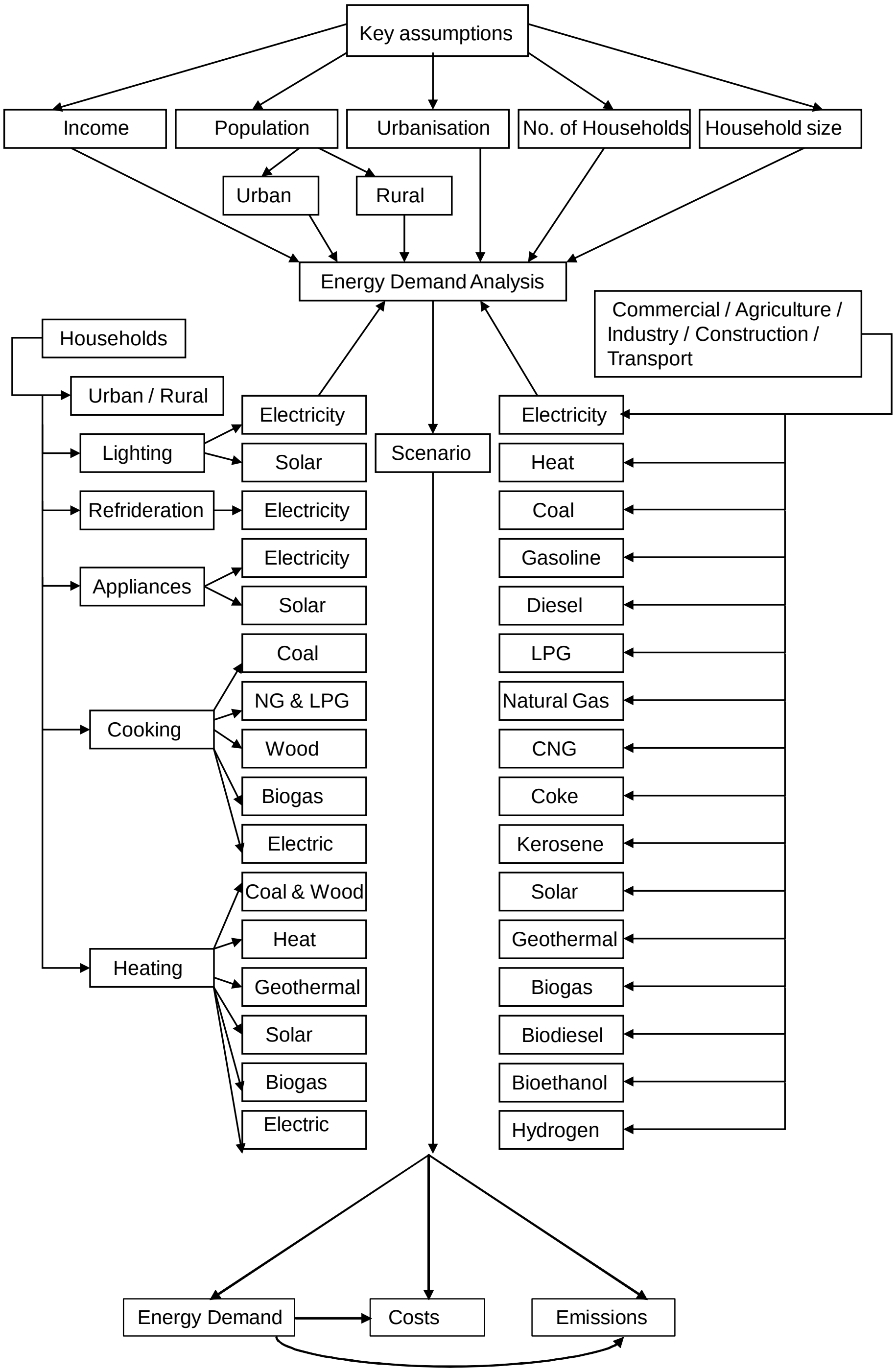

Figure 23: Modelling framework for LEAP.

For the commercial, agricultural, industrial, construction, transport sector and heating only aggregated data was available. All energy carriers used in Beijing were modelled. These are the following: coal, coke, coke oven gas, other coking products, oil products such as gasoline, diesel, (jet) kerosene, LPG, other petroleum products, natural gas (NG) and compressed natural gas (CNG), refinery gas, electricity and heat, further renewable energy. The following renewable energy were modelled: solar energy e.g. photovoltaic (PV) panels, solar lamps and solar water heaters, geothermal energy, biogas from agricultural waste, landfills and municipal solid waste, biodiesel, bioethanol and hydrogen. Bioethanol is however only expected to be used marginally due to limited resources and hydrogen is expected to be commercially used as of 2020. Energy from wind and hydro power is installed in rural areas, but its share among the total energy demand is negligible and has therefore not been modelled. For electricity and heat two different types are modelled: the “existing” and the “efficient”, with the “efficient” having a greater share of non-fossil fuels to generate electricity and heat. For the rural areas, fuel wood and biopellets are considered in addition to the available technologies.

The time frame of the modelling is mid-term, namely from 2005 to 2020. 2005 was chosen as the base year, because of two reasons: 1. because the most recent data available were from 2005 and 2. because of a renewable energy policy framework starting after 2005. The first year to be simulated is 2006. The choice of years is well suitable for a policy analysis, because the Chinese Renewable Energy Law is effective since 1st January 2006, thus allowing the model to directly assess possible policy implications.

An overview of the modelling framework is displayed in Figure 23.

5.2.3 Scenario-making

Two scenarios were developed to explore several ways of how Beijing’s energy future might develop: the business-as-usual (BAU) scenario and the renewable energy (RE) scenario. Both are policy scenarios aiming at the implementation of government projections. The major difference between these scenarios is a policy-induced transition to renewable energy for the RE scenario. Main drivers in these scenarios are socio-economic key assumptions such as GDP and GDP per capita, urban and rural population, degree of urbanisation, household number and size as can be seen in Table 14. Other main drivers are technological change such as the shares of certain fuels and/or end-uses (activity levels), energy intensity, emission factors, costs and policy. For assessing the costs, six scenarios were developed, three for the renewable energy scenarios and three for the business-as-usual scenarios.

The BAU scenario takes into account the present setting and simulates the future energy demand by following the past and present policies. The RE scenario takes into account the present setting and simulates the future energy demand by implementing a new policy strategy, namely policies inducing energy saving and transitions to renewable energy. Since the introduction of the Chinese Renewable Energy Law in 2006, the Government of Beijing has considered a number of ways how to implement this law in Beijing (Study Team of the Development Strategy of Renewable Energy in Beijing DSRE, 2006), therefore the RE scenario is developed according to this framework. For the RE scenario, no cut-backs on consumption are made. The saving in the energy demand refers to savings in fossil fuel resources only. Table 14 shows the differing general assumptions and policy frameworks for the BAU and RE scenarios.

Scenario	General assumptions	Policy options
Business-as-usual	Historical trends will proceed No major change in policy No major fuel switching No major technology switching Energy efficiency will increase Energy intensity will decrease Coal will remain the predominant fuel until 2010 Share of natural gas, oil, electricity, heat will increase	No major change in policy Aiming at implementing energy intensity and efficiency improvements according to 11th Five-Year-Plan
Renewable energy	Fuel switching will occur following principles of the Energy Ladder and Decarbonisation Technology switching will occur Energy efficiency will increase rapidly Energy intensity will decrease rapidly Less reliance on coal, more on RE, NG, oil, electricity, heat Electricity will become a major energy carrier New natural gas pipelines and power plants will be built Transportation: Hydrogen introduced by 2020, biofuels introduced as common fuel by 2015, share of LNG and CNG will increase Construction: The share of geothermal energy, solar energy (PV cells) and biofuels will increase Industry: The share of geothermal energy and biofuels will increase Agriculture: The share of solar, geothermal and biofuels will increase Commercial: The share of NG, solar, geothermal & biogas will increase, particularly for heating Households: Solar energy will be a common source of lighting by 2020; 2 kinds of electricity and heat will be available: the "existing" conventional and the "efficient" with a lower share of coal used for production; biogas, electricity, NG, LGP will be used for cooking; geothermal energy, solar water heaters, electricity & biogas will be commonly used for heating; the share of fuel wood will dimish to <5% in rural areas by 2020	The RE Law will be implemented RE targets for 2010: 4% of total energy demand met by RE RE targets for 2020: 6% of total energy demand met by RE Aiming at implementing energy intensity and efficiency improvements according to 11th Five-Year-Plan Subsidies for RE will be in place More R&D for RE Electricity market will be stronger regulated in favour of RE producers Encouraging policies for natural gas will be in place CNG will be promoted Energy-saving will be promoted including financial incentives for energy-saving technologies and public awareness campaigns

Table 14: General assumptions and policy frameworks for the BAU and RE scenarios

5.2.4 Data issues

The data used for the modelling mainly come from the Statistical Yearbooks of the Beijing Municipal Bureau of Statistics (BMBS, 2007) and the National Bureau of Statistics of China (NBS, 2007). This data are official government data. Supplementary data comes from the TED database of LEAP which is based on data from the IEA, the IPCC and the US Department of Energy (SEI, 2007b). For future trends, own assumptions were developed partly based on estimates by Chinese government officials and energy-economic experts (Wang, 2007). Emissions factors for “existing” and “efficient” electricity and heat are calculated based on the IPCC´s emission factors (2006) and the share of fuels used to generate electricity and heat in Beijing in 2005 as indicated by Philippe (2007). Data for the activity costs are based on the BMBS (2007). Detailed disaggregated data were available for household energy demand describing end-use technologies. For the other sectors, only aggregated data were available which did not allow breaking down the total energy demand into different end-use technologies. However these aggregated data were used to perform a fuel/energy carrier analysis of the total energy demand of each sector.

In chapter 5.3 the results are highlighted concerning energy demand, CO_2 emissions and costs and technology and policy implementations.

5.3 Results

5.3.1 Energy demand

The scenarios are modelled based on a business-as-usual approach and energy transitions to renewable energy.

Our results show that between 2005 and 2020, the energy demand is likely to increase in the BAU scenario from 55.2 mio tce in 2005 to 68.0 mio tce in 2010 and 99.6 mio tce in 2020 as can be seen in Figure 24. For the RE scenario, the energy demand is expected to increase to 62.5 mio tce in 2010 and 84.0 mio tce in 2020. The RE scenario could save 5.5 mio tce equalling 8% of carbon resources in 2010 and 15.6 mio tce equalling 15.7% carbon resources in 2020 compared to the baseline scenario scenario. No cut-backs in consumption levels have to be made for achieving this reduction. The saving in the energy demand refers to savings in fossil fuel resources only which are replaced by renewable resources.

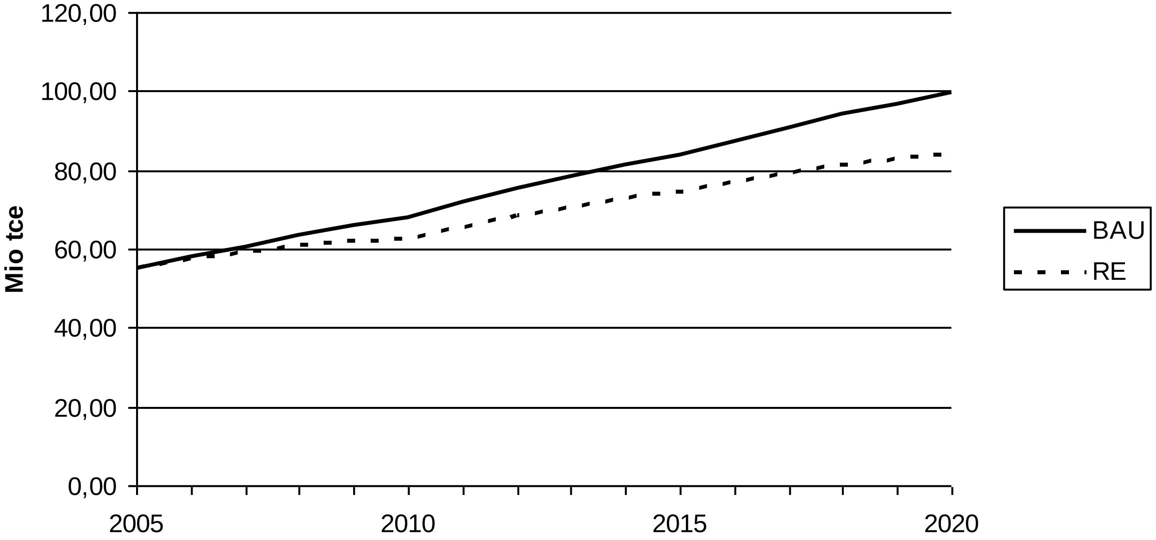

Figure 24: Energy demand for the BAU and RE scenarios in million tonnes coal equivalents.

Figures 25 to 27 indicate the development of the energy demand between 2005 and 2020 for all economic sectors for the BAU and RE scenario. There is an increase of the energy demand for all sectors in the BAU scenario. There is an increase of the energy demand for all sectors except households in the RE scenario until 2020, but the increase will be particularly steep in the transport sector, the construction, commercial sector and agricultural sectors.

In the BAU scenario, the energy demand in the transport sector is likely to increase by 170% until 2020 as projected in Figure 25. The energy demand in the commercial sector could double until 2020 as indicated in Figure 26. The energy demand in the construction sector is likely to increase by 180% until 2020 as shown in Figure 27. In the agricultural sector, the energy demand is also likely to double by 2020 as indicated in Figure 27. In the industrial sector, the energy demand could increase by 70% and for heating by 50% as shown in Figure 25. The energy demand for households (excluding heating) is expected to rise only slightly by 10% in the BAU scenario until 2020 as indicated in Figure 26. The urban residential sector accounted for about half of the total residential energy demand in 2005 (excluding heating) and is expected to account for 75% of the total residential energy demand by 2020, while the rural residential sector (including heating) will have a slower pace of energy consumption growth.

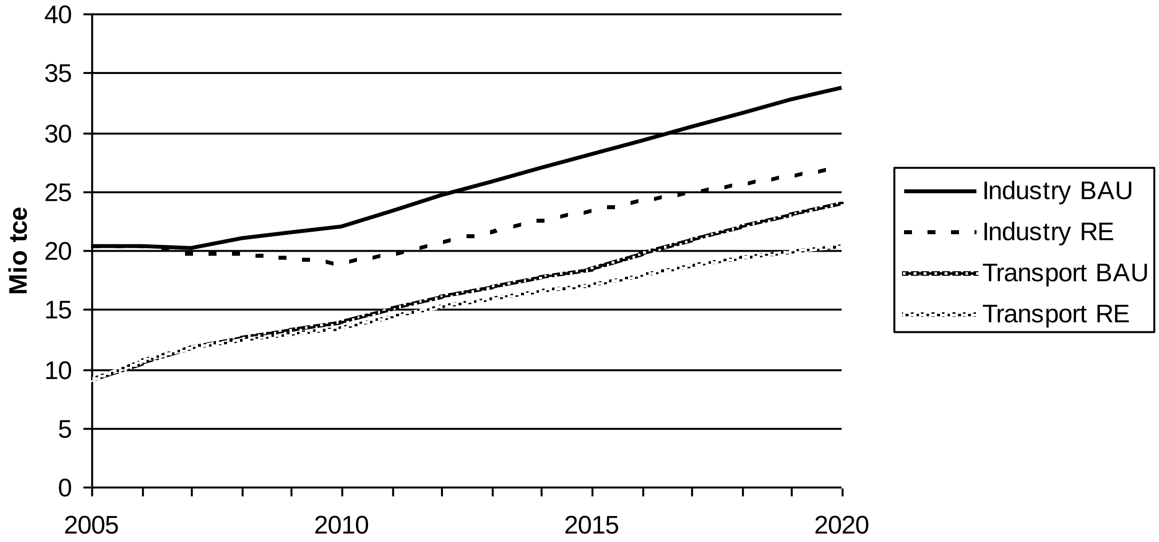

Figure 25: Energy demand for the BAU and RE scenarios for industry and transport

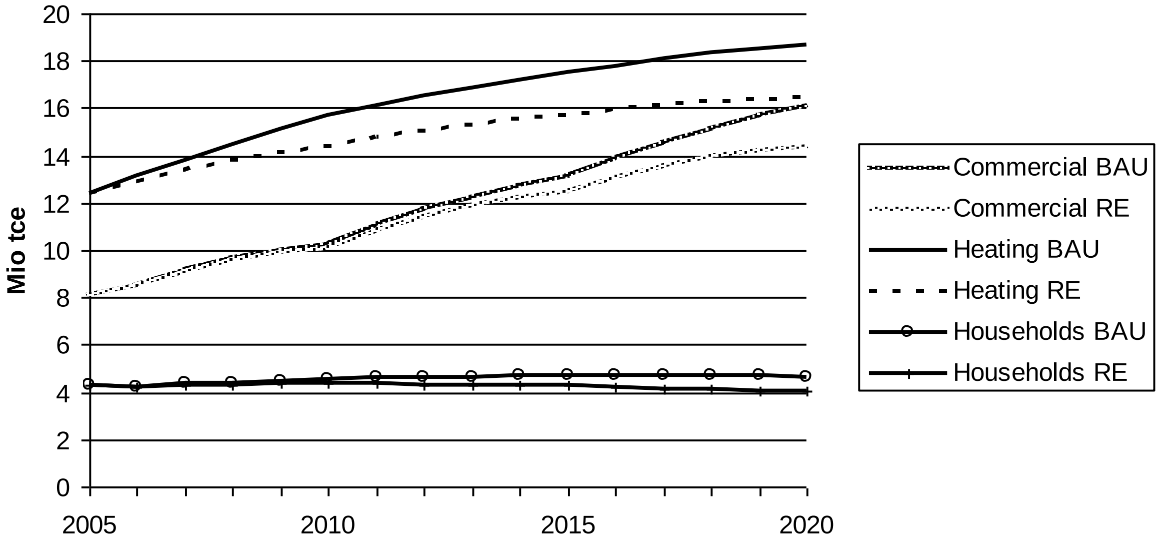

Figure 26: Energy demand for the BAU and RE scenarios for commerce, heating and households.

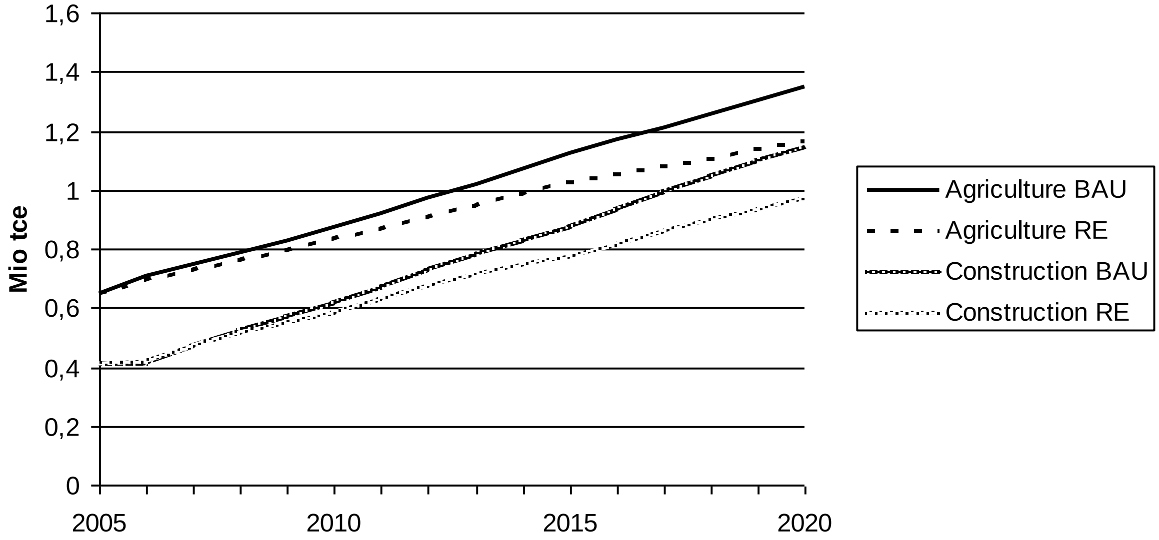

Figure 27: Energy demand for the BAU and RE scenarios for agriculture and construction.

In the urban residential sector, cooking accounted for 47% of the energy demand, hot water for 19.8%, refrigeration for 13.1%, air conditioning for 11.8%, lighting for 5% and other uses for 3.3% in 2005. Heating for urban households is accounted for separately in the heating category as shown in Figure 26. In the rural residential sector, cooking and fossil fuel heating accounted for 89% of the energy demand, other uses accounted for 4.5%, refrigeration for 2.6%, air conditioning for 1.2%, hot water for 1%, lighting for less than 1% and heating from renewable energy sources for less than 1% in 2005.

In the urban residential sector, the shares of air conditioning and other appliances like TVs, radios, computers and electronic appliances are expected to increase the most significantly in both scenarios until 2020, while the energy demand for other end-uses is likely to stay more homogeneous. It is expected that the share of cooking and fossil fuel heating among the total rural energy demand is likely to decrease rapidly for both scenarios until 2020, while the share of heating from renewable energy sources is expected to increase rapidly. The share for other uses will also rise.

A total decrease of 5.5 million tonnes carbon resources in 2010 and 15.6 million tonnes carbon resources in 2020 might be possible due to renewable energy transitions, as indicated in Figure 24. The decrease of fossil fuel demand and therewith carbon saving in the RE scenario is particularly high in the industrial sector, in which 20.2% carbon resource saving could be achieved by 2020. The carbon saving is also high in the transport sector in which 15.4% of the energy demand could be saved and in the construction sector with a saving of 15.1% in the RE scenario by 2020. In the agricultural sector the fossil fuel demand could decrease by 13.7%, household energy demand by 13.5%, heating energy demand by 12.2% and commercial energy demand by 10.8% in 2020 according to the RE scenario compared to the BAU scenario. The trend of increasing carbon consumption in the household sector could be reversed after 2010 in the RE scenario.

5.3.2 CO_2 and other greenhouse gas emissions

In 2005, 149.2 million tons of CO_2 equivalents were emitted in Beijing. GHG emissions could increase by 60% between 2005 and 2020 under the BAU scenario, as indicated in Figure 28. In 2010, 170.6 mio t CO_2 eq could be emitted according to the baseline scenario scenario. Under the RE scenario, 153,8 mio t CO_2 eq could be emitted which is a saving of 9.8% or 16.8 mio t CO_2 equivalents compared to the baseline scenario in 2010. In 2020, 236.2 mio t CO_2 eq are likely to be emitted according to the baseline scenario scenario. Under the RE scenario, 182.6 mio t CO_2 eq are likely to be emitted which is a saving of 53.6 mio t CO_2 equivalents or 22.7% compared to the baseline scenario in 2020.

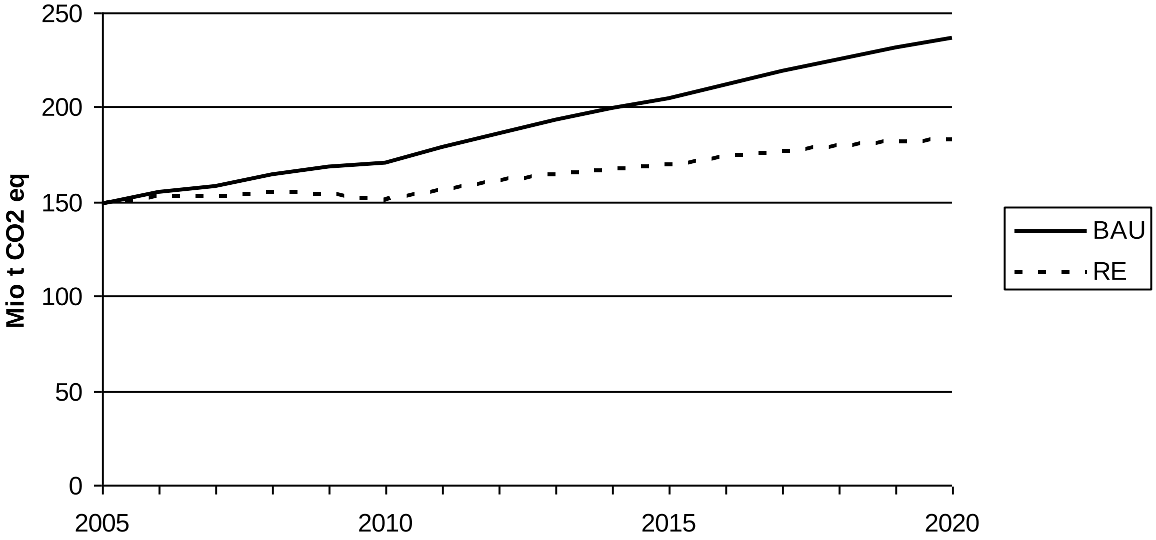

Figure 28: Emissions for BAU and RE scenario in million tons CO2 equivalents

With a share of 35.3%, the industrial sector accounted for the highest share of GHG emissions in 2005. The commercial sector accounted for 15.7%, the transport sector for 12.7%, the household sector for 4%, the agricultural sector for 1.4%, the construction sector for >1% of total GHG emissions in 2005 and heating for 30.5%. 87.8% of the GHG emissions from the household sector came from the urban areas in 2005. This share is expected to decrease slightly in 2020, because consumption levels and energy use are expected to rise in rural areas.

GHG emissions are likely to increase in all sectors in the BAU scenario. In the RE scenarios GHG emissions are likely to increase at lower levels for all sectors, except for heating where emissions are similar in 2005 and 2020. The emissions of the transport and construction sectors could augment by about 2.5 times between 2005 and 2020 in the BAU scenario, whereas the implementation of the RE strategy could save 20.7% of total GHG emissions from transport and 21.1% of GHG from the construction sector. The emissions from the commercial sector are likely to double until 2020 in the BAU scenario, while the RE scenario could save 20.2 % of GHG emissions from the commercial sector. The implementation of the RE strategy could further save 8.2% of total GHG emissions from the household sector which is expected to increase by 30% in the BAU scenario, 16.9% from the agricultural sector which is expected to increase by 70% in the BAU scenario, 20.2% from heating which is likely to increase by 30% in the BAU scenario and 29.4% of total GHG emissions from the industrial sector in 2020 which is likely to increase by 40% in the BAU scenario.

5.3.3 Costs

To assess the costs, six different scenarios were run, three RE scenarios and three BAU scenarios. The RE and BAU Cost I scenarios are the minimal cost scenarios, assuming that total costs increase minimally in terms of investment costs and energy prices. In the RE and BAU Costs II and III scenarios, it is assumed that overall costs increase more significantly. For each scenario, there is an average growth rate per year as indicated in Table 15. The Cost II scenarios are the intermediate scenarios and the Cost III scenarios are the extreme scenarios.

Scenario	Total increase %	Coal products	Oil & gas products	Electricity, heat, RE
Cost I	1	0,5	1,5	1
Cost II	2,5	2	3	2,5
Cost III	4	3	5	4

Table 15: Average annual growth rates of energy costs in percentage for each scenario

Total energy costs are estimated at 200 billion CNY in 2005, including both expenditures for energy purchases and investments in the energy infrastructure. Figure 29 indicates that costs are expected to increase rapidly until 2020. Even if energy prices increase only minimally, costs will increase by 300% in the BAU Cost I scenario and increase by 350% in the RE Cost I scenario until 2020. Major investments in energy infrastructure will be needed to sustain the rapid growth of Beijing’s consumption, regardless if renewable energy are being implemented or not. However, total energy-related costs for transitions to renewable energy will be higher than those of a business-as-usual approach. Costs in the RE Cost I scenario are 9% higher than in the BAU Cost I scenario. Costs in the RE Cost II are 9.7% higher and in the RE III scenario 7.5% higher than in the BAU scenarios. The difference between the costs in the RE and BAU scenarios seems to be the smallest when energy prices are the highest, although there seems to be a certain threshold level (see RE Costs II compared to BAU Costs II).

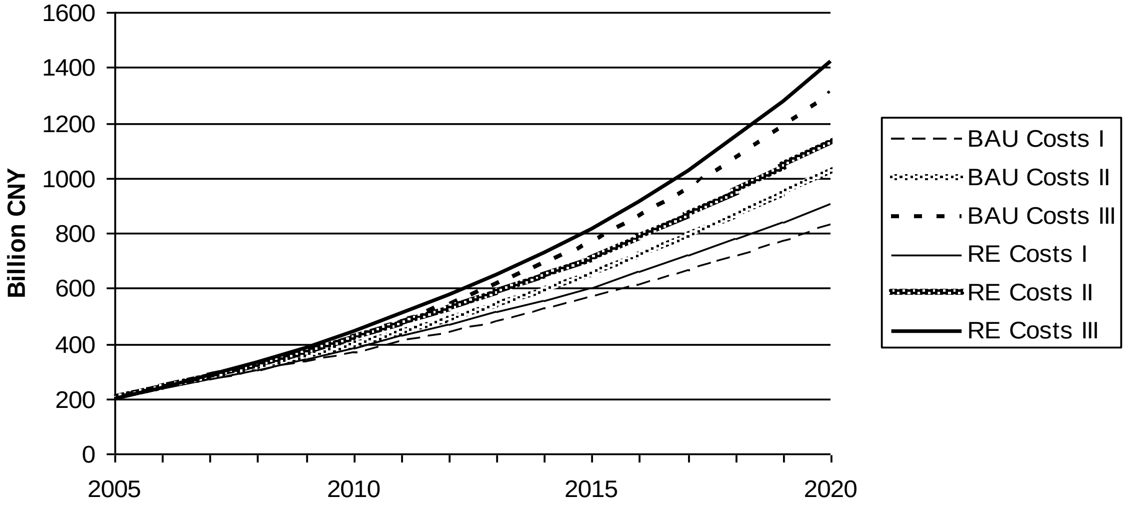

Figure 29: Costs for various BAU and RE scenarios in billion CNY

In 2005, most energy-related costs arose for transport, households, commerce, industries and heating. Between 2005 and 2020, costs are likely to increase particularly in the transport, commercial and construction sector, while they are expected to increase least in the household sector. In the household sector 71% of the costs were caused in the urban areas in 2005. It is expected that this share will rise up to 76% in 2020, due to rapidly growing income and consumption levels in the urban areas.

Costs are expected to increase for all sectors in all scenarios. Costs for satisfying the energy demand in the residential sector could remain lower during all times in the RE scenario compared to the BAU scenario. The cost saving is expected to account for 1.2% in 2020. Costs in the commercial and agricultural sector could remain similar in both scenarios. In 2020, the costs in the RE scenario could be 17.2% higher than in the BAU scenario for the industrial sector, 15.1% higher for the transport sector and even 40% higher for the construction sector. The costs for heating could increase by 8.7% in the RE scenario compared to the BAU scenario in 2020.

5.3.4 Technology and policy implementations

For modelling transitions to renewable energy, it is assumed that Beijing's governmental goals of gaining 4% of the total energy demand from renewable energy in 2010 and 6% in 2020 will be achieved. In Figure 30a the fuel mix in the business-as-usual scenario and the strong dependence on fossil fuels is displayed. In Figure 30b the fuel mix in the renewable energy scenario and the growing importance of renewable energy is indicated.

To achieve the governmental renewable energy goal, new technology choices have to be made.

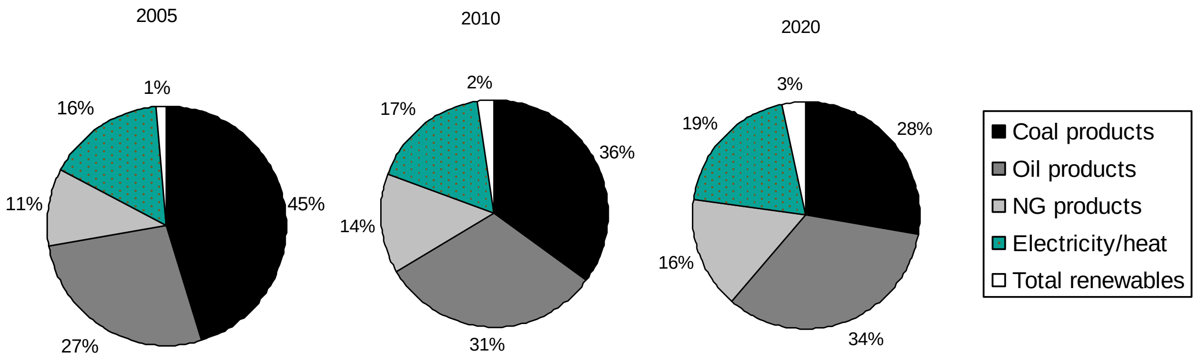

Figure 30a: Share of fuels in the BAU scenario

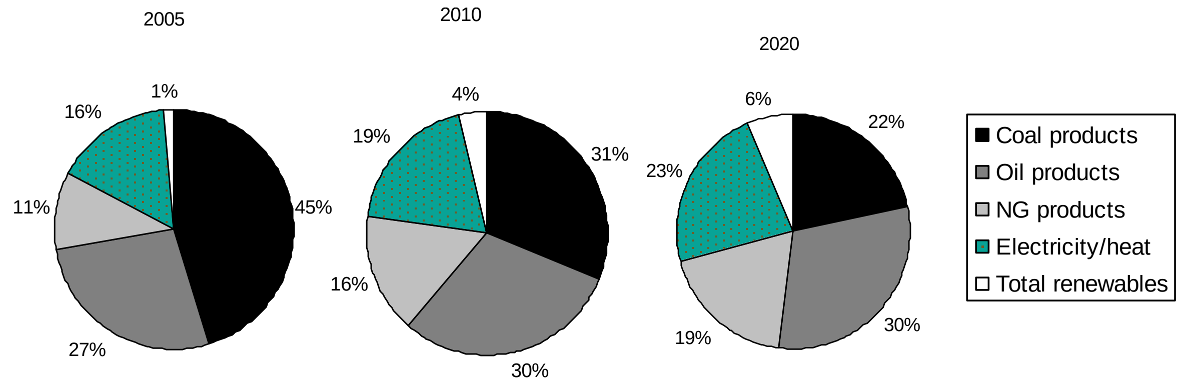

Figure 30b: Share of fuels in the RE scenario

In both scenarios, the energy portfolio will develop more sustainable in the future: the share of coal products among the total demand will decrease, while the share of natural gas products, oil products, electricity and heat will increase.

For the household sector, there are seven main end-uses: lighting, heating, cooking, hot water, refrigeration, air-conditioning and other uses including appliances such as radios, TVs, computers etc. The following end-uses, which today are mainly fossil fuel-driven, could be substituted by renewable energy technologies: lighting, heating, cooking, hot water and other uses. *Refrigeration* and *air-conditioning* can only benefit from a fuel substitution in case a switch from conventional electricity to green or "efficient" electricity is an option. Both appliances consume too much electricity to be driven by renewables only, such as PV panels. As for *lighting*, PV panels and solar lamps can provide light. As solar radiation is high throughout the year in Beijing, PV panels are already installed on many buildings and are also used for street lighting. Also, solar lamps are available at low costs and wide-spread in China. *Other uses* such as radios could also be driven by electricity from PV panels assuming that the devices are not too energy-consuming. The solar energy goals of Beijing's 11th Five-Year-Plan are to install a generation capacity of 4.5 GWh electricity from PV panels and to install a total capacity of 3.7 million m^2 floor surface of solar water heaters until 2010 (Philippe, 2007). So far, it seems that these plans will even be exceeded (Wang, 2008). Solar water heaters are already used at a high rate in Beijing and throughout China and are expected to gain importance in the future. Other technology options for residential *heating* are geothermal heat pumps, as some neighbourhoods of Beijing are situated above geothermal active fields. The Olympic Village for instance is planned to be heated by geothermal energy. Beijing's 11th Five-Year-Plan aims at installing a total capacity of 3.6 million m^2 floor surface of geothermal heating (Philippe, 2007). Another possible option for heating is biogas heating. Biogas is already produced on a large-scale from livestock and poultry waste in the rural areas, and from landfills and municipal solid waste in the urban areas. Heating with biogas instead of natural gas is particularly an option in the rural areas where biogas from livestock and poultry-farming is abundant. The 11th Five-Year-Plan also indicates that biogas is planned to be widely used for electricity with a generating capacity of about 957 GWh (Philippe, 2007). The biogas-based electricity could then again be used for heating and other purposes. Biogas is also used for *cooking* in rural areas as an alternative to coal and fuel wood. In the rural areas, biopellets are also increasingly used for heating and cooking.

For *hot water*, solar water heaters are already in place in many households, especially in rural areas.

For the commercial sector, lighting, heating, cooking, refrigeration, air-conditioning and other uses such as radios, TVs and computers do also play an important role. Therefore PV panels, solar lamps, solar water heaters and geothermal heaters are also viable technologies for substituting the predominant coal products, oil products and natural gas products.

For the agricultural sector, solar energy, geothermal energy and biogas are used in agricultural processes as substitutes for fossil fuels. Biofuels such as biodiesel is further vital for running agricultural machines which would otherwise run mainly on diesel.

For the industrial sector, biofuels for machines, biogas and geothermal energy play a role. Other renewable energy technologies are not viable for the industrial sector, because processes are energy-intensive and large-scale.

For the construction sector, biofuels, biogas and geothermal energy play a role, similar to the other industrial processes. However, solar energy might also play a role in form of PV panels or solar lamps for smaller-scale processes.

For the transport sector, biofuels such as biodiesel, bioethanol and biogas and hydrogen are of growing importance. Also other fuels such as CNG and LGP are already employed in the public transport sector. There are currently successful initiatives to increase the share of public buses running on CNG (BMBS, 2007) and it is reported that a few public buses seem to be driven on hydrogen as a demonstration project (Wang, 2007). This research indicates that fueling vehicles with alternative fuels or even with hydrogen would make an impact, although today hydrogen technologies are still not commercially employed. It is assumed for the future that more vehicles will drive on biofuels as vehicle producers will develop more environmental vehicles. It is assumed that by 2020, hydrogen will be a common energy carrier in the commercial transport sector. In urban areas, private transport plays so far a small, but increasingly important role (Zhang, 2007; BMBS, 2007). In 2004, there were 11 cars per 100 permanent residents. In 2007, there were already 18 cars per 100 permanent residents (BMBS, 2007). According to the Beijing Municipal Transportation Commission (2007), 29.8% of the urban population used public transport for commuting, another 29.8% used private cars, while the remaining 40.4% either used taxis or cycled or walked to work in 2005. Unfortunately, public transport tends to be crowded and buses are often slow, so that people tend to opt for other options such as taxis or private cars. In rural areas, car ownership is very low, so that private transport does not play a role (BMBS, 2007).

To achieve the transitions to renewable energy, strict policies are needed to encourage environmental change. Some policies stimulating renewable energy are officially in place in China, such as among others investment subsidies and tax reductions for renewable energy projects, renewable obligations for grid companies and the Clean Development Mechanism (CDM). The efficiency of implementing these policies is however variable. Strict implementation of existing policies and introduction of additional policies is therefore necessary. Policies focusing on local scale might even be more effective than national ones, because of lower organisation and management scales.

More financial incentives must come into place to stimulate the development and usage of renewable energy technologies, such as renewable energy credits or rewards for research and development in the field of renewable energy technologies. Multinational companies could play a role in importing their newest technologies to China e.g. hybrid cars; however the local industry should also be rewarded for developing cleaner technologies.

On the other hand, restricting policies could also be useful to achieve transitions to renewable energy. This could happen for instance as a reduction of subsidies for coal, as carbon taxes for fossil fuels or as reasonably high fees for climate-unfriendly emissions according to the “polluter-pays-principle”. This combination of rewards and punishments might change the behaviour of both the providers of goods and services and the consumers to make conscious and environment-sound decisions about their energy choices.

5.4 Discussion

5.4.1 Discussion of the method and data

The results of this research are dependent on three important inputs: the modelling method and the model itself, the scenario assumptions and the input data.

1. The modelling method determines how to model the energy demand and its impacts. The model used for this research is the bottom-up accounting tool LEAP which is used for scenario simulation. With the same data, using a different model or a different modelling method would result in only slightly different outputs, because LEAP is a reliable tool which has been calibrated and validated. One of the major advantages of LEAP is its bottom-up approach which allows to model technological details resulting in a disaggregated description of energy technology processes. One of the major disadvantages is that economic processes are modelled in a rather aggregated way, as LEAP is not an economic equilibrium or optimisation model.

2. The underlying scenario assumptions determine the results of the modelling. Other scenario assumptions would result in different outputs e.g. nuclear energy scenario or hydrogen scenario. Different aggregations of end-uses and sub-sectors can also influence the outcome. Based on the available data, the industrial sector is analysed in different sub-sectors: construction and other industries. Heating was also analysed as a separate sector. This approach allows a more differentiated analysis.

3. Both official governmental data from the BMBS and the NBS and international data from the IPCC, IEA and the US Department of Energy were used. As far as possible, the data from the BMBS and NBS were compared to similar data available from the IEA Energy Statistics (IEA, 2008). It was found that there are differences between the official Chinese government data and the IEA data, mainly indicating a slightly lower energy consumption, production and emissions in the Chinese data, but in total the data from both sources are consistent.

5.4.2 Uncertanties

There are a number of uncertainties in the system which makes it impossible to predict the future. There is full awareness of the uncertainties involved in the modelling as shown in Table 16. The scenarios presented are therefore an indicator of possible future developments, but not a prediction.

Uncertainty	Effect on scenario-making
Energy prices	Prices tend to be volatile & hard to model Prices for RE are in many cases higher than for fossil fuels, but can become lower subject to subsidies
Macro-economic growth	Macro-economic growth is often hard to forcast There are rapid changes in macro-economic growth in rapidly developing countries
Technological development & innovation	Technological development can result in leap-frogging Leap-frogging can result in skipping over periods observed in historic data Difficulty in modelling the state of development of a technolgy at a certain time
Policies	Drafting & implementation of policies depend on governments Policies tend to depend on legislation periods and/or central plans Public debates may spur political decisions unexpectedly

Table 16: Uncertainties involved in energy modelling and scenario-making.

5.4.3 Discussion of the results

Energy use and GHG emissions are expected to increase by 80% until 2020 if no counter measures are taken. According to this research and beyond according to research of the IPCC (2007a; 2007b), consequences will be a high reliance on fossil fuels, a decrease of energy security, an increase of energy imports -particularly oil and gas, but also coal from coal-rich provinces-, higher levels of air pollution and consequences on human health such as lung cancer and chronic respiratory air diseases, a higher contribution to global climate change and associated impacts such as extreme weather events like droughts, sand storms etc. This will lead to high externalities resulting in additional costs for fossil fuels which have so far not been assessed.

There is a gap between the share of renewable energy among the energy demand and the share of coal savings and emission savings. The coal and emission savings do not increase at a proportion of 1:1 relatively to the increase of renewable energy. A coal saving of 15.7% might be less striking than a GHG emission saving of 22.7%. There are several explanations for high coal and emission savings: 1. Renewable energy replaces predominantly coal products. 2. The shares of other lower-emission fuels such as natural gas, CNG, LPG and oil also increase to a larger extent in the RE scenario than in the BAU scenario. 3. Electricity and heat become cleaner in the RE scenario, because more renewable energy and lower-emission fuels are used for their generation. 4. The technological improvement is higher in the RE scenario resulting in lower energy intensities and higher efficiencies. 5. The emissions are calculated as CO_2 equivalents, not as CO_2 emissions. Other GHGs with higher global warming potentials increase the total amount of CO_2 equivalents.

The energy demand and GHG emissions are likely to increase particularly rapidly in the transport sector, because of the following reasons: 1. Rising affluence levels are likely to allow the large majority of people to use taxis and the public transport system, while walking and cycling will soon become a negligible means of transportation. 2. Car ownership is likely to rise significantly in the next decades. Both could result in an increase of the total number of vehicles and larger traffic volumes in Beijing. 3. Freight transport is expected to increase as more goods will be manufactured, consumed and exported, but also as more goods from abroad will be imported. Besides environmental and health issues, the consequences of an increase of the transport demand will be a growing dependency on energy imports particularly oil products, higher traffic volumes, longer peak-hours, a higher frequency and duration of traffic jams and an insufficient transport infrastructure. In the city of Beijing a number of new subway and light rail lines were finished for the 2008 Olympics. This is a big step forward towards decreasing private vehicle and road dependency.

There is an ongoing debate among experts about the competition between land for food production and for biofuel production (e.g. Nonhebel, 2005 and 2007; Chakravorty, 2007; Ignaciuk, 2006). This might also be an important issue for Beijing and for the regions transporting biofuels to Beijing. More research is needed to address the question whether enough land is available for sustaining both Beijing's food consumption and its biofuel consumption. Since biofuels are currently only produced from animal waste oil in Beijing, it is rather likely that not enough land will be available for a high introduction of biofuels. Another critical issue with biofuels is the low efficiency. In most countries, currently a blend of about 5-20% biofuel and 80-95% conventional fuel is used, which decreases its environmental value. Another problem is the CO_2 emissions from biofuels. These are only significantly lower than the emissions from conventional fuels if the CO_2 uptake of plants used for biofuel production is considered. Finally, growing biocrops on a large-scale might be a threat to biodiversity and might increase deforestation. Second-generation biofuels could be a solution to these problems, but they are not yet commercially available.

Heating is treated as a separate sector. Most of the heating is used for urban residential and commercial purposes. Rural residential heating is accounted for separately in the residential sector. The overall potential for the reduction of energy demand and emissions is therefore in total higher in the urban residential and commercial sector when heating is considered. Total energy use in the urban household and commercial sector is thus also be higher.

Costs will rise rapidly, similar to energy consumption, income levels and purchasing power parity. Rising costs might be less problematic at higher income levels. Rising costs could be reduced if energy saving and energy efficiency will be effective. Costs are higher for the RE scenarios, however externalities are not added to the costs for the BAU scenarios as mentioned before. An increase of energy prices of 4% annually might seem high for a developing country, but recent oil price increases have shown that this assumption is very realistic. Even higher prices might be likely. Nevertheless, costs are always a sensitive issue and can hardly be predicted correctly. Average costs were modelled; no extreme fluctuations are simulated such as oil price shocks, even though fluctuations in prices can result in fuel switching.

Even in 2020, there will be significant differences between urban and rural areas in terms of income and life styles. The rural population will adapt only slowly to the increasingly Westernised life styles of their urban neighbours. Renewable energy are more likely to be installed in rural areas, because of abundant renewable resources and lack of access to fuel markets. For the future it is therefore important to promote sustainable and equitable growth. In urban areas it is particularly important to ensure that both poorer and richer citizens gain equal access to sustainable energy to avoid unequal consumption and distribution of energy.

With Beijing having the size of about half of the Netherlands, there is enough space for installing renewable energy. Some renewable technologies do also not require much space, such as roof-top PV panels, solar water heaters, geothermal heating systems from geothermal fields situated under some parts of the city or biogas coming from existing landfills. The fact that high-rise buildings are the prevalent type of buildings in Beijing results however in the effect that less space is available for installing solar water heaters and PV cells than in cities with a larger number of low-rise buildings.

Technological leapfrogging is likely to play a role as new technologies such as hybrid or hydrogen cars and high-efficiency power plants could be implemented. Leapfrogging is an assumption in this simulation concerning hydrogen cars. With a growing emphasis on the service sector, dematerialisation and decarbonisation can be possible in Beijing. The “dirty road” of the industrialised countries´ development does not necessarily have to be followed.

It is assumed in both scenarios that Beijing´s economy will develop similar to the last years. These assumptions are based on governmental projections (Wang, 2007). It could nevertheless happen that the economy of Beijing develops differently in the future. Heavy-polluting industries could move into poorer neighbouring provinces where production costs are lower. Especially the coking, chemical and steel industries are likely to decline in Beijing in the near future. Beijing might become an administrative and service-oriented city with only few industries. In this case, environmental issues in Beijing could resolve positively. However, Beijing could be influenced negatively by the industries in neighbour provinces. In the last few years, some of Beijing’s polluting industries were moved to neighbouring provinces such as Hebei. Beijing is however affected from these neighbouring industries when the wind blows “trans-provincial air pollution” back into the city. It could be possible that some of Beijing’s environmental problems could soon become problems beyond its municipal boundaries. Trans-provincial cooperation on energy planning could therefore be needed.

5.4.4 Recommendations

Several recommendations are derived from the discussion of the results:

For decreasing the transport energy demand, Beijing needs a three-fold approach: 1. To re-adapt the transport infrastructure by decreasing the dependency on road transport and increasing the infrastructure for other forms of transport. Possible options could be to invest into further extensions of the subway and light rail, more train stations, introduction of trams and possibilities for car pooling. Congestion charges might also be a viable option, like experience from other large cities such as London has shown. City-planning needs to be re-adapted to avoid importing problems similar to American cities such as dependency on cars, car infrastructure and urban sprawl. 2. To encourage individuals to use public transport or taxis instead of purchasing own cars or motorcycles. Public awareness campaigns might be necessary. Auctioning vehicle plates like it is already common practise in Shanghai might further be an option to restrict private car ownership. 3. To switch to alternative fuels. Fueling public transport and maybe also taxis with biofuels and CNG and later with hydrogen might make a high impact. Biofuels could become competitive if subsidies on fossil fuels were decreased and/or if gasoline and diesel were carbon-taxed like in other countries. Using the tax revenues or switching subsidies to finance biofuels could make them cheaper than conventional fuels and could therefore save costs on the consumer-side. There could be investment subsidies for hybrid cars or other forms of cleaner cars to encourage individuals to drive cleaner.

Also for the other sectors, there are serious policy implications which arise from Beijing’s energy use. Energy saving is vital, regardless if renewable energy will be implemented or not. In 2006, Beijing’s energy intensity decreased by more than 5% in comparison to 2005. The province of Beijing is one of the few Chinese provinces that can realistically achieve the energy saving targets set in the national 11th Five-Year Plan (Wang, 2007). However, a range of strict policies need to be implemented to increase energy saving and energy efficiency. Schemes for energy saving and energy efficiency could help to increase public awareness. Energy saving devices like energy saving light bulbs, energy efficient refrigerators and air conditionings need to be installed where possible. However, energy saving devices are not enough. Instead a behavioural shift in consumption patterns is necessary to prime the consumer from energy-intensive to energy saving. Behavioural change can be achieved through education; however rewards like subsidies or other financial incentives could be much more effective, especially for enterprises with high stakes. “Punishments” like reduction of subsidies, fines and taxes could also be an option, especially for climate-unfriendly enterprises and product groups e.g. reduction of coal subsidies, carbon tax on gasoline/diesel.

5.5 Conclusions

This article elaborated the future of the energy supply and demand of Beijing and assessed the impacts on energy resources, GHG emissions, technology choices and costs. LEAP was used to model a business-as-usual approach and transitions to renewable energy. The renewable energy scenario simulates the government’s targets to implement 4% of renewable energy in 2010 and 6% in 2020. This research indicates that transitions to renewable energy is strongly needed as the energy demand will increase by 80% between 2005 and 2020 in the baseline scenario scenario, while a 15.7% reduction of fossil fuel demand is achieved in the renewable energy scenario, equalling a carbon saving of 15.6 mio tce. The CO_2 emissions will increase by 60% between 2005 and 2020 in the business-as-usual scenario, while transitions to renewable energy could save 22.7%, equalling 53.6 mio t CO_2 emission equivalents in 2020 alone.

If no counter measures will be taken there could be severe consequences such as increasing levels of air pollution, consequences on human health, rising contributions to global climate change and a high reliance on energy imports.

Installing a modest share of renewable energy can already have significant effects. Consumption levels do not have to be restricted as fossil energy is replaced by renewable energy. The most effective reduction of energy demand and GHG emissions due to transitions to renewable energy could be possible for industries and construction. Effective GHG reduction could also be implemented for heating and commerce. Transitions to renewable energy could be most cost-effective in households, agriculture, commerce and heating. The most cost-effective way to switch from fossil fuel energy to renewable energy seems to be in places where processes remain the same, while only small-scale devices have to be switched. Renewable energy could therefore particularly be employed in households, the commercial sector and heating where technologies such as PV panels, solar water heaters, solar lamps, geothermal heating and biogas stoves/heating could be used. A decrease of energy demand in the household sector is however only expected to be possible if renewables energy are employed on large-scale. Governmental programs and/or financial incentives should be in place to achieve a large-scale implementation. In other sectors fuel switching might be more expensive, such as in the industrial and construction sector where large-scale processes or machinery might have to be amended. However, this work has proven that transitions to fossil fuels could be particularly effective in these sectors.

It is recommended to increase the share of renewable energy, particularly in the industrial, construction and transport sector where most effects can be obtained, and in the household sector where renewable energy are relatively easy and cost-effective to install. Switching to CNG and hybrid vehicles is recommended in the rapidly growing transport sector. Research on hydrogen vehicles could be valuable and might allow possibilities for Chinese market leadership in this technology. However, renewable energy may only be one part of solving Beijing’s traffic problems. Another –maybe even more important- part is to re-adapt the transport infrastructure to reduce dependency on roads and private cars and to encourage the local population to use public transport. Possible solutions could be to further extend the subway and light rail lines, to add train stations, to build a tram system and to promote public transport and car pooling.

Governmental programs, financial incentives and/or environmental rewarding and taxation schemes should be in place to achieve a large-scale implementation. Energy saving is also crucial to decrease the rapid expansion of energy demand and emissions.

5.6 Acknowledgements

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6. Energy for rural India[11]

Abstract

About 72 million households in rural India do not have access to electricity and rely primarily on traditional biofuels. This research investigates how rural electrification could be achieved in India using different energy sources and what the effects for climate change mitigation could be. We use the Regional Energy Model REM to develop scenarios for rural electrification for the period 2005 to 2030 and to assess the effects on greenhouse gas emissions, primary energy use and costs. We compare the business-as-usual scenario (BAU) with different electrification scenarios based on electricity from renewable energy, diesel and the grid. Our results indicate that diesel systems tend to have the highest CO_2 emissions, followed by grid systems. Rural electrification with primarily renewable energy-based end uses could save up to 99% of total CO_2 emissions and 35% of primary energy use in 2030 compared to BAU. Our research indicates that electrification with decentral diesel systems is likely to be the most expensive option, due to high oil dependence. Rural electrification with renewable energy tends to be the most cost-effective option when end-uses are predominantly based on renewable energy, but turns out to be more costly than grid extensions when electric end-use devices are predominantly used. This research therefore elaborates whether renewable energy is a viable option for rural electrification and climate change mitigation in rural India and gives policy recommendations.

6.1. Introduction

Energy is a vital commodity. It is commonly recognised that access to energy is closely linked with development and economic well-being (DFID, 2002; IEA, 2002a; WEC, 2001; WEC, 2000; WHO, 2006) and that alleviating energy poverty is a prerequisite to fulfill the Millennium Development Goals (DFID, 2002; WHO, 2006). Especially access to modern energy, like electricity, is vital for development in low-income countries. With 412 million people not having access to electricity in 2005, India hosts the world's largest population deprived of electricity. 92% of this population lives in rural India, equaling about 380 million people or 71.7 million households (IEA, 2007). The Indian government takes rural energy poverty serious and issued numerous rural electrification schemes since the Indian independence (Bhattacharyya, 2006a; Liming, 2008). Rural electrification plays a major role in the current and future energy setting of India.

This article therefore aims to investigate how complete rural electrification could be achieved in India using different energy sources and what the effects for climate change mitigation could be. Scenarios were developed for rural electrification for the period 2005 to 2030 with the Regional Energy Model (REM). REM is a bottom-up simulation model which analyses the energy supply and demand of a country or region for all sectors. Using REM, the effects of rural electrification were assessed on greenhouse gas emissions (GHG), primary energy use and costs. Five main scenarios were developed: the business-as-usual scenario (BAU1), in which no electrification takes place, and four electrification scenarios based on

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[11] This chapter is a slightly adapted version of Urban, F., Benders, R.M.J., Moll, H.C., 2009. Energy for rural India. *Applied Energy*, resubmitted.

electricity from renewable energy (2 scenarios), diesel and the grid. Six cost scenarios were developed in addition.

Related earlier research focused primarily on two issues: a) on household energy use and b) on rural electrification. Literature on household energy use is mainly on Indian-wide or urban level, rather than on rural level. On urban level, Alam et al. (1998) assess household energy use for Hyderabad and Gupta and Köhlin (2006) for Kolkata. On an Indian-wide level, Pachauri (2004a) analyses the variations in total household energy and discusses ways to measure energy poverty in Indian households (Pachauri et al., 2004), while Reddy and Balachandra (2006) discuss energy end-use technology shifts in the household sector and Viswanathan and Kumar (2005) explore the Indian cooking fuel use pattern. On rural level, Sarmah et al. (2002) compare rural household energy use in non-electrified villages in India and Devi et al. (2007) discuss community energy use in decentralised areas of rural India. Concerning rural electrification, Sinha and Kandpal (1991) found already in the '90s that decentralised renewable energy can be a cost-effective measure for rural electrification in India compared to the grid. Chakrabarti and Chakrabarti (2002) elaborate possibilities for rural electrification of remote island communities in India. Nouni et al. (2008) explore several options of providing decentralised electricity access to remote areas in India and Bastakoti (2003) relates rural electrification to ways of creating energy enterprises. Bhattacharyya (2006a) argues that rural electrification alone might not be a solution to the energy access problem. Bhattacharyya (2006b) also assumes that the rural poor are not likely to become a major market for renewable energy. Kadian et al. (2007) assess energy-related emissions and mitigation options in the household sector for Delhi. Though energy-related research on India is broad, research on rural electrification and its impacts on climate change mitigation for rural India, as performed in this study, has not been done before.

6.2. Methodology

6.2.1 Modelling with the Regional Energy Model REM

REM originated from the global energy and GHG emission model ESCAPE[12] (CEC, 1992; Hulme et al., 1995; Hulme, 1992a; Hulme, 1992b; Rotmans et al., 1994). The ESCAPE model, as well as the slightly adapted REM model, is based on the end-use approach.

An end-use function in a certain sector at time t=0 is taken as a starting point e.g. the function lighting in the residential sector. The useful energy demand (UED) for lighting can be calculated from the amount of kilowatt-hours (kWh) needed for lighting, the fraction (Fr) and the used efficiency (Eff) of the appliances (see Equation 1).

$$UED_{t=0} = \sum_{s=1}^{s=n} \sum_{f=1}^{f=m} ED_{sf_{t=0}} * \sum_{a=1}^{a=k_{sf}} (Fr_a * Eff_a)_{sf} \qquad \text{Equation 1}$$

Where:
UED=useful energy demand; ED=energy demand; Fr=fraction; Eff=efficiency. t=time; s=sector; f=function; a=appliance.

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[12] ESCAPE (the Evaluation of Strategies to address Climate change by Adapting to and Preventing Emissions) is an integrated climate change assessment model constructed between 1990-1992 by a consortium of research institutes. It was designed to enable users to generate future scenarios of GHG emissions through an energy-economic model and to examine their impact on global climate and sea level (CEC, 1992; Hulme et al., 1995; Hulme, 1992a; Hulme, 1992b; Rotmans et al., 1994).

In equation 1, the total UED for the region or country is calculated for sector (s) for s=1 to s=n, for function (f) for f=1 to f=m and for appliance (a) for a=1 to a=k.

The next step is to calculate the UED in the future for time t=t. Several variables can influence this future demand: population at time t (Pop), GDP at time t (GDP) and sector shifts (SAE) as indicated in Equation 2.

$$UED_t = \sum_{s=1}^{s=n}\sum_{f=1}^{f=m}(UE_{sf_{t-1}} * Pop_t * GDP_t * SAE_{s_t}) \qquad \text{Equation 2}$$

Where:
UED=useful energy demand; UE=useful energy; Pop=population at time t; GDP=GDP at time t and SAE=sectoral activity; t=time; s=sector; f=function; a=appliance.

In the last step, the energy demand in time t=t is calculated based on the UED in t=t, the fractions and efficiencies of the appliances in time t=t (see Equation 3).

$$TED = \sum_{s=1}^{s=n}\sum_{f=1}^{f=m}\sum_{a=1}^{a=k_{sf}}(UED * Fr_a / Eff_a)_{sf} \qquad \text{Equation 3}$$

Where:
TED=energy demand at t=1; UED=useful energy demand; ED=energy demand; Fr=fraction; Eff=efficiency; s=sector; f=function; a=appliance.

Figure 31 shows a schematic overview of these three steps.

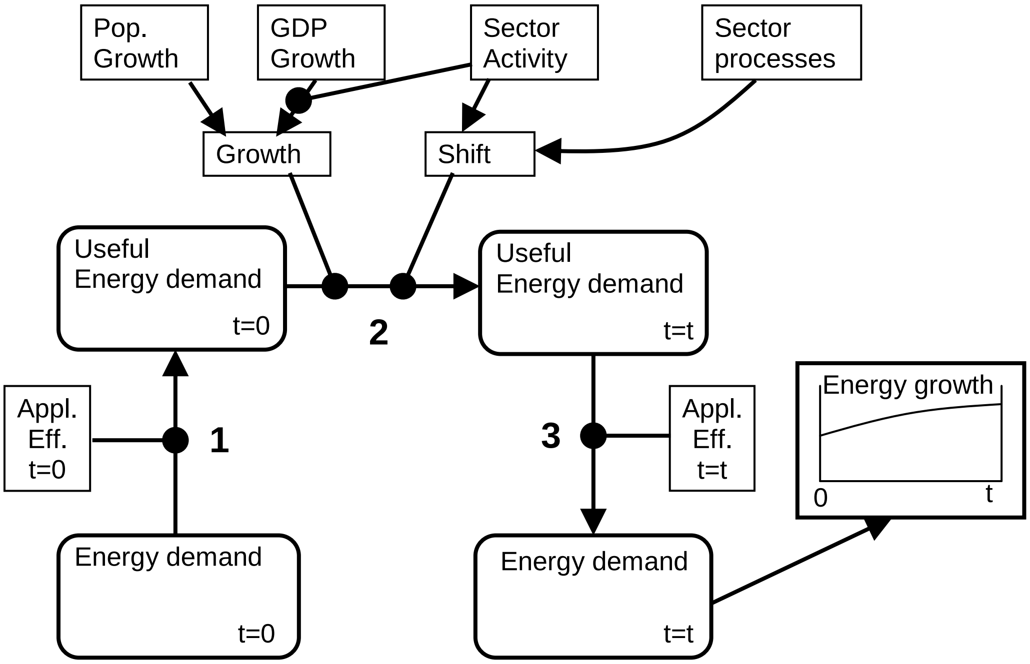

Figure 31: Schematic overview of the calculation model in REM and the three calculation steps described in equations 1-3.

The above described end-use approach forms the core of the model. Since the model is very flexible, the user can define own sectors (e.g. agriculture, industry, residential, services and transport) and functions (e.g. cooling, cooking, lighting, space heating). For all sectors, the same functions are defined, but can be used optionally. All appliances present in a certain sector should be placed in one of these defined functions for energy demand. Several appliances per function for a certain sector are allowed. For example, the function lighting in the residential sector of rural India has five types of lamps: kerosene lamps, photovoltaic (PV) lamps, conventional light bulbs, energy-saving light bulbs and Light Emitting Diode (LED) light bulbs. The efficiency of each appliance can increase over time and a sector can shift within a function from one appliance to another, e.g. from mainly kerosene lamps to conventional light bulbs.

Besides this sector–function matrix, REM contains a module for the supply side: the energy conversion sector accounting for electricity production, refineries and Combined Heat and Power (CHP). For the supply side, several types of technologies can be defined. The fractions determine how much electricity, heat or oil is generated with a certain technology e.g. wind, coal-fired power plant, district heating etc.

6.2.2 Modelling rural India

Most energy models assess energy resources, technologies, and emissions. Only few energy models analyse the needs and services related to energy, like the latent energy demand in rural areas in developing countries. This part of the system is hardly modelled, because of its complexity and uncertainty about the underlying processes and assumptions. This chapter however addresses the energy needs and services for rural India.

With 1.1 billion inhabitants in 2006, India is the second most populous country in the world (World Bank, 2008) and is expect to be the world’s most populous country in 2050 (UN PRB, 2006). In terms of energy, India is the world’s fourth highest consumer of energy just after the USA, China and the Russian Federation (IEA, 2008). India is also one of the world’s top five GHG emitters measured in absolute terms. In per capita terms however, an average Indian citizen uses about 15 times less energy than an average US American citizen, emits about 17 times less GHG emissions and uses about 30 times less electricity (World Bank, 2008).

In economic terms, India has a steeply increasing GDP growth and an expanding economy. At the same time, India hosts a large population living below poverty line, namely 35% of its total population in 2003 (World Bank, 2008). High differences between urban and rural areas prevail. While the Indian economy generates most of its income from services and industries, more than 70% of the total population live in rural areas (UN PRB, 2006) and depend primarily on non-mechanised agriculture for sustaining their living. Energy poverty is clearly an issue: electrification rates were as low as 50% in rural areas and 62% in total India in 2005 (IEA, 2007). Electricity consumption in the rural areas is estimated as ranging between 0.3 kWh (Dijkstra, 2007) to 1 kWh per household per day (Puri, 2006; Bhattacharyya; 2006a). The predominant fuels used in rural India are solid traditional biofuels such as fuel wood, dung and agricultural residues which are assumed to have high impacts on human health (WHO, 2006; 2005; 2000).

In average 80-90% of all energy used in rural households is needed for cooking and heating water (Devi et al., 2007). The remaining energy is used for lighting, heating in winter and for basic appliances such as radios and fans (Chakrabarti and Chakrabarti, 2002). In 2005, the total primary energy use in non-electrified rural Indian households consisted in average of 73% traditional biofuels, 19% oil products, 7% solar energy and 1% coal, mainly charcoal. For cooking and heating water, in average 75-95% of the energy is fuel wood and dung (Reddy and Balachandra, 2006; Devi et al., 2007). Most of the cooking is done on so-called chulhas, simple stoves with very low efficiencies (Reddy and Balachandra, 2006). Other fuels used for cooking are liquid petroleum gas (LPG), biogas, kerosene, solar power, coal and electricity in electrified households. For lighting, non-electrified households depend completely on kerosene, solar energy and candles. For lighting in electrified households, in average about 50-75% electricity is used and 25-50% kerosene (Reddy and Balachandra, 2006; Devi et al., 2007). For heating in winter, traditional biofuels are used with fuel wood and dung both being used to the same extent (Devi et al., 2007). In non-electrified households, appliances such as refrigerators or TVs are not used, since they usually require electricity. Solar- / battery-powered radios may be used in non-electrified households.

Once access to modern energy is provided, fuel switching may occur. While the poorer income groups tend to cook predominantly with traditional biofuels, the wealthier income groups tend to use cleaner and more efficient fuels such as LPG besides using traditional biofuels (Bhattacharyya, 2006a). The most important key assumptions for the modelling are displayed in Table 17.

Key assumptions	Value in 2005	Reference
Total Indian electrification rate	62%	IEA, 2007
Non-electrified rural households	71.7 million	IEA, 2007
Energy use per capita	4.4 GJ	Pachauri, 2004 and IEA, 2007
Energy use per household	23.4 GJ	Based on Pachauri, 2004; IEA, 2007
Increase of energy demand	1.6%	IEA, 2007
Population growth rate	1.4%	World Bank, 2008
GDP growth rate	9.2%	World Bank, 2008

Table 17: Key assumptions for the modelling of rural non-electrified India.

Indian rural electrification schemes were in the past mainly linked to rural development in form of promoting irrigation for increased agricultural productivity. Recent electrification schemes mainly aimed at electrifying villages and households, with an emphasis on households below poverty line as in the Kutir Jyoti programme (Bhattacharyya, 2006a). The governments´ ambitious plans to achieve complete village and household electrification by 2010, under the Rajiv Gandhi Grameen Vidhyutikaran Yojana scheme, are challengeable, as 71.7 million households were still non-electrified in 2005 (IEA, 2007). The term ‘electrification’ is interpreted in various ways in India, meaning until recently that electricity was used for any purpose within a village’s boundaries and meaning at present that at least 10% of all households in the village must have access to electricity (IEA, 2007; Bhattacharyya, 2006a). The greatest challenge considering rural electrification is the electrification of remote households, which are often located in inaccessible terrain. In hilly terrain, grid electrification can be up to ten times more expensive than in plain terrain (Nouni et al., 2008). The Indian government therefore uses renewable energy for electrifying remote households and also offers high capital investments for these projects (Puri, 2006).

Function / technology	Energy use & fractions in 2005 and 2030 in the scenarios						
	2005	**BAU1**	**BAU2**	**RE1**	**RE2**	**GRID**	**DIESEL**
Cooking	14.6 GJ	19.6 GJ	12.7 GJ	12 GJ	19.6 GJ	35.0 GJ	47.6 GJ
Wood stove (Chulha)	30%	30%	10%	5%	0%	0%	0%
Dung stove (Chulha)	25%	25%	10%	5%	0%	0%	0%
Improved wood stove	30%	30%	30%	12%	0%	0%	0%
Improved dung stove	2%	2%	0%	0%	0%	0%	0%
Kerosene stove	0%	0%	0%	0%	0%	0%	0%
Improved kerosene stove	0%	0%	4%	0%	0%	0%	0%
Electric stove	0%	0%	20%	5%	80%	80%	80%
LPG stove	5%	5%	20%	0%	20%	20%	20%
Coal stove (Charcoal Chulha)	1%	1%	1%	0%	0%	0%	0%
Biogas stove	5%	5%	3%	30%	0%	0%	0%
Solar cooker	1%	1%	1%	23%	0%	0%	0%
Parabolic solar cooker	1%	1%	1%	20%	0%	0%	0%
Hot water	5.0 GJ	6.8 GJ	6.3 GJ	4.4 GJ	6.4 GJ	11.5 GJ	15.2 GJ
Electric HW heater	0%	0%	5%	7%	100%	100%	100%
Solar HW	17%	17%	30%	71%	0%	0%	0%
Wood stove (Chulha)	20%	20%	10%	2%	0%	0%	0%
Dung stove (Chulha)	35%	35%	20%	2%	0%	0%	0%
Improved wood stove	15%	15%	15%	2%	0%	0%	0%
Improved dung stove	0%	0%	2%	0%	0%	0%	0%
Kerosene stove	2%	2%	2%	0%	0%	0%	0%
Improved kerosene stove	0%	0%	10%	0%	0%	0%	0%
Electric stove	0%	0%	0%	0%	0%	0%	0%
LPG stove	5%	5%	10%	0%	0%	0%	0%
Coal stove (Charcoal Chulha)	1%	1%	1%	1%	0%	0%	0%
Biogas stove	5%	5%	5%	15%	0%	0%	0%
Lighting	3.2 GJ	4.3 GJ	10.6 GJ	2.4 GJ	13.3 GJ	23.5 GJ	32.4 GJ
Conventional light	0%	0%	20%	25%	85%	85%	85%
Energy-saving bulb	0%	0%	20%	25%	10%	10%	10%
LED light	0%	0%	10%	0%	5%	5%	5%
Kerosene lamp	95%	95%	45%	0%	0%	0%	0%
PV lamps	5%	5%	5%	50%	0%	0%	0%
Heating	0.6 GJ	0.6 GJ	2.1 GJ	0.6 GJ	3.4 GJ	5.7 GJ	7.7 GJ
Wood stove (Chulha)	25%	25%	12.5%	5%	0%	0%	0%
Dung stove (Chulha)	25%	25%	12.5%	5%	0%	0%	0%
Improved wood stove	25%	25%	25%	43%	0%	0%	0%
Improved dung stove	25%	25%	25%	43%	0%	0%	0%
Electric stove	0%	0%	25%	2%	100%	100%	100%
Cooling	0 GJ	0.1 GJ	4.2 GJ	0.1 GJ	9.6 GJ	16.6 GJ	22.9 GJ
Refrigerator / small freezer	0%	0%	40%	0%	50%	50%	50%
Electric fan	0%	0%	50%	0%	40%	40%	40%
Air-condition	0%	0%	10%	0%	10%	10%	10%
Electronics	< 0.1 GJ	0.1 GJ	6.3 GJ	0.1 GJ	9.6 GJ	16.6 GJ	22.9 GJ
Electronics	0%	0%	20%	5%	30%	30%	30%
Radio / TV	0%	0%	39%	20%	65%	65%	65%
Computers	0%	0%	1%	0%	5%	5%	5%
Solar-powered radio	100%	100%	40%	75%	0%	0%	0%

Table 18: End-use functions, technologies, energy use and fractions for 2005 and 2030 per scenario for an averaged rural non-electrified Indian household. The starting point in 2005 is based on earlier surveys on Indian

household energy use (Pachauri, 2004; Reddy et al., 2006; Devi et al., 2007; Bhattacharyya, 2006a; Bhattacharyya, 2006b).

6.2.3 Scenario-making

Direct household energy requirements in rural areas were in average 3.7 GJ per capita in 1993/94 according to survey data (Pachauri, 2004) and estimates by the IEA indicate that household energy use was increasing every year by 1.6% between 1990 and 2005 (IEA, 2007), thus leading to 4.4 GJ per capita in 2005. Consequently, household energy use per household in rural non-electrified India is estimated at 23.4 GJ in average for 2005. It is assumed that the energy use keeps increasing at 1.6% per year as indicated by the IEA (2007) for the start year

2005 and the consequent years and increases at a slightly higher rate afterwards. This development takes into account population growth and increases in incomes and affluence levels. Six end-use functions are employed in Indian households: cooking, heating, lighting, hot water, cooling and electronics. Table 18 indicates the technologies employed per end-use function and shows whether these technologies were used in rural non-electrified households in India in 2005. It is assumed that full access to technologies can be achieved until 2030 depending on each specific scenario.

Six main scenarios were developed: two business-as-usual scenarios (BAU1 and BAU2) and four electrification scenarios based on electricity from renewable energy (RE1 and RE2), diesel (DIESEL) and the grid (GRID) as shown in Table 19. Six cost scenarios were developed in addition.

Scenario	Type of scenario	Characteristic
BAU1	Business-as-usual pessimistic	No electrification takes place
BAU2	Business-as-usual optimistic	Modest electrification takes place with grid extensions
RE1	Renewable energy scenario	Electrification with RE, RE-based end-use appliances
RE2	Renewable energy scenario	Electrification with RE, electric end-use appliances
DIESEL	Diesel scenario	Electrification with decentral diesel systems
GRID	Grid extension scenario	Electrification with central grid extensions
BAU_200%	Oil price scenario BAU	Oil price doubles between 2005 and 2030
DIESEL_200%	Oil price scenario DIESEL	Oil price doubles between 2005 and 2030
GRID_200%	Oil price scenario GRID	Oil price doubles between 2005 and 2030
GRID_10km	Grid distance scenario	Distance from households to grid is 10 km
GRID_15km	Grid distance scenario	Distance from households to grid is 15 km
GRID_25km	Grid distance scenario	Distance from households to grid is 25 km

Table 19: Scheme of the scenarios.

The BAU1 scenario is the baseline scenario scenario in which no electrification takes place. Traditional biofuels are predominantly used and small shares of kerosene, renewable energy and coal. While the amount of energy used increases between 2005 and 2030 due to population growth and economic growth, the share used per energy source stays stable. This is mainly due to the unavailability of energy markets and infrastructure, like natural gas pipelines in urban areas, and due to a lack of access to energy services and facilities, like access to natural gas stoves. In BAU1, technology and fuel use do not change over the coming decades due to the absence of electricity.

The BAU2 scenario is the optimistic baseline scenario in which a grid electrification of 50% takes place until 2030. The share of traditional biofuels declines, while the share of fossil fuels rises due to fossil-intense electricity consumed from the grid. The BAU2 scenario is a varied scenario compared to the extreme scenarios BAU1, RE2, DIESEL and GRID. Traditional biofuels, oil, coal and gas products, renewable energy and nuclear energy are consumed. Consumption levels remain below consumption levels in the universal electrification scenarios RE, GRID and DIESEL.

In DIESEL, universal electrification takes place through decentral diesel systems which can form mini-grids. This is an extreme scenario, because traditional biofuels, kerosene, renewable energy and coal are phased out until 2030 and are completely replaced by diesel. LPG is however partly used for cooking throughout 2030, as LPG is often used even among the top rural income groups (Reddy, 2003 Pachauri, 2007; ESMAP, 2003). Diesel systems are used for supplying electricity to satisfy the demand.

In GRID, universal electrification takes place through the central electricity grid. This is also an extreme scenario, because traditional biofuels, kerosene, renewable energy and coal are phased out until 2030 and are completely replaced by electricity from the grid which mainly comes from coal. Grid extensions are used for supplying electricity to satisfy the demand.

In RE1, universal electrification takes place through decentral renewable energy. Oil-based products like kerosene are almost completely phased out until 2030 and replaced by sustainable energy, coal is completely phased out and the share of traditional fuels declines rapidly after 2030. Rural electrification is achieved (1) by establishing decentral mini-grids based on renewable energy systems like solar energy technology, small-hydro power stations (SHP), wind turbines and biomass gasifiers and (2) by using off-grid self-sufficient devices like solar cookers and solar water heaters. The RE1 scenario depends less on mini-grids (20%) and more on self-sufficient devices (80%). Renewable energy-based off-grid devices are predominantly used, while electric devices are only minimally used. In the RE1 scenario, all end-use functions are used, but cooling and electronics are only marginally used, since both cooling and electronics usually require too much electricity to be run by renewable end-use devices and since not much electricity is used.

Also in RE2, electrification takes place through decentral renewable energy. This is an extreme scenario, as traditional biofuels, kerosene and coal are phased out until 2030 and completely replaced by renewable energy. Most oil-based products like kerosene are almost completely phased out until 2030 with the exception of LPG which is used for cooking throughout 2030. Rural electrification is achieved by establishing decentral mini-grids based on renewable energy systems like solar energy technology, small-hydro power stations (SHP), wind turbines and biomass gasifiers (100%). No renewable energy-based off-grid devices are used in the RE2 scenario, instead the same electric appliances and end-use functions as in the GRID and DIESEL scenarios are used. More electricity is therefore used in RE2 than in the RE1 scenario.

In RE, DIESEL and GRID, fuel switching and technology switching occur due to access to electricity. It has however been observed that complete fuel switching is rare both in poorer and wealthier households. Instead modern fuels and traditional fuels tend to be used parallel to each other (Bhattacharyya, 2006a; Chapter 2). Since electric devices are associated with high investment costs, fuel and technology switching is not expected to happen within a few years, but is likely to occur over a few decades as modelled here. Investment costs and installation time are also high, usually making electrification a lengthy process.

In addition to the main scenarios, six cost scenarios were developed: three oil price scenarios based on doubling oil prices between 2005 and 2030 and three grid distance scenarios based on different distances to the grid. The increasing oil price affects the costs of kerosene, diesel, LPG and other oil products. It also affects the costs of running combined cycle plants and oil turbines. The transmission costs of centralised grid-power and decentralised PV-power is about equal at a distance of about 10 km to the nearest grid, while the transmission costs double for grid-power at a distance of about 25 km (Chakrabarti and Chakrabarti, 2002; Dijkstra, 2007).

This paper models the implications of providing 100% of all currently un-electrified rural households with electricity in the RE, DIESEL and GRID scenarios. In the BAU1 scenario, electrification rates remain stable after taking into account population and household growth. In the BAU2 scenario, 50% of households are electrified by 2030.

Cost calculations for the demand-side are based on data from Reddy and Balachandra (2006), who provide data on costs per type of fuel and end-use per year and per household and on data from the IEA (2007; 2008). Cost calculations for the supply-side are based on data from the IEA [6; 31], the Central Electricity Authority (2008), the Ministry of Power (2008) and the Ministry of Non-conventional Energy Sources MNES (2008). It is assumed that operation and maintenance costs are low on the demand-side as devices are rather simple (e.g. wood chulhas, electric light bulbs etc.), while fuel costs are more substantial.

6.2.4 Data issues

The data used for this article come from three major sources: a) studies on Indian household energy use (Pachauri, 2004; Reddy et al., 2006; Devi et al., 2007; Bhattacharyya, 2006a; Bhattacharyya, 2006b), b) Indian data on the power sector like the Central Electricity Authority (2008), the Ministry of Power (2008) and the Ministry of Non-conventional Energy Sources MNES (2008), c) international organisations like the IEA/OECD (IEA, 2008; IEA, 2007; IEA, 2002a; IEA; 2002b), the United Nations (2006) and the World Bank (2008). Data on energy demand are derived from studies on India. Data on the energy supply come from the Indian authorities and international organisations. Emission factors for CO_2 and other greenhouse gas emissions are based on IPCC 2006 guidelines (IPCC, 2006).

6.3. Results

6.3.1 Primary energy use

Both the energy demand and supply for non-electrified households in rural India have been assessed in this study, thus targeting 380 million people or 71.7 million households without access to electricity in 2005. Equations 1-3 in section 2.1 indicate in detail how the energy demand is calculated based on the useful energy demand (Eq. 1), the useful energy demand in the future (Eq. 2, taking into account changes in population, income and sectoral activity) and the energy demand in time (Eq. 3, taking into account changes in fractions of technology use and efficiency of appliances). The energy supply takes into account the central and decentral energy supply. In terms of primary household energy use, significant changes take place in the different scenarios. Table 20 indicates for each scenario the share per fuel type of total primary energy use in 2005.

Share (%)	Trad. biomass		Oil		Coal & Gas		Solar		Other REs*		Nuclear	
Scenario	2005	2030	2005	2030	2005	2030	2005	2030	2005	2030	2005	2030
BAU1	73	73	19	19	1	1	7	7	0	0	0	0
BAU2	73	18	19	20	1	40	7	11	0	9	0	2
RE1	73	10	19	2	1	0	7	55	0	33	0	0
RE2	73	0	19	2	1	0	7	17	0	81	0	0
DIESEL	73	0	19	100	1	0	7	0	0	0	0	0
GRID	73	0	19	10	1	67	7	1	0	19	0	3

Table 20: Share of total primary energy demand per fuel type per main scenario in 2005 and 2030. * Other renewables include small and large-hydro power, biogas and wind energy.

The total primary energy use from rural non-electrified households was estimated in REM at about 1,651 PJ in 2005, which is about 23.4 GJ per household, compared to 22,497 PJ total primary energy supply for the whole Indian economy (IEA, 2008). In BAU1, the total primary energy use is likely to increase by about 48% to 2,441 PJ in 2030, which is about 31.5 GJ per household. In the BAU2 scenario, about 25% more primary energy use is expected to occur than in the BAU1 scenario in 2030, compared to about 340% more primary energy use in the GRID scenario. In the DIESEL scenario, about 460% more primary energy use is likely to occur than in the BAU1 scenario in 2030. In the RE2 scenario, primary energy use is expected to almost double in comparison to the BAU1 scenario in 2030. A small share of fossil fuels is used, namely for cooking with LPG. In the RE1 scenario, energy resources are however likely to be safeguarded as 35% less primary energy use could occur than in the BAU1 scenario in 2030 as can be seen in figure 32. The primary energy use in the RE1 scenario is 3% less than the starting level of 2005.

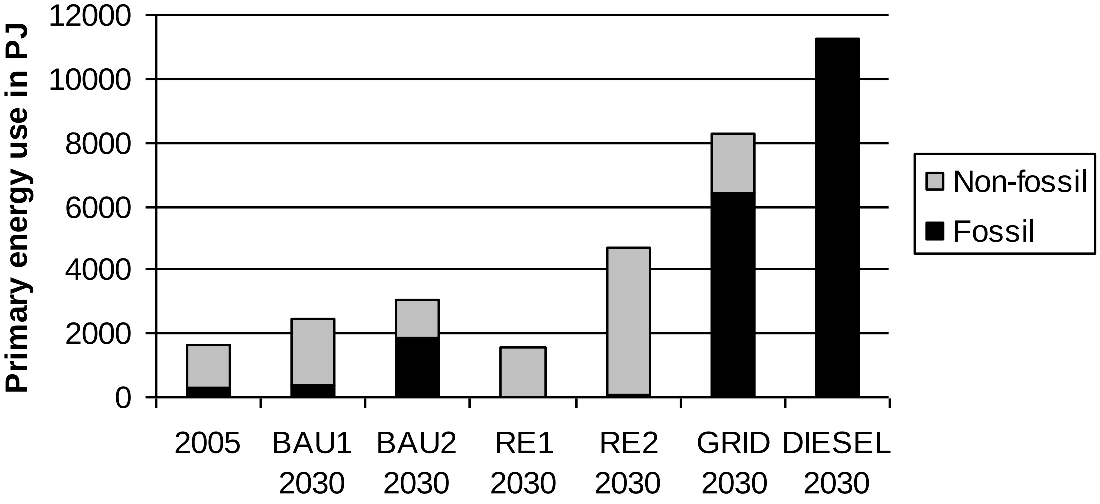

Figure 32: Primary energy use in PJ for the BAU, GRID, DIESEL and RE scenarios in 2030 in comparison to the baseline in 2005. Non-fossil energy sources include traditional biomass, modern renewable energy (solar, small and large hydro, wind, biogas) and nuclear energy. Fossil energy sources include oil, coal and natural gas products.

The increase in primary energy use is likely to be higher in the BAU2, RE2, GRID and DIESEL scenarios compared to the RE1 scenario, because electric devices could be introduced like electric lamps, electric stoves, electronic appliances, electric geysers, potentially even TVs, refrigerators, air-conditioning and computers. These devices require more energy than the renewable energy-based end-use devices employed in the RE1 scenario. The end-uses cooling and electronics remain marginally served by renewable energy-based end-use devices. Therefore less energy is likely to be used in the RE1 scenario compared to the other scenarios. The GRID and DIESEL scenarios also tend to have a higher energy use than the RE2 scenario, because conversion losses are considered. The energy use in the BAU2 scenario is only modestly higher than in BAU1, because only 50% of households will be electrified compared to 100% in the other electrification scenarios. The energy use in the BAU2 scenario is also more varied and less electricity-dominated.

The RE1 scenario serves the same end-use functions as the BAU1 scenario, but requires less primary energy, because of efficiency improvements. The renewable energy technologies predominantly used in the RE1 scenario, like solar cookers, are more efficient than the traditional fuel technologies used predominantly in BAU1, like wood stoves. Primary energy use increases in BAU1 due to population growth, GDP growth and sector activity as indicated in figure 31.

6.3.2 GHG emissions

CO_2 is the most important GHG contributing to climate change. In 2005, the CO_2 emissions from non-electrified households in rural India were very low, equalling about 25 Mtons CO_2, which is about 350 per household, compared to 1148 Mtons total CO_2 emissions for the whole Indian economy (IEA, 2008). CO_2 emissions came primarily from the use of kerosene for lighting, while the use of traditional biomass and renewable energy is considered as CO_2-neutral[13].

In the BAU1 scenario, the CO_2 emissions are expected to increase by 46% until 2030, to about 36 Mtons, which is about 500 kg per household. The CO_2 emissions could increase by 440% in the BAU2 scenario and 1480% in the GRID scenario compared to BAU1 in 2030. The CO_2 emissions could increase by 2300% in the DIESEL scenario compared to BAU1 in 2030. In the RE1 scenario, the CO_2 emissions are expected to decline sharply by 2030, saving 99% of total CO_2 emissions in 2030 compared to BAU1 and 99.9% compared to DIESEL and GRID. A similar development can be seen in the RE2 scenario: the CO_2 emissions are expected to decline saving 96% of total CO_2 emissions in 2030 compared to BAU1, DIESEL and GRID. See Figure 33.

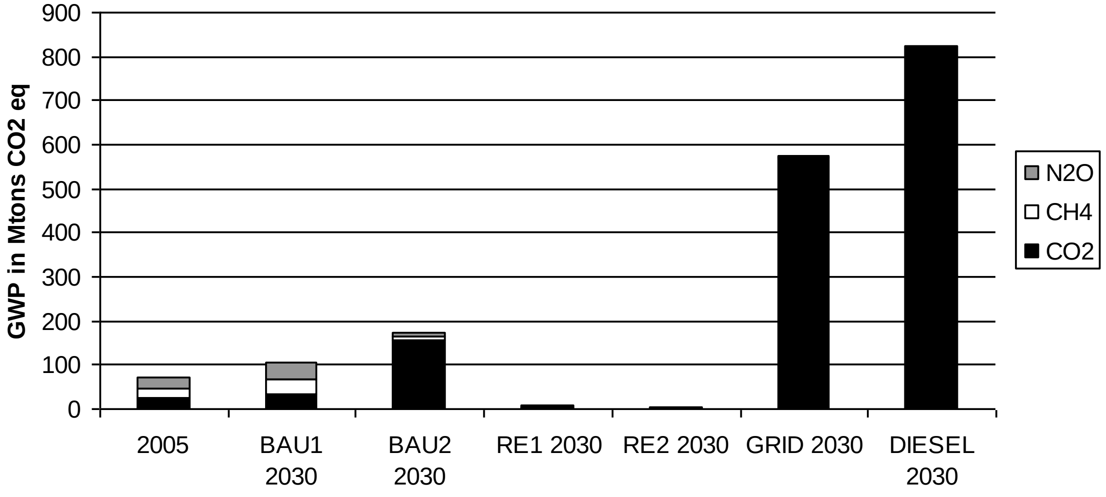

Figure 33: Global warming potential GWP in Mtons CO2 equivalents from the main GHG CO2, CH_4 and N_2O for the BAU, GRID, DIESEL and RE scenarios in 2030 in comparison to the baseline in 2005.

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[13] Traditional biofuels like fuel wood are considered CO_2-neutral. When combusted, they do emit CO_2, but this is compensated by CO_2 up-take during their lifetime due to biological activity.
Renewable energy technologies are close to zero-carbon technologies. Unlike fossil fuels, they do not emit any GHG emissions during energy generation. If the complete life cycle of renewable energy is taken into account, there will be GHG emissions from the production, transport and waste phases. These GHG emissions are substantially below the GHG emission of fossil fuels.

Concerning other emissions, the REM model also assesses the emissions of other important GHG like methane (CH_4) and nitrous oxide (N_2O). The global warming potential (GWP) was calculated for these emissions to assess their contribution to climate change.

Figure 33 also indicates that although other GHG emissions also play a role, the major global warming potential is due to CO_2. The GWP is 47% higher in the BAU1 scenario in 2030 than in 2005 and more than doubles in the BAU2 scenario. The GWP is 91% lower in the RE1 scenario and 94% lower in the RE2 scenario in 2030 compared to BAU1, but 540% higher in the GRID scenario and 770% higher in the DIESEL scenario in 2030 compared to BAU1.
Switching from solid traditional fuels to electricity can reduce CH_4 and N_2O emissions as figure 33 indicates. This development is likely to have positive effects on health (WHO, 2000).

6.3.3 Costs

In this research, we assess whole system costs, thus taking into account both fixed and variable costs. The total costs for providing household energy in rural non-electrified India in 2005 are estimated in REM at around 620 billion Indian Rupees (INR), which is about 8,650 INR per household[14]. In the BAU1 scenario, the costs could more than double to about 1,353 billion INR in 2030, which is about 18,870 INR per household and increase by about 225% in the BAU2 scenario. In the DIESEL scenario, the costs could rise by about 1730% compared to the BAU1 scenario. In the GRID scenario, the costs could rise by about 720% compared to the BAU1 scenario. In the RE2 scenario, costs are expected to increase by 1330%, while costs could increase by 60% in the RE1 scenario compared to the BAU1 scenario. See figure 34 for details. The costs for RE2 are much higher than for RE1, because more extensive mini-grids are needed to generate more electricity than in RE1. In RE1 many self-sufficient devices are used, like solar cookers and biogas stoves.

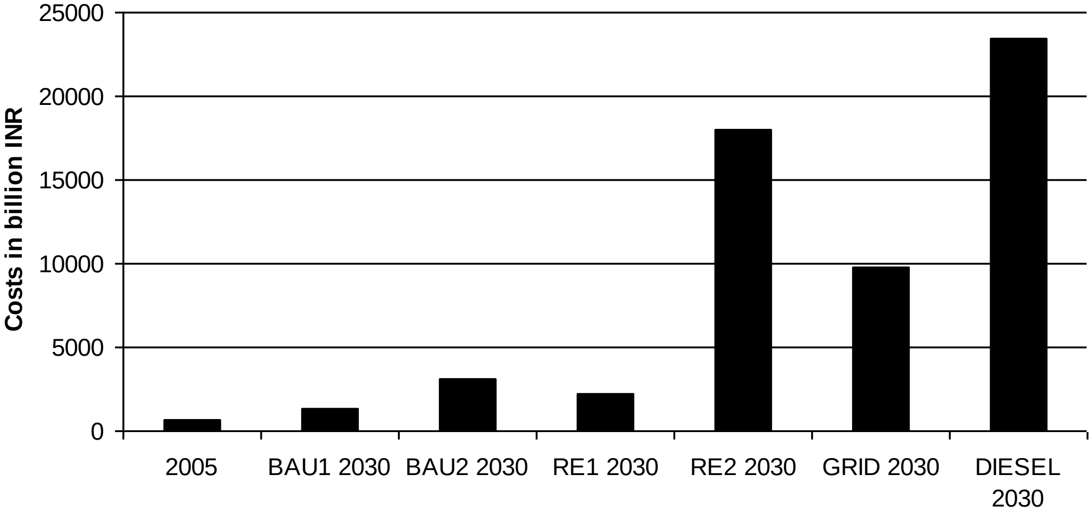

Figure 34: Whole system costs for the RE, BAU, DIESEL and GRID scenarios for 2005 to 2030.

Figure 35 shows the costs for different grid distance scenarios and the BAU1 and DIESEL scenarios. The system costs are linked to the grid distance: the longest grid distance is

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[14] About 14 billion US$ or about 37 US$ per capita or about 185 US$ per average household.

the most expensive option. Rural electrification with an average grid distance of 25 km (GRID_25km) might cost about 940% more than in BAU1. Rural electrification with an average grid distance of 15 km (GRID_15km) might cost about 830% more than in BAU1. Rural electrification with an average grid distance of 10 km (GRID_10km) might cost about 730% more than in BAU1. With no particular rises in oil prices, electrification with different grid distances might be between 185 to 240% lower than electrification with diesel systems and between 140 to 185% lower than electrification with renewable energy as in RE2. Electrification with predominantly renewable energy-based devices, as in RE1, would by far be the most cost-effective option.

Recent oil price shocks have shown that oil prices tend to be volatile. It could happen that oil prices might double between 2005 and 2030. The following scenarios take this into account. Figure 35 also shows the costs for the doubling oil price scenarios. The doubling oil price does not make a cost difference in the RE scenarios, because oil products are almost completely phased out until 2030. The DIESEL_200% scenario might cost about 3285% more than in BAU1. The GRID_200% scenario might cost about 840% more than in BAU1. The BAU1_200% scenario might cost about 45% more than in BAU1. In the oil price scenarios, it is assumed that the distance between households and the nearest grid is in average 10 km, thus the cheapest option. Greater distances to the grid are likely to result in higher costs as indicated in Figure 35.

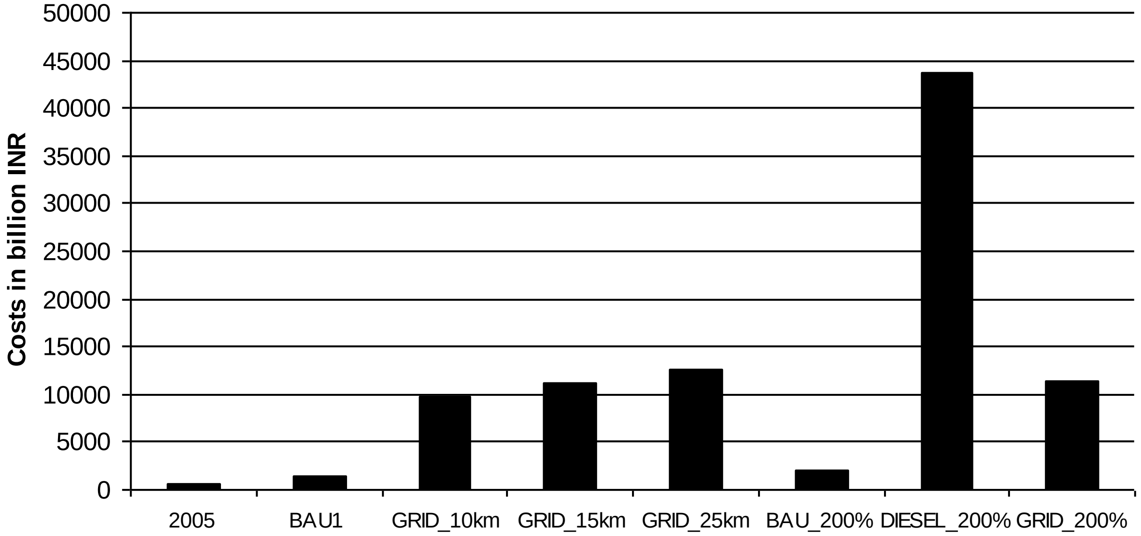

Figure 35: Whole system costs for the doubling oil price scenarios and the grid distance scenarios and the BAU1 scenario for 2005 to 2030.

It is assumed in all scenarios so far that the consumption levels will only increase by 1.6%/year between 2005 and 2030, because of the very limited financial situation of rural non-electrified households in India. For determining whether the costs of electrification will change with increasing consumption levels, additional scenarios were developed in which a doubling and tripling of consumption levels is assumed until 2030. It was found that with doubling and tripling consumption levels, the scenarios tend to have similar cost increases compared to BAU1 in 2030 as with an increase in consumption levels of only 1.6/year%, namely about 60% and 1355% for RE1 and RE2 respectively and 750% and 1765% for GRID and DIESEL respectively.

6.4. Discussion

6.4.1 Discussion of method and data

The results are dependent on three methodological inputs: the model, the scenarios and the data. The simulation model REM was used. REM is a reliable tool which has been calibrated and validated. Other models should produce very similar output using the same data. Since REM is a bottom-up tool, its technological detail is high, while economic processes are modelled in a rather aggregated manner.

Electrification scenarios were developed based on grid extensions, diesel systems and renewable energy systems. These scenarios determine the results. Other scenario assumptions will produce different results, such as mixed fuel scenarios or scenarios on hydrogen.

Concerning data, there are differences on electrification between Indian and international sources. In the Indian sources, electrification rates are assumed to be higher than in the international sources. One reason could be the recent changing of the definition ‘electrified’ in India as discussed earlier. Another reason could be a bias of the Indian authorities towards lower numbers of people living in energy poverty. In the case of electrification, it was therefore decided to opt for the most recent data from international organisations like the IEA (2007). Due to data restrictions, mean values of average rural households in India were used. There is full awareness that the Indian subcontinent is vast and diverse. Households are located in variously tempered regions which affects their energy demand (e.g. for cooling and heating). Households are located in various terrains and have various distances to the grid which affects costs. Some of these possibilities were assessed in these scenarios, but it is not possible to model all the possibilities due to restricted data. The effects of electrification on various income groups were not analysed, because REM is not an economic model and data on this issue are rare. The costs are calculated as whole system costs indicating how high the overall costs for fueling rural households with electricity could be. Since electricity is treated as a fuel in the end-use approach, disaggregating into further cost categories is currently not possible and would require further research. Further research into the costs of electrification may be better performed by economic equilibrium or optimisation models; however most of these models do not model electrification explicitly (Chapters 2 and 3).

6.4.2 Uncertainties

Various uncertainties exist in the system. Since all models are simplifications of the real world, all models have limitations. These two issues make it impossible to predict the future. These scenarios are therefore indicators of possible future developments, not predictions. There is full awareness of the complexities and uncertainties involved in the modelling. These uncertainties affect particularly energy prices, macro-economic growth of the economy and effects on rural populations, technological development and policies as elaborated in Table 21.

Uncertainty	Effect on scenario-making
Energy prices	Prices tend to be volatile, particularly oil and gas prices Coal/oil products are highly subsidised in India, making RE less competitive Access to energy markets and services is limited in rural India Most fuels consumed in rural India do not have an economic value and might never enter energy markets
Macro-economic growth	Macro-economic growth is often hard to forcast Rapid changes occur in macro-economic growth in India Effects of macro-economic growth on rural areas/low-income groups is disputed (Rozelle et al., 1998; Bigsten et al., 2003; Lofgren and Richards, 2003)
Technological development & innovation	Technological development can result in leap-frogging Leap-frogging can result in skipping over periods observed in historic data Difficulty in modelling the state of a technolgy at a certain time in the future
Policies	Drafting & implementation of policies depend on governments Policies tend to depend on legislation periods and/or national plans Public debates may spur political decisions unexpectedly

Table 21: Uncertainties of energy modelling for rural India.

6.4.3 Discussion of results

The pessimistic business-as-usual scenario BAU1 was developed as a purely hypothetical and theoretical elaboration to compare the effects of no electrification as an extreme baseline versus universal electrification. The optimistic BAU2 scenario was developed to compare a more realistic development of household energy use and electrification dynamics until 2030 versus other options of electrification. Other studies suggest that the pattern of rural household energy use will change in the future contrary to BAU1 (ESMAP, 2003; Pachauri, 2007), thus the BAU2 scenario is likely to be more realistic.

GRID, DIESEL and RE are extreme scenarios simulating the effects of energy delivered almost completely from the grid/diesel mini-grids/renewable energy-based mini-grids and achieving a universal electrification by 2030. However, for cooking purposes LPG is used also in 2030 based on past trends (ESMAP, 2003; Pachauri, 2007; Reddy, 2003). In reality, a mix of fuels is however more likely. We performed research on mixed-fuel scenarios and found that for GRID and DIESEL CO_2 emissions, energy resource use and costs are still likely to be much higher than for BAU1 and RE1, though somewhat lower than in the extreme scenarios. RE1 is a mixed fuel scenario in comparison to RE2. The BAU2 scenario is a mixed fuel scenario with households using a variety of different fuels and 50% of all households being electrified by the grid in 2030.

There is a rapid increase of primary energy use once access to electricity is provided (as can be seen in RE2, GRID and DIESEL), because of a high latent energy demand. The latent energy demand describes a situation in which the energy demand exceeds the supply. Due to the absence of electricity supply, the latent demand for electricity can not be meet. Instead, this demand is compensated by other less efficient forms of energy like fuel wood, dung and kerosene. Once electricity becomes available, the energy use can increase for satisfying the demand. This increase is also subject to consumer patterns and purchasing power. Concerning electrification with renewable energy, there are two options: using mainly electric devices like in RE2 or using a higher share of renewable energy-based devices and a modest share of electric devices like in RE1. One could argue that employing many renewable energy-based end-use devices will meet the basic needs of rural households, like basic lighting, cooking, water heating and heating, but that a similar high increase of primary energy use as in the GRID and DIESEL scenarios is unlikely, since most devices require too much energy. Such high energy use could only be obtained when electric devices are employed on a larger scale like in the RE2 scenario. The RE1 scenarios is therefore likely to sustain a modest quality of life at modest costs and very low emissions, while the RE2, GRID and DIESEL scenarios could sustain higher levels of consumption at higher costs and in the case of the GRID and DIESEL scenarios this would also result in higher emissions. The prerequisite for higher levels of electricity consumption is however that funding is available for purchasing and operating electric devices.

The Indian power sector suffers from high electricity load shedding and power deficits being as high as 14% for peak loads (IEA; 2007). Quality of supply is an important issue in India. To enable reliable electricity supply from renewable energy, storage needs to be in place. On rural household level, batteries could be suitable options and are sometimes already a part of renewable energy systems; however batteries tend to be expensive. Once hydrogen storage technology will be commercially available, this might also be an option, but might also be rather costly.

In 2005, the central electricity generated in India came predominantly from coal. In this research, it is assumed that the Indian electricity generation will also depend predominantly on fossil fuels in the future. If in the future the energy mix was to change, the CO_2 emissions would also change.

There might be a particularly high increase in CO_2 emissions and energy resource use in the DIESEL scenario, because oil is used predominantly. With still a very low electric consumption in 2030, rural households might emit between 530 and 825 Mtons CO_2 using grid or diesel systems. This is a high amount which could increase India´s CO_2 emissions significantly and which is likely to have effects on climate change. The emissions would be even higher, if higher consumption levels were attained in rural households. Renewable energy was found to have the lowest CO_2 emissions and thus the highest climate change mitigation potential, with levels substantially below baseline scenario. Other GHG emissions also decline significantly in the renewable energy scenarios. Emissions associated with local air pollution and indoor air pollution decrease rapidly when less traditional biofuels are used, thus potentially having a positive effect on health.

Concerning the RE scenario, physical requirements –like the availability of land, sun, water, wind- have to be considered. For solar energy, such as PV cells and solar end-use devices, a high solar potential is needed. Most of India receives about 300 days of sunlight per year (Varun, 2007) and the average PV potential in India is about 20 W/m^2 (Dijkstra, 2007). India also has a domestic solar industry. For SHP, running water from rivers or streams is needed. One SHP station may usually be enough to supply a rural Indian household or small village with basic electricity. For wind energy, one powerful modern turbine could supply up to 50,000 rural Indian households in windy areas, assuming that rural Indian households consume at least 10 times less energy than Western households (Dijkstra, 2007; Enercon, 2007). Wind turbines do not require much land, but require windy conditions. In India, especially the regions along the coastline are windy and India has a domestic wind industry. For biomass gasification, agricultural wastes need to be available. The land requirements for biomass were modelled in the RE scenarios and it was found that between 3.9 and 18.9 million hectares might be needed, thus 0.01 to 0.06 times the surface of India. It was concluded from this analysis, that land requirements for biomass will not be a restricting factor.

Concerning costs, electrification using mainly off-grid renewable energy-based end-use appliances could be the most cost-effective option, while decentral diesel systems could be the most expensive option. Other research also indicates that decentral renewable energy can be financially attractive compared to conventional central grid energy (Abe et al., 2007; Nouni et al., 2008; Sinha and Kandpal, 1991), also due to low load factors, long distribution lines and high associated transmission and distribution losses (Sinha and Kandpal, 1991). It was however found that electrification based mainly on running electric appliances with electricity generated from renewable energy-based mini-grids, could be more expensive than grid extensions. The IEA (2007) estimates that between 2006 and 2030, 956 billion US$ equalling 40,875 billion INR will be needed as investments for new power infrastructure alone. Our research takes into account not only the investment costs, but also the operation and maintenance costs (O&M) and the fuel costs. Investment costs are assumed to make up less than one third of the total costs. For the period 2005 to 2030, the whole system costs, averaged for all scenarios, are estimated in REM to be 137,590 billion INR for the complete rural households which are still to be electrified[15]. This takes into account the investment costs to be paid by investors, the O&M costs to be paid by utilities and the fuel costs to be paid both by utilities and by private households. Diesel systems are expected to have the highest costs, ca. 222,090 billion INR[16] and renewable energy systems using mainly renewable energy-based end-use devices are likely to have the lowest costs, ca. 32,700 billion INR[17] for the period 2005 to 2030.

Finally, this study is a simulation to assess how India's many poor could get electricity and what the effects could be. It has to be investigated more thoroughly whether the governmental universal electrification schemes by 2010 are realistic, but also whether universal electrification by 2030 is realistic as assessed in this study. As rural electrification is a lengthy process and the rural non-electrified population in India is large, this process could even take more time and be more complex.

6.4.4 Policy recommendations

Since renewable energy is considered climate- and resource-friendly, while diesel power and coal-based grid power are not, policy-makers should promote renewable energy for rural electrification, particularly in view of climate change mitigation and adaptation.

Off-grid renewable energy-based appliances like biogas cookers and solar devices (e.g. lamps, cookers, water heaters) are relatively cost-effective options of bringing modern forms of energy to rural households -also in combination with modest use of electric appliances driven by electricity from renewable energy-based mini-grids and could provide possibilities for increased development. Even though rural electrification with mainly renewable energy-based end-use devices is likely to be the most cost-effective option for rural electrification, high investments will be needed. The Indian government has already mobilised large investments for rural electrification (IEA; 2007). In addition to their conventional financing mechanisms, new innovative financing mechanisms could be developed. Industrialised countries should also be committed to supporting sustainable development. Historically, industrialised countries are considered responsible for a great share of global climate change. Also today, industrialised countries emit high CO_2 emissions due to their prosperous lifestyles. It should therefore be their responsibility to support climate change mitigation in developing countries like India.

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[15] About 3,200 billion US$ for the period 2005-2030 or about 8,420 US$ per person or about 44,600 US$ per household.

[16] About 5,160 billion US$ for the period 2005-2030 or about 13,580 US$ per person or about 71,970 US$ per household.

[17] About 760 billion US$ for the period 2005-2030 or about 2,000 US$ per person or about 10,600 US$ per household.

Development assistance may be a viable financing mechanism to achieve this. Another option could be to strengthen technology transfer, as under the Clean Development Mechanism, for enabling the use of modern electric equipment.

6.5. Conclusions

In this study, electrification options for rural non-electrified households in India were modelled. The impacts of four types of electrification were assessed: central grid-based using electric appliances, decentral diesel-based using electric appliances, decentral renewable energy-based using electric appliances and decentral renewable energy-based using mainly renewable energy-based appliances like solar cookers, biogas stoves and solar water heaters.

It was found that rural electrification with decentral renewable energy could reduce up to 99% of total CO_2 emissions from the residential sector compared to electrification with grid and decentral diesel systems and therefore has very high climate change mitigation potentials. A decentral renewable energy based-electrification could also reduce primary energy use compared to electrification with grid and diesel systems and thereby save energy resources. It was also found that rural electrification with mainly renewable energy-based appliances is likely to be the most cost-effective option for rural electrification, followed by grid extensions. Electrification based on decentral renewable energy, but mainly using electric appliances could however be more expensive than grid extensions. Electrification with decentral diesel systems could be particularly undesirable for climate, primary energy use and costs.

This research therefore suggests that decentral renewable energy is a viable option of climate change mitigation for rural India. Concerning costs, rural electrification based on decentral renewable energy end-use appliances is clearly the most viable option. Renewable energy sources are assumed to spur sustainable energy transitions in rural India. Policies may need to be adapted for subsidising access to electricity for the rural poor, to increase technology transfer between India and the industrialised countries and to increase sustainable rural electrification. Development assistance and Indian government efforts could be some of the key strategies to achieve rural electrification in India.

6.6 Acknowledgements

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7. Conclusions

7.1 Introduction

In the past, global energy use increased primarily due to rising consumption levels in industrialised countries. Today, industrialised countries, countries in transition and rapidly developing countries play a major role in increasing global energy demand. The Pareto principle acknowledges that the poorer 80% of the world's population only consume about 20% of global resources, including energy resources, while the richer minority consumes the vast majority of resources (Ehrlich and Holdren, 1971). This has changed in recent years as rapidly developing countries have become more and more developed and consume more and more energy.

Characterising the changing energy systems of rapidly developing countries is therefore a very timely necessity. Energy models can be used for this assessment to analyse past, present and future energy systems. Energy models may serve as planning tools, scenario analysis tools and policy assessment tools and can be important for an efficient planning of a country’s or region’s future energy setting.

Even though traditional biomass plays an important role in rural areas, rapidly developing countries like China and India rely in total primarily on fossil fuels, mainly on coal, for their energy supply and demand (IEA, 2008). This may increase their efforts to guarantee energy security, reduce pressure on energy resources and to ensure a higher environmental and climate quality. Renewable and clean energy sources are low- and near zero-carbon energy sources which are considered viable alternatives to fossil fuels and which can contribute to solving some of the addressed challenges. For designing pathways to solve these challenges, sustainable energy transitions can be modelled.

In this thesis, the characteristics of energy systems in developing countries are first elaborated and it is analysed if and how they are considered in energy models. Energy modelling approaches were then adapted through scenario-making for the use in developing countries. Sustainable energy transitions were then modelled for the Chinese power sector, Beijing’s economy and the non-electrified residential sector of rural India.

This chapter provides a summary of the findings presented in Chapters 2-6 and addresses the research questions by highlighting the key findings in Chapters 7.2-7.4. A reflection on modelling approaches is elaborated in Chapter 7.5. The overall conclusions and recommendations are elaborated in Chapter 7.6.

7.2 Energy systems of developing countries: characteristics and potential changes

The first research question is: How are energy systems of developing countries characterised, with a focus on developing Asia? What are the factors influencing these energy systems and how will they change in the process of development? How is this modelled in present-day energy models and how could the modelling be improved? Chapters 2 and 3 elaborate these issues. The results are presented below.

It is found that the energy systems of developing countries are characterised among others by a high dependence on traditional biofuels such as fuel wood and dung, particularly in rural areas, by low electrification rates and limited access to modern energy, by supply shortages, poor performance of the power sector and high differences in energy access, supply and demand between urban and rural areas. The prevalence of the informal economy and structural economic change also influence the energy setting. These characteristics can be observed in general in developing countries; however the extent to which these characteristics play a role varies between countries and regions. In developing Asia, there are high differences between the energy systems of various countries. China for example has a very high electrification rate while India has a much lower electrification rate. China also uses much more coal for the total primary energy supply than India, while India uses more combined renewables and waste, also more (traditional) biofuels.

Factors influencing the energy systems and triggering changes are among others population growth, economic growth, fuel switching, technological change/leapfrogging and policies. Energy systems of developing countries are likely to change over time when these countries will become wealthier and gain access to modern technology. It has to be noted that this development is not likely to be equally distributed within a country, but that rural areas are likely to lag behind the developments in urban areas even within a few decades. Rural energy poverty and energy-related social exclusion are thus prevailing issues that have to be considered for energy planning. In general, it is assumed that with increasing development of a country the use of modern energy is likely to increase while dependency on traditional fuels is likely to decrease. It has to be considered though that fuel switching and the concept of the Energy Ladder have not been observed fully in reality. Some uncertainty about these concepts remains. With increasing development of a country, the power sector is also assumed to perform better due to access to modern technologies with higher efficiencies, less supply shortages, better planning and more adequate investments and subsidies. The extent of this development is specific for each country and can not be generalised, because non-energy related factors such as economic and political stability do also play a major role in the changes of energy systems. There is also a scientific debate on how the economic well-being of countries affects the economic well-being of people, particularly in rural areas.

This thesis also elaborates in Chapters 2 and 3 that many present-day energy models tend to neglect important characteristics of the energy systems of developing countries. Characteristics which are seldom explicitly modelled are for example among others the high prevalence of fuel wood, low access to electricity and the poor performance of the power sector and the overall economy. Non-development-adapted energy models may work very well for industrialised countries, but tend to lack important features for developing countries. However these models are used for a world-wide coverage, thus including developing countries. Some of these models are used for the IPCC/SRES scenarios to support international climate policy negotiations. It needs to be noted that a poor characterisation of the energy systems of developing countries might lead to a poor modelling of the future energy and climate settings, which might have implications for policy-making. As a consequence, energy models need to be improved. They need to be adapted to specifically suit the energy systems of developing countries, thus incorporating explicitly the characteristics of developing countries´ energy systems. Adapting energy models for developing countries was therefore done for this thesis. Three approaches to adapt existing energy models to the energy settings in developing countries are presented in Chapters 4 to 6. Chapters 7.3 to 7.5 present the results, with special focus on energy modelling in Chapter 7.5.

7.3 Energy transitions in rapidly developing countries

The second research question is: How could sustainable energy transitions take place in specific economic sectors of China and India? In Chapters 4-6 energy modelling approaches are adapted for exploring how sustainable energy transitions could take place in specific economic sectors of China and India. The results are presented below.

7.3.1 The Chinese power sector

Chapter 4 elaborates how the installation of renewable and clean energy such as small and large-hydro power, modern biomass, solar energy, wind energy, tidal energy, and nuclear power could lead to energy transitions in the Chinese electricity supply sector. It is suggested that sustainable electricity is likely to be a viable mitigation option for climate change. It is also indicated that the electricity system is expected to stay stable in the future when implementing a high share of renewable energy technology. Installing a high share of renewable energy technology in the Chinese power sector could though be a costly option.

7.3.2 Beijing's economy

Chapter 5 elaborates how energy transitions to renewable energy could take place in the energy demand of Beijing based on governmental targets. End-use technologies such as solar water heaters, PV cells, biogas stoves, geothermal heating, biofuel-driven vehicles etc. could replace fossil fuel technologies in all sectors of Beijing's economy. This is likely to have positive effects on climate change mitigation, while only a moderate cost increase is expected. The use of biofuels must however be carefully assessed considering the competition for land and water between biofuel and food production. To avoid food crisis, there must be enough land for supplying the local population with food.

7.3.3 Rural residential India

Chapter 6 suggests how energy transitions in non-electrified rural households in India could take place. It is found that transitions to decentral renewable energy could be viable options of electrification and climate change mitigation in rural India. Decentral renewable energy could be used for the energy supply and demand. Solar energy, biogas from agricultural residues, small-hydro power and wind turbines can provide sustainable electricity for driving electric devices. Renewable energy-based devices can be used in addition for cooking, (water) heating, lighting and some appliances (using a.o. solar cookers, biogas stoves, solar water heaters). Decentral renewable energy could be an effective way to electrify rural Indian households and to keep primary energy use and greenhouse gas emissions at low levels.

7.4 Effects of sustainable energy transitions in rapidly developing countries

The third research question is: What could be the effects of these energy transitions on emissions, resource use, the electricity system, costs and social issues (e.g. access to electricity, effects on the urban and rural population) for China and India? What policy recommendations would be useful? Chapters 4 to 6 elaborate these issues. The results are presented below.

7.4.1 Effects on the Chinese power sector

High increases in energy supply and CO_2 emissions are expected in China's coal-based power sector until 2030. Energy transitions to renewable energy might save between 17-57% of CO_2 emissions compared to the baseline scenario in 2030, depending on type and share of renewable energy technology installed. 20% renewable energy among the total installed capacity might reduce CO_2 emissions by up to 27%, while 30% renewable energy installed might save up to 57% CO_2 emissions compared to the baseline scenario in 2030. A combination of biogas and small-hydro power plants is likely to achieve the highest CO_2 emissions savings, compared to mixed renewables and a combination of PV and wind power. 20% nuclear energy among the total installed capacity could reduce CO_2 emissions by up to 38% compared to the baseline scenario in 2030. It is suggested that renewable and low-carbon technologies can have high climate change mitigation potentials. NO_x and SO_2 are also likely to decrease due to sustainable energy transitions with positive impacts on local air pollution. Concerning resource use, it is found that high amounts of coal waste and radioactive waste could be avoided due to sustainable energy transitions, while coal resources and uranium resources would be safeguarded. It is also found that the overall performance of the electricity system is likely to stay stable in the future even when a higher share of renewable energy will be installed. Costs might increase due to sustainable energy transitions by between 20-180% in the Chinese power sector compared to the baseline scenario in 2030. It is found that the higher the share of renewable or nuclear energy, the higher the costs.

As policy recommendations, there are several possibilities and several cost options for transitions to a more sustainable power sector in China. China could be face with two main options: choosing for high climate change mitigation and high costs or choosing for moderate climate change mitigation and moderate costs. If high climate change mitigation options are chosen, costs are expected to increase significantly. Development assistance is likely to be needed to cover these costs. Even though China itself will have to choose which climate policy it will follow, it could be of global importance to assist the world's most populous country in achieving sustainable development. Industrialised countries might need to show responsibility to contribute to climate change mitigation in China considering their financial means, technological advancement and their own current and historic contributions to climate change.

7.4.2 Effects on Beijing's economy

Similar to national developments, high increases in energy demand and CO_2 emissions are expected in Beijing's coal-based economy until 2020. The government's targets to implement 6% of renewable energy among the total energy demand in 2020 could save 23% of total GHG emissions in 2020. The fossil resource use saving is expected to be 16% in the renewable energy scenario compared to the baseline scenario in 2020. Local air pollution, which is a serious problem in Beijing, might also be reduced due to renewable energy transitions in Beijing. It is likely that renewable energy transitions could reduce SO_2 emissions by 9%, NO_x by 5%, NO by 20% and CO emissions by 2% compared to the baseline scenario in 2020. This conclusion is derived from the energy modelling for Beijing, but is not included in the original paper in chapter 5, because the paper is only intended to focus on climate change mitigation. The highest GHG emission reductions are likely to occur in the industrial and construction sector, for heating, transport and in the commercial sector. The highest fossil resource use saving is also likely to be achieved in the industrial and construction sector. This is also, because the energy intensity in the industrial and construction sectors will decline faster than in other sectors due to additional measures such as introducing a higher level of cleaner fuels to replace coal. Costs are assumed to increase by about 10% due to renewable energy transitions compared to the baseline scenario in 2020. Transitions to renewable energy might be most cost-effective in households, agriculture, commerce and heating. Even in 2020, it is expected that there will be significant differences between urban and rural areas in the municipality of Beijing in terms of income, life style and energy consumption. For the future, it is therefore important to promote sustainable and equitable energy growth both in rural and urban areas. In urban areas, it is particularly important to ensure that both poorer and wealthier citizens gain equal access to sustainable energy to avoid unequal consumption and distribution of energy.

As policy recommendations, it is suggested to increase the share of renewable energy, particularly in the industrial, construction and transport sector where most effects can be obtained, and in the household and commercial sector where renewable energy technology is relatively easy and cost-effective to install. For Beijing's transport sector, clean and renewable energy may only be one part of solving its heavy traffic problems. Another part is to re-designing the transport infrastructure to reduce dependency on roads and private cars and to encourage the local population to use public transport. Energy saving should also be promoted. Governmental programs, financial incentives and/or environmental rewarding and taxation schemes should be in place to achieve sustainable energy transitions.

7.4.3 Effects on rural residential India

Energy use in rural non-electrified households in India is still very low and inefficient. Traditional biofuels, like fuel wood, dung and agricultural residues, are predominantly used due to the absence of access to more efficient and cleaner energy, infrastructure and energy markets. Electrifying India's rural households could be achieved through three major strategies: grid extensions, decentral diesel systems and decentral renewable energy. If grid extensions and diesel systems were to be used for rural electrification, CO_2 emissions and resource use could increase significantly, exceeding the baseline scenario several-fold. A decentral renewable energy-based electrification might save about 99% of total CO_2 emissions and up to 35% of total primary energy use in 2030 compared to the baseline scenario. Rural electrification with decentral diesel systems is likely to be the most expensive option, due to high oil dependence. Rural electrification with decentral renewable energy tends to be the most cost-effective option when renewable energy-based devices are predominantly used, but turns out to be more costly than grid extensions when electric devices are predominantly used. Introducing electricity from decentral renewable energy may also have positive effects on social issues like providing access to electricity and improving the living conditions of the rural population. It might also be a way of alleviating poverty and of reducing urban-rural differences.

Since renewable energy is considered climate- and resource-friendly, while diesel power and coal-based grid power are not, policy-makers are advised to promote decentral renewable energy for rural electrification. Policies may need to be adapted for financing access to electricity for the rural poor, to increase technology transfer between India and the industrialised countries and to increase sustainable rural electrification. Development assistance and Indian government efforts are likely to be some of the key strategies to achieve rural electrification in India.

7.5 The role of energy modelling for developing countries

Most present-day energy models are developed in industrialised countries and are based on the experience of energy systems in industrialised countries. Although these energy models work usually very well for industrialised countries, it is mentioned in chapters 2 and 3 that many energy models tend to neglect some of the main characteristics of developing countries' energy systems. Their results might therefore be imprecise or in the worst case might even be misleading, which might in some cases affect policy recommendations. This should be addressed in a time of global climate change, when negotiations about emission caps for developing countries are on the global agenda.

Hence, there is a need to adapt energy modelling approaches to make them more suitable for the changing energy setting of developing countries, particularly for rapidly developing countries like China and India. This is done for this thesis as elaborated in Chapters 4 to 6. The thesis presents three case studies for China and India in which existing energy modelling approaches are adapted to suit the rapidly changing energy systems of these countries. Main characteristics of developing countries’ energy systems, like the carbon-based and low efficient power sector (Chapter 4), electrification (Chapters 4-6, especially Chapter 6), the prevailent use of traditional biofuels (Chapters 5-6, especially Chapter 6) and the urban-rural divide (Chapters 4-6, especially Chapters 5 and 6) are modelled specifically for China and India.

The PowerPlan and REM models used in this research are adapted specifically for the use in developing countries with focus on the Chinese power sector and rural non-electrified India. The LEAP model is used specifically for modelling the energy setting Beijing. These models take into account the level of detail needed to model the energy systems of these selected developing regions. The modelling approach used in this thesis applies smaller geographic scales, uses detailed disaggregated datasets, includes characteristics of developing countries´ energy systems (e.g. traditional biofuels, the urban-rural divide etc.), uses modelling techniques which take into account the specific energy settings in developing countries (e.g. modelling electrification/the performance of the power sector explicitly) and uses specific individual assumptions for these regions. These adapted models are therefore likely to allow a more detailed approach for specific developing regions than many generalised global energy models or models which have not been adapted for developing countries. This could lead to improved results.

The three different models in this thesis were chosen for being adapted individually based on individual research questions and scales. Scales are important, as they determine the precision of the model. Global energy models, like those used for the IPCC/SRES scenarios, tend to use large scales by clustering geographic regions in a rather aggregated and generalised manner, grouping continents and large regions such as Asia or (Formerly) Centrally Planned Asia into one cluster without further disaggregation. This may result in lack of representing regional differences. However, the energy systems within these geographic regions often differ substantially. The energy system of China, with an electrification rate of about 99%, differs substantially from the energy system of Laos, which is also a Formerly Centrally Planned Asian country, but which has an electrification rate of only about 11% (UNDP, 2008). Large differences exist within these countries as well, for example in urban and rural areas. A disaggregated tailor-made modelling approach, as used in this thesis for the PowerPlan, LEAP and REM models, could therefore be preferable for modelling energy transitions in developing countries compared to an aggregated “one fits all” approach. The “one-fits all” approach showed to be very useful and adequate for OECD countries: countries which have about the same level of development and mostly follow market economic principles. Such an approach could however be problematic for developing countries, because these countries are very varied compared to each other and within each other, have different levels of development and different types of economies. Also, such an aggregated “one fits all” approach may work well for analysing countries or continents, but might be problematic for smaller scales at local level. For modelling energy transitions in developing countries, a detailed tailor-made approach is therefore likely to be preferable due to smaller geographical scales, applicability for each country´s/region´s specific settings, detailed representation of important development issues such as the urban-rural divide, electrification, traditional fuels and specific individual assumptions for each country/region. This tailor-made approach was followed in this thesis (see Chapters 4 to 6). These tailor-made models which are adapted for developing countries could therefore be potentially more useful than other models for serving as tools for international climate negotiations.

Concerning the case study for rural India, it has to be noted that the Regional Energy Model REM was used, which is not evaluated in Chapter 3, because it does not fulfill the selection criteria (b): “the model is widely used by institutions in developing regions or widely used by institutions cooperating with developing regions” (Chapter 3). REM is however used for rural India, because of its flexibility, which makes it possible to analyse the energy demand and supply of a non-electrified developing region.

It was also noted during the modelling that each type of energy model brings along a number of advantages and disadvantages. The bottom-up simulation models used in this thesis have the advantage that they model very well technological processes, like electrification or the performance of the power sector. It though becomes apparent that they tend to lack the depth and disaggregation level which is often needed for modelling economic processes like electricity prices or energy investment costs. Top-down economic equilibrium models or optimisation models are preferable for cost-related energy research, but they often lack the technological perspective needed to model technological processes. Using hybrid models for these integrated tasks might be preferable; however they tend to be extensive so that substantially more time and human resources are needed for performing similar research. Finally, not every model can be used for every task; the usefulness of the result also depends on the purpose of the model, the research question and the scale.

7.6 Overall conclusion and recommendations

This thesis aims a) at elaborating the differences between energy systems in (rapidly) developing countries and in industrialised countries, b) at adapting energy modelling approaches to increase their suitability for rapidly developing countries and c) at developing scenarios using these adapted models to simulate sustainable energy transitions and their effects for rapidly developing countries. The focus of this thesis is on China and India.

In Chapters 2 and 3, the various characteristics of the energy setting in developing countries are elaborated and it is analysed how energy models could respond to these challenges. Three models are adapted to suit the energy setting in China and India to ensure an improved representation of their energy future and to model the possibilities and implications of energy transitions to renewable and clean energy (Chapters 4-6). It is assumed that these adapted models are likely to be more suited for modelling energy systems of developing countries than other energy models which have not been adapted for developing countries.

It is found that low-carbon energy transitions could be possible in China and in India for various sectors. It is found that CO_2 emissions could be substantially reduced due to sustainable energy transitions. This study shows that natural resources could be safeguarded and fossil energy use could be reduced when renewable energy is employed. The future electricity system is likely to stay stable even if a higher share of renewable energy will be installed. Sustainable energy transitions might reduce social disparities such as urban-rural differences. Concerning costs, the research outcomes suggest a rather mixed picture: In the Chinese power sector, energy transitions to sustainable energy tend to be (much) more expensive than continued reliance on fossil fuels. In Beijing’s economy, energy transitions to sustainable energy tends to increase costs only moderately, with households, agriculture, commerce and heating enabling the most cost-effective energy transitions. In the non-electrified residential sector of rural India, rural electrification with decentral renewable energy could be several times cheaper than electrification by other energy sources, but only when off-grid renewable energy-based devices are predominantly used like solar cookers, biogas stoves and solar water heaters. When electricity from renewable energy-based mini-grids predominantly drives electric devices, like electric stoves, electric geysers or other electronics, costs tend to increase to a greater extent than for grid extensions. This may lead to the conclusion that for low-energy requiring processes and small-scale processes, sustainable energy could be more cost-effective than other energy sources, while for high-energy requiring processes and large-scale processes, sustainable energy tends to be more costly than other energy sources. Costs for fossil fuels would however become more expensive, if subsidies were reduced, in return making sustainable energy more competitive. High oil price increases also showed recently that fossil fuel prices tend to be volatile and will probably increase more and more, potentially making sustainable low-carbon-based energy more attractive in the future. It also has to be considered that the system is highly complex, that high uncertainties exist (as elaborated in the uncertainty chapters in Chapter 4-6) and that regional differences prevail, with India differing from China and rural areas differing from urban areas.

As an overall conclusion, this thesis shows a) that energy modelling needs to take into account the growing importance of rapidly developing countries. This can be done by adapting energy modelling approaches to suit the energy systems of developing countries and by using a specific tailor-made approach for each specific developing region, like done in this thesis. This thesis also shows b) that renewable and clean energy could be viable options of climate change mitigation for rapidly developing countries like China and India and c) that these sustainable energy transitions to a low-carbon economy could also have other positive effects on the environment and society. Hence, sustainable energy transitions are likely to have positive effects in rapidly developing countries. To ensure an adequate planning of these energy transitions adequate energy modelling is needed which is suited for developing countries.

To mitigate and to adapt to global climate change, several measures should be implemented besides the introduction of sustainable energy, namely energy saving and energy efficiency improvements. To achieve low-carbon transitions, rapidly developing countries should implement stringent policies and might require the support from industrialised countries. Development assistance and technology transfer might be suitable options of support, though more research is needed in this area. More research is also needed for assessing the possibilities of increased participation of developing countries in international climate policy and the implications of having binding targets for developing countries. The main research recommendation is to adapt more energy models for the use in developing countries.

Since climate change is a global problem, it is the responsibility of both developing and industrialised countries to cooperate to achieve a sustainable energy future. Such cooperation is crucial for the success of international climate policy negotiations. Energy models which are adapted for the needs of developing countries might increase the success of international climate policy negotiations, as they can be useful tools to support the energy and emission planning of developing countries.

List of Abbreviations

CCGT	Combined-Cycle-Gas-Turbine
CDM	Clean Development Mechanism
CER	Certified Emission Reduction
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
EKC	Environmental Kuznets Curve
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GNI	Gross National Income
GNP	Gross National Product
IPCC	Intergovernmental Panel on Climate Change
GT peak	peak Gas Turbines
LED	Light Emitting Diode
LDC	Load Duration Curve
LOLP	Loss-Of-Load-Probability
LPG	Liquid Petroleum Gas
MER	Market Exchange Rates
NG	Natural Gas
NIMBY	Not In My BackYard
O&M	Operation & Maintenance
PPP	Purchasing Power Parity
PV	PhotoVoltaic
R&D	Research & Development
SHP	Small Hydro Power
SMD	Simultaneous Maximum Demand
SRES	Special Report on Emission Scenarios
TED	Technology and Environmental Database
UED	Useful Energy Demand
UNFCC	United Nations Framework Convention on Climate Change
WDI	World Development Indicators

English summary:

Sustainable energy for developing countries

- Modelling transitions to renewable and clean energy in rapidly developing countries

1. Background

1.1. Energy and its impacts

Energy is vital. Energy is needed for basic human needs: cooking, heating, lighting, boiling water and for other household-based activities. Energy is also required to sustain and expand economic processes like agriculture, electricity production, industries, services and transport. It is commonly suggested that access to energy is closely linked with development and economic well-being.

Today about 80% of the world's primary energy comes from polluting fossil fuels such as coal, oil and natural gas. However, fossil energy resources are not endlessly abundant, but can be depleted. Energy has thus become a major geo-political and socio-economic issue. Recent oil price shocks have shown the world's dependency on a scarce fuel. Fossil energy use is also associated with a number of negative environmental effects like air pollution and global climate change. During the combustion of fossil fuels large amounts of carbon dioxide (CO_2) and other so-called greenhouse gases (GHG) are emitted, which are reported to contribute to global climate change. Global climate change, sometimes also called global warming, is a phenomenon which is indicated to have multiple impacts. The United Nations' Intergovernmental Panel on Climate Change (IPCC) reports that some of the observed impacts are an increase in global surface temperatures, increases in heavy precipitation events, higher frequency of droughts, changes in the large-scale atmospheric circulation and increases in tropical cyclone activity. This could mean increased water stress, flood risks, drought risks, food insecurity, reduction of living standards and health risks. Developing countries are likely to be most vulnerable to climate change, due to their limited financial and structural means which could hinder quick adaptation and mitigation.

1.2. Energy transitions and the role of renewable and clean energy

These energy-climate implications put pressure on all countries around the world. The pressure on developing countries may be even greater, because they are currently in the process of development which requires substantial energy resources for achieving higher living standards. High population levels and high fossil fuel reliance increase this pressure even more. The share of low-polluting renewable and clean energy should therefore be increased to meet energy security, to reduce pressure on fossil energy resources, to mitigate climate change and to ensure a higher environmental quality. Renewable and clean energy are likely to spur sustainable energy transitions.

Energy transitions can be defined as shifts from a country's economic activities based on fossil fuels to an economy partially based on renewable and low-polluting clean energy sources. This means that substitutions take place from fossil fuel-based technologies to clean energy technologies. Such transitions can take place in every sector of a country's or a region's economy. For example, electricity can be generated from wind instead of being generated from coal. Sustainable energy transitions could open up new possibilities for developing countries to achieve higher development and higher living standards while at the same time safeguarding energy resources, the environment and human health due to lower pollution levels.

1.3. Energy modelling

Energy models can be important tools for analysing and planning energy transitions. Computer models are simplifications of the real world and can also be useful for energy planning. Complex real-life problems can be observed and analysed by computer models. The future can be simulated with these models to assist the energy planning of years and decades to come. Since most present-day energy models are developed by and for industrialised countries, they often tend to be biased towards the energy systems of these countries and they may thereby overlook that the situation is very different in developing countries. Developing countries usually differ from industrialised countries in terms of energy consumption, production and distribution, energy infrastructure and energy economy. For example, in many developing countries a large part of the rural population uses fuel wood for cooking meals and heating homes. In industrialised countries, the majority of the population uses electricity or natural gas for cooking and heating. These differences in energy systems between developing countries and industrialised countries result in the need to adapt energy modelling approaches for the use in developing countries.

2. Objective of the thesis and research approach

The main objective of this thesis is first to adapt energy models for the use in developing countries and second to model sustainable energy transitions and their effects in rapidly developing countries like China and India.

The focus of this thesis is three-fold: a) to elaborate the differences between energy systems in (rapidly) developing countries and in industrialised countries, b) to adapt energy modelling approaches to improve their suitability for rapidly developing countries and c) to develop scenarios using these adapted models to simulate sustainable energy transitions for rapidly developing countries and to assess the implications of these energy transitions. The core of this research is to develop scenarios for sustainable energy transitions for China and India. China and India are chosen, because they are currently considered the most rapidly developing countries, and thereby also the most energy-consuming, most climate-relevant and most economically-growing developing countries. Their development is expected to have global impacts. Implementing renewable and clean energy sources in these countries is likely to mitigate climate change. Three case studies are chosen for China and India which assess different levels and scales of energy transitions: national/regional, urban/rural and supply/demand. These three case studies are corresponding with current energy policy in China and India. A case study for Beijing was developed based on the local government’s renewable energy target for 2020 and was performed in cooperation with Chinese researchers.

The sustainable energy technologies which are assessed in these case studies are renewable energy sources coming from the sun, wind, water, biomass and so-called “clean” energy technologies which emit less greenhouse gases than conventional coal and oil, such as nuclear energy, natural gas and more efficient fossil fuel technology. It has to be noted that the term “clean” energy actually describes less polluting energy, keeping in mind that there is no completely clean energy. Sustainable energy scenarios are compared to business-as-usual scenarios or baseline scenarios in which unsustainable fossil fuel technologies prevail as it is the case today in China and India. Energy models are specifically adapted in this thesis for the use in developing countries with a focus on the Chinese power sector, Beijing's economy and rural non-electrified India. These models take into account important characteristics and the level of detail needed to model the energy systems of the developing regions selected.

3. Findings

3.1 Energy systems of developing countries: characteristics and modelling approaches

In chapters 2 and 3, the various characteristics of the energy setting in developing countries are elaborated and it is analysed how energy models address these.

The energy systems of developing countries tend to differ from those of industrialised countries. It is found that the energy systems of developing countries are usually characterised among others by a high dependence on traditional biofuels such as fuel wood and dung, by low electrification rates and limited access to modern energy sources, by supply shortages, poor performance of the power sector and high differences in energy access, supply and demand between urban and rural areas. Some economic issues, like the prevalence of the so-called unofficial or informal (thus non-taxed) economy and changes in the structure of the economy, can also influence the energy setting. These characteristics can generally be observed in developing countries, but the extent to which these characteristics play a role varies between countries and regions. Factors which influence the energy systems and trigger changes are among others population growth, economic growth, fuel switching, technological change and policies. Concepts of energy and development are elaborated in Chapter 2, like the Energy Ladder (which relates increasing income to the use of cleaner and more efficient energy) and the Environmental Kuznets Curve (which relates income levels to pollution levels). These concepts can be observed in the results of the IPCC/Special Report on Emission Scenarios (SRES) models, but improvements can be made in modelling the issues that underlie these concepts.

Most present-day energy models were built by and for industrialised countries and are based on the experience of energy systems in these countries. Although these energy models work usually very well for industrialised countries, it is found that many of them tend to oversee the different energy setting in developing countries. Their results might therefore be imprecise or at worst even misleading, which might in some cases affect policy recommendations. This should be addressed in a time of global climate change, when negotiations about potential emission caps for developing countries are on the global agenda. Hence, there is a need to adapt energy modelling approaches to make them more suitable for the changing energy systems of developing countries, particularly for rapidly developing countries like China and India. Chapter 3 concludes that particularly those characteristics of developing countries' energy systems need to be modelled for which reliable data are available and the system dynamics are sufficiently understood. As a result of the energy model comparison in Chapter 3, which tests the suitability of models for developing countries, it is suggested that for an improved use in developing countries adapted energy models should preferably follow a bottom-up or hybrid approach and be scenario-simulation models or toolbox models. In Chapters 4 to 6, three existing energy models were adapted for the use in developing countries according to this approach.

3.2 Energy transitions in rapidly developing countries

In chapters 4 to 6, three case studies for China and India are presented in which existing energy modelling approaches are adapted to suit the rapidly changing energy systems of these countries. Some of the main characteristics of developing countries' energy systems are modelled, like the fossil fuel-based and low efficient power sector, electrification, the prevailing use of traditional biofuels and the urban-rural divide.

The energy models used for this thesis are specifically adapted for China and India. With these models, it is found that sustainable energy transitions could be possible in China and in India for various sectors.

For the Chinese power sector, energy transitions to renewable energy might save between 17-57% of total CO_2 emissions from electricity generation compared to the business-as-usual scenario in 2030, depending on type and share of renewable energy technology installed. 20% renewable energy among the total installed capacity might reduce total CO_2 emissions from electricity generation by up to 27%, while 30% renewable energy installed might save up to 57% CO_2 emissions compared to the business-as-usual scenario in 2030. A combination of biogas and small-hydro power plants is likely to achieve the highest CO_2 emission savings, compared to mixed renewables and a combination of PV and wind power. 20% nuclear energy among the total installed capacity could reduce total CO_2 emissions from electricity generation by up to 38% compared to the business-as-usual scenario in 2030. The electricity system is likely to stay stable in the future also when higher shares of low-carbon energy will be implemented. Fossil resources are expected to be safeguarded, while costs are likely to rise (Chapter 4).

Possible energy transitions are elaborated for the economic sectors of Beijing, including agriculture, industry, residences, services and transport. The Government of Beijing's targets to implement 6% of renewable energy among the total energy demand in 2020 could save 23% of total GHG emissions in 2020. The fossil resource use saving is expected to be 16% in the renewable energy scenario compared to the business-as-usual scenario in 2020. Local air pollution, which is a serious problem in Beijing, is likely to decline modestly due to renewable energy transitions in Beijing. Costs are assumed to increase by about 10% due to renewable energy transitions compared to the business-as-usual scenario in 2020. Even in 2020, it is expected that there will be significant differences between urban and rural areas in the municipality of Beijing in terms of income, life style and energy consumption (Chapter 5).

Electrifying India's rural households could be achieved by three major strategies: grid extensions, decentral diesel systems and decentral renewable energy systems. If grid extensions and diesel systems were to be used for rural electrification, CO_2 emissions and resource use could increase significantly, exceeding the business-as-usual scenario several-fold. A decentral renewable energy-based electrification might save about 99% of total CO_2 emissions and up to 35% of total primary energy use in 2030 compared to the business-as-usual scenario. Rural electrification with decentral diesel systems is likely to be the most expensive option, due to high oil dependence. Concerning whole system costs, rural electrification with decentral renewable energy could be the most cost-effective option when renewable energy-based devices are predominantly used, but could be more costly than grid extensions when electric devices are predominantly used. Rural electrification may have positive effects on social issues like providing access to electricity, improving the living conditions of the rural population and reducing urban-rural differences (Chapter 6).

In summary, it is found that CO_2 emissions could be substantially reduced due to sustainable energy transitions. This thesis shows that natural resources could be safeguarded and fossil energy use could be reduced when renewable energy is used. The electricity system is likely to stay stable in the future even if a higher share of sustainable energy will be installed. Sustainable energy transitions might reduce social disparities such as urban-rural differences. Concerning costs, the research outcomes suggest a rather mixed picture: In the Chinese power sector, energy transitions to sustainable energy tend to be (much) more expensive than continued reliance on fossil fuels. In Beijing's economy, energy transitions to sustainable energy tend to increase costs only moderately, with households, agriculture, services and heating enabling the most cost-effective energy transitions. In the non-electrified residential sector of rural India, rural electrification with decentral renewable energy could be several times cheaper than electrification with grid extensions or decentral diesel systems. This is however only the case when renewable energy-based devices are predominantly used like solar cookers, biogas stoves and solar water heaters. When electricity is generated from decentral renewable energy and predominantly drives electric devices, like electric stoves, electric geysers or other electronics, costs increase to a greater extent than for grid extensions. This may lead to the conclusion that for low-energy requiring processes and small-scale processes sustainable energy could to be more cost-effective than other energy sources. For high-energy requiring processes and large-scale processes, sustainable energy tends to be more costly than other energy sources. However, costs for fossil fuels would increase if subsidies were reduced, in return making sustainable energy more competitive. High oil price increases also recently showed that fossil fuel prices tend to be volatile and are likely to increase even more, potentially making sustainable non-fossil energy more attractive in the future. Moreover, the system is highly complex, high uncertainties exist and regional differences prevail, with India differing from China and rural areas differing from urban areas.

4. Conclusion

This thesis aims a) at elaborating the differences between energy systems in (rapidly) developing countries and in industrialised countries, b) at adapting energy modelling approaches to increase their suitability for rapidly developing countries and c) at developing scenarios using these adapted models to simulate sustainable energy transitions for rapidly developing countries and to assess the impacts of these energy transitions. The focus of this thesis is on China and India.

As an overall conclusion, the thesis shows a) that energy modelling needs to take into account the growing importance of rapidly developing countries. This can be done by adapting energy modelling approaches to suit the energy systems of developing countries as was done in the thesis. This thesis also shows b) that renewable and clean energy could be viable options of climate change mitigation for rapidly developing countries like China and India and c) that these energy transitions to a sustainable economy could also have other positive effects on the environment and society. Hence, sustainable energy transitions are likely to have positive effects in rapidly developing countries. To ensure an adequate planning of these energy transitions adequate energy modelling is needed which is suited for developing countries.

Since climate change is a global problem, it is the responsibility of both developing and industrialised countries to cooperate to achieve a sustainable energy future. Such cooperation could be crucial for the success of international climate policy negotiations. Energy models which are adapted to the needs of developing countries are likely to increase the success of climate policy negotiations, as they can be useful tools to support the energy planning of developing countries.

Nederlandse samenvatting:

Duurzame energie voor ontwikkelingslanden

- Modellering van transities naar hernieuwbare en schone energie in zich snel ontwikkelende landen

1. Achtergrond

1.1 Energiegebruik en de gevolgen hiervan

Energie is essentieel. Energie is nodig voor de basisbehoeften van de mens: koken, verwarming, licht maar ook voor de productie van o.a. voedsel en onderdak. Energie is dus nodig in die economische sectoren die deze goederen produceren zoals landbouw, elektriciteitsproductie, industrie, diensten en vervoer. Men neemt aan dat de toegang tot energie nauw verbonden is met ontwikkeling en economisch welzijn.

Vandaag de dag komt ongeveer 80% van het mondiale primaire energiegebruik uit fossiele brandstoffen zoals steenkool, olie en aardgas. Fossiele energiebronnen zijn echter niet eindeloos beschikbaar, zij kunnen uitgeput raken. Energie is daarom een belangrijk geopolitiek en sociaaleconomisch vraagstuk geworden. De gevolgen van de recente olieprijsschokken laten goed zien hoe afhankelijk we zijn van schaarse brandstoffen. Het fossiele energieverbruik wordt ook geassocieerd met een aantal negatieve milieugevolgen zoals luchtvervuiling en mondiale klimaatverandering. Door de verbranding van fossiele brandstoffen worden veel kooldioxide (CO_2) en andere zogenaamde broeikasgassen (GHG) uitgestoten. Deze broeikasgassen dragen bij aan de mondiale klimaatverandering. De mondiale klimaatverandering, ook bekend als opwarming van de aarde, is een verschijnsel met meerdere gevolgen. Het Intergouvernementele Comité voor de Klimaatverandering van de Verenigde Naties (IPCC) rapporteert enkele waargenomen effecten: een stijging van mondiale oppervlaktetemperaturen, toename van zware neerslag, meer kans op droogten, grootschalige veranderingen in de atmosferische circulatie en een toename van tropische cycloonactiviteit. Dit kan een verhoogd risico betekenen op overstromingen en extreme droogten, voedselonzekerheid, vermindering van de levensstandaard en gezondheidsrisico's. Ontwikkelingslanden zijn waarschijnlijk de kwetsbaarste landen bij de klimaatverandering, vanwege hun beperkte financiële middelen, die snelle aanpassing (o.a. dijkverhoging) moeilijk of onmogelijk maken.

1.2. Energie transities en de rol van hernieuwbare en schone energie

De huidige energie– en klimaatproblematiek zet alle landen in de wereld onder druk. De druk op ontwikkelingslanden is misschien nog groter, omdat zij momenteel in een fase verkeren, waarin grote hoeveelheden energie nodig zijn voor het bereiken van een hogere levensstandaard. Een toenemende bevolking en een sterke afhankelijkheid van fossiele brandstof verhogen deze druk nog meer. Het aandeel van minder vervuilende hernieuwbare en schone energie zou daarom moeten worden verhoogd om de levenszekerheid van energie te garanderen, de druk op fossiele energiebronnen te verminderen, klimaatverandering tegen te gaan en een hogere milieukwaliteit te waarborgen. Hernieuwbare en schone energie kunnen een stimulans zijn voor de transitie naar duurzame energie.

Energietransities kunnen worden gedefinieerd als verschuivingen van op fossiele brandstoffen gebaseerde economische activiteiten, naar die op (deels) hernieuwbare en minder vervuilende energiebronnen. Dit betekent dat op fossiele brandstof gebaseerde technologieën worden vervangen door schone(re) energietechnologieën. Dergelijke transities kunnen in elke economische sector van een land of regio plaatsvinden. Zo kan Elektriciteit kan met behulp van windenergie worden geproduceerd in plaats van met steenkool. Duurzame energietransities kunnen ontwikkelingslanden nieuwe mogelijkheden bieden voor ontwikkeling en verhoging van de levensstandaard terwijl tegelijkertijd energiebronnen, milieu en volksgezondheid beschermd worden door lagere energiegebruik en emissies.

1.3 Energiemodellering

Energiemodellen kunnen belangrijke hulpmiddelen zijn om energietransities te analyseren en te plannen. Computermodellen zijn vereenvoudigingen van de echte wereld. Complexe problemen in de echte wereld kunnen met computermodellen worden doorgerekend en worden geanalyseerd. De toekomst kan met deze modellen worden gesimuleerd om de energieplanning van de komende jaren en decennia te ondersteunen.

De meeste huidige energiemodellen zijn door en voor industrielanden ontwikkeld en nemen de energiesystemen van deze landen als uitgangspunt en kunnen daardoor niet onderkennen dat de situatie in ontwikkelingslanden heel anders is. Industrielanden en ontwikkelingslanden verschillen ondermeer in energiegebruik, productie en distributie, energie-infrastructuur en energie-economie. In veel ontwikkelingslanden bijvoorbeeld, gebruikt een groot deel van de plattelandsbevolking hout voor het koken van de maaltijd en het verwarmen van de huizen. In industrielanden gebruikt de meerderheid van de bevolking elektriciteit of aardgas voor het koken en het verwarmen. Deze verschillen in energiesystemen tussen ontwikkelingslanden en industrielanden maken het noodzakelijk om gangbare energiemodellen aan te passen voor het gebruik in ontwikkelingslanden.

2. Doel van het proefschrift en de onderzoeksbenadering

De belangrijkste doelstelling van dit proefschrift is ten eerste om energiemodellen voor het gebruik in ontwikkelingslanden aan te passen en ten tweede om daarmee duurzame energietransities en hun gevolgen in zich snel ontwikkelende landen zoals China en India te onderzoeken.

Het doel van dit proefschrift is drieledig: a) de verschillen tussen energiesystemen in zich (snel) ontwikkelende landen en industrielanden uit te werken b) energiemodellen aan te passen zodat hun geschiktheid voor deze ontwikkelingslanden wordt verbeterd en c) scenario’s te ontwikkelen die deze aangepaste modellen gebruiken om duurzame energietransities voor deze ontwikkelingslanden te simuleren en de implicaties van deze energietransities te beoordelen. De kern van dit onderzoek is het ontwikkelen van scenario’s voor duurzame energietransities voor China en India.

China en India zijn gekozen, omdat zij zich economisch momenteel het snelst ontwikkelen, en daardoor ook de meest energieverbruikende, meest klimaat-relevante ontwikkelingslanden zijn. Hun ontwikkeling kan gevolgen op wereldschaal hebben. Implementatie van hernieuwbare en schone energiebronnen in deze landen zal waarschijnlijk de klimaatverandering in gunstige zin beïnvloeden. Drie case studies zijn gekozen in China en India die verschillende niveaus en schalen van energietransities beoordelen: nationaal/regionaal, stedelijk/landelijk en energievraag/-aanbod. Deze drie cases corresponderen met het huidige energiebeleid in China en India. Een case die voor Peking werd ontwikkeld is gebaseerd op de doelstelling voor hernieuwbare energie van de lokale regering voor 2020 en werd uitgevoerd in samenwerking met Chinese onderzoekers.

De duurzame energietechnologieën die in deze cases worden beoordeeld zijn gebaseerd op hernieuwbare energiebronnen zoals zon, wind, water, biomassa dan wel behoren tot de zogenaamde „schone“ technologieën. “Schone” energietechnologieën zijn technologieën zoals kernenergie, aardgas en efficiëntere fossiele brandstoftechnologieën, die minder broeikasgassen uitstoten dan conventionele technologieën met steenkool en olie. De term „schone“ energie betekent hier eigenlijk minder vervuilende energie, want er is geen volledig schone energie. De duurzame energiescenario’s worden vergeleken met ‘business-as-usual’ of referentie scenario’s waarin de niet-duurzame fossiele brandstoftechnologieën de overhand hebben zoals op dit moment het geval is in China en India. De energiemodellen zoals gebruikt in dit proefschrift, zijn aangepast aan de landen en sectoren waarvoor ze gebruikt worden: de Chinese elektriciteitssector, De Beijing regio en het nog niet geëlektrificeerde platteland van India.

3. Resultaten

3.1 Energie systemen van ontwikkelingslanden: kenmerken en modelleringsbenaderingen

Eerst (hoofdstukken 2 en 3) worden de diverse kenmerken van het energiesysteem uitgewerkt en wordt geanalyseerd hoe energiemodellen hier mee omgaan.

De energiesystemen van ontwikkelingslanden verschillen van die van industrielanden. Energiesystemen van ontwikkelingslanden worden gekenmerkt o.a. door een hoge afhankelijkheid van traditionele biobrandstoffen zoals hout en mest, een lage elektrificatie, beperkte toegang tot moderne energiebronnen, leveringstekorten van de elektriciteitssector en door grote verschillen tussen stedelijke en plattelandsgebieden m.b.t. de energievraag en -aanbod. Het bestaan van een sterke informele economie en de veranderingen in de structuur van de economie, kunnen het energiesysteem ook beïnvloeden. Deze kenmerken gelden over het algemeen in ontwikkelingslanden, maar de mate waarin deze kenmerken een rol spelen varieert tussen landen en gebieden. De factoren die de energiesystemen beïnvloeden en veranderingen teweegbrengen zijn o.a. bevolkingstoename, de economische groei, brandstofsubstitutie, technologische verandering en beleid. Concepten aangaande energie en ontwikkeling zoals de ‘Energy Ladder’ (die stijgend inkomen en het gebruik van schonere en efficiëntere energie met elkaar in verband brengt) en de ‘Environmental Kuznets Curve’ (die inkomensniveaus en verontreinigingniveaus met elkaar in verband brengt), worden uitgewerkt in Hoofdstuk 2. Deze concepten worden geïllustreerd m.b.v. de resultaten van de IPCC/Speciaal Rapport over Emissie Scenarios (SRES) modellen.

De meeste huidige energiemodellen werden ontwikkeld door en voor industrielanden en zijn gebaseerd op de ervaring met energiesystemen in deze landen. Hoewel deze energiemodellen gewoonlijk zeer goed werken voor de industrielanden zelf, gaan deze modellen voorbij aan de verschillen van de energiesystemen met de ontwikkelingslanden. De resultaten van deze modellen zouden daarom onnauwkeurig of in het slechtste geval zelfs misleidend kunnen zijn. Deze modelonzekerheden kunnen weer leiden tot verkeerde beleidsaanbevelingen. In een tijd van mondiale klimaatverandering zou deze onzekerheden aan de orde moeten komen, omdat de onderhandelingen over potentiële emissiebegrenzingen voor ontwikkelingslanden thans hoog op de wereldagenda staan. Daarom is het belangrijk om bestaande energiemodellen geschikter te maken voor de energiesystemen van ontwikkelingslanden, in het bijzonder voor die van de zich snel ontwikkelende landen als China en India. Hoofdstuk 3 concludeert dat in het bijzonder die kenmerken van de energiesystemen van ontwikkelingslanden moeten worden gemodelleerd waarvoor betrouwbare gegevens beschikbaar zijn en waarvan de systeemdynamica voldoende wordt begrepen. In Hoofdstuk 3, waarin de geschiktheid van modellen voor ontwikkelingslanden is onderzocht, wordt gesteld, dat de energiemodellen bij voorkeur een ‘bottom-up’ of hybride benadering zouden moeten volgen en dat het scenario simulatiemodellen of toolboxmodellen zouden moeten zijn. In Hoofdstukken 4 t/m 6 zijn volgens deze benadering drie bestaande energiemodellen aangepast voor het gebruik in ontwikkelingslanden.

3.2 Energie transities in zich snel ontwikkellende landen

Vervolgens (hoofdstukken 4 t/m 6) worden drie cases uitgewerkt voor China en India waarin de bestaande energiemodellen worden aangepast om de snel veranderende energiesystemen van deze landen goed te kunnen simuleren. Enkele belangrijke kenmerken van de energiesystemen van ontwikkelingslanden worden hier bestudeerd, bijvoorbeeld de lage efficiëntie van de op fossiele brandstof gebaseerde elektriciteitssector, de elektrificatie van het platteland, het overheersende gebruik van traditionele biobrandstoffen en de stad-platteland tegenstelling.

De energiemodellen die voor dit proefschrift worden gebruikt zijn specifiek aangepast voor China en India. De resultaten van modelberekeningen tonen aan dat duurzame energietransities in China en India voor diverse sectoren mogelijk zijn.

De CO_2-emissie van de Chinese elektriciteitssector zou tot 57% kunnen afnemen als resultaat van de energietransitie naar hernieuwbare energiebronnen. Wanneer 20% van de totale geïnstalleerde capaciteit vervangen wordt door hernieuwbare energiebronnen neemt de CO_2-emissie van de elektriciteitssector maximaal 27% af, terwijl 30% hernieuwbare energiebronnen de CO_2-emissie tot 57% zal doen afnemen. Beiden in vergelijking met het ‘business-as-usual’ scenario in 2030. De CO_2 reductie is ook afhankelijk van het gebruikte type hernieuwbare bron. Een combinatie van biogas en kleinschalige waterkracht centrales zal waarschijnlijk de hoogste CO_2-emissiereductie opleveren, meer dan een mix van hernieuwbare energiebronnen en een combinatie van PV (Photo Voltaisch) en windenergie. Wanneer 20% van de totale geïnstalleerde capaciteit door kernenergie wordt vervangen zal de CO_2-emissie van de elektriciteitssector maximaal met 38% afnemen in vergelijking met het ‘business-as-usual’ scenario in 2030. De stabiliteit van het elektriciteitssysteem zal waarschijnlijk in de toekomst ook goed blijven, ondanks de toename van minder betrouwbare hernieuwbare bronnen.

In de tweede case worden mogelijke energietransities voor de gemeente Peking gemodelleerd voor de economische sectoren: landbouw, industrie, huishouden, diensten en vervoer. In deze case is de doelstelling van de overheid van Peking om 6% van de totale energiebehoefte in 2020 te voorzien met hernieuwbare bronnen gemodelleerd. Het resultaat is een besparing van 23% op de totale broeikasgasemissies in 2020. Deze overheidsdoelstelling levert een besparing van 16% op het fossiele brandstofgebruik in vergelijking met het ‘business-as-usual’ scenario in 2020. De lokale luchtvervuiling, een ernstig probleem in Peking, zal waarschijnlijk licht dalen vanwege de transitie naar hernieuwbare energiebronnen. De kosten zullen in dit scenario met ongeveer 10% stijgen vanwege de toename van hernieuwbare energiebronnen in vergelijking met het ‘business-as-usual’ scenario in 2020. Zelfs in 2020 verwacht men significante verschillen tussen stedelijke en plattelandsgebieden in de gemeente van Peking, bijvoorbeeld in inkomen, levensstijl en energiegebruik (Hoofdstuk 5).

In de derde case worden drie belangrijke strategieën om de plattelands huishoudens van India van elektriciteit te voorzien met elkaar vergeleken. Deze drie strategieën zijn: uitbreidingen van het centrale net, decentrale dieselsystemen en decentrale hernieuwbare energiesystemen. Als de netuitbreidingen en de dieselsystemen worden gekozen voor de elektrificatie van het platteland dan zullen de CO_2-emissies en het brandstofgebruik aanzienlijk stijgen, en zelfs hoger uitkomen dan het ‘business-as-usual’ scenario. Een decentrale, op hernieuwbare energie gebaseerde elektrificatie zou ongeveer 99% van de totale CO_2-emissies kunnen vermijden en tot 35% van het totale primaire energieverbruik kunnen besparen in vergelijking met het ‘business-as-usual’ scenario in 2030. De elektrificatie van het platteland met decentrale diesel systemen zal waarschijnlijk de duurste optie zijn, dit vanwege de hoge olieafhankelijkheid. Als naar het geheel van systeemkosten wordt gekeken dan kan de elektrificatie van het platteland met decentrale hernieuwbare energiebronnen de meest rendabele optie zijn, wanneer hoofdzakelijk op hernieuwbare energie gebaseerde apparaten gebruikt worden. Het kan echter duurder zijn dan netuitbreidingen wanneer hoofdzakelijk elektrische apparaten gebruikt worden. De elektrificatie van het platteland kan positieve gevolgen hebben voor sociale vraagstukken, zoals toegang tot elektriciteit, het verbeteren van de levensomstandigheden van de plattelandsbevolking en het verminderen van verschillen tussen stad en platteland (Hoofdstuk 6).

Samengevat kan men stellen dat de CO_2-emissies wezenlijk kunnen worden verminderd door duurzame energietransities.. Dit proefschrift toont aan dat natuurlijke hulpbronnen kunnen worden behoed voor uitputting en het fossiele energieverbruik kan worden verminderd wanneer hernieuwbare energie wordt gebruikt. Het elektriciteitssysteem zal waarschijnlijk in de toekomst betrouwbaar blijven zelfs met een hoger aandeel van duurzame energie. Duurzame energietransities zouden sociale ongelijkheden zoals verschillen tussen stad en platteland kunnen verminderen. Wat betreft de kosten geven de onderzoekresultaten een gemengd beeld te zien: In de Chinese elektriciteitssector lijken energietransities naar duurzame energie (veel) duurder te worden dan een op fossiele brandstoffen gebaseerd productiepark. In de economie van Peking lijken energietransities naar duurzame energie de kosten slechts matig te verhogen. Energietransities in de huishoudens, landbouw, dienstensector en ruimteverwarming lijken het meest rendabel te zijn. In de niet-geëlektrificeerde plattelands huishoudens van India, zou de elektrificatie van het platteland met decentrale hernieuwbare energie veel goedkoper kunnen zijn dan elektrificatie met netuitbreidingen of decentrale diesel systemen. Dit is slechts het geval wanneer hoofdzakelijk op hernieuwbare energie gebaseerde apparaten worden gebruikt zoals zonnekooktoestellen, biogasfornuizen en zonneboilers. Wanneer echter de elektriciteit ook wordt gebruikt om te koken, voor verwarming en warm water e.d , stijgen de kosten boven die van de netuitbreidingen uit. Dit leidt tot de conclusie dat voor processen met een lage energievraag en kleinschalige processen duurzame energie rendabeler is dan energie uit andere bronnen. Voor processen die veel energie vragen en grootschalige processen wordt duurzame energie duurder dan die uit andere bronnen. Als de kosten voor fossiele brandstoffen zouden stijgen of als de subsidies worden verminderd, dan wordt hierdoor duurzame energie concurrerender. De olieprijsverhogingen van de laatste tijd tonen aan dat de fossiele brandstofprijzen instabiel zijn en mogelijk op termijn nog meer zullen stijgen, wat het duurzame energie potentieel kan vergroten. Verder is het systeem hoogst complex, er bestaan grote onzekerheden en grote regionale verschillen, zoals tussen India en China en tussen plattelandsgebieden en stedelijke gebieden.

4. Conclusie

Dit proefschrift had als doel a) het bepalen van de verschillen in energiesystemen tussen ontwikkelingslanden en industrielanden, b) het aanpassen van energiemodellen om hun geschiktheid voor de zich snel ontwikkelende landen te verhogen en c) het ontwikkelen van scenario's, m.b.v. deze aangepaste modellen om duurzame energietransities voor de zich snel ontwikkelende landen te simuleren en de effecten van deze energietransities te beoordelen. De nadruk van dit proefschrift ligt op China en India.

Als algemene conclusie toont dit proefschrift aan dat a) energiemodellering rekening moet houden met het groeiende belang van de zich snel ontwikkelende landen en ontwikkelingslanden. Dit kan worden gedaan door energiemodellen aan te passen aan de energiesystemen van ontwikkelingslanden zoals in dit proefschrift wordt beschreven Dit proefschrift toont ook aan dat b) hernieuwbare en schone energie technologieën haalbare opties zijn voor het beperken van de klimaatverandering door de zich snel ontwikkelende landen zoals China en India en dat c) deze energietransities naar een duurzame economie mogelijk ook andere positieve gevolgen voor het milieu en de maatschappij kunnen hebben. Daarom zullen duurzame energietransities waarschijnlijk positieve gevolgen hebben in de zich snel ontwikkelende landen. Om een adequate planning van deze energietransities te garanderen is een adequate energiemodellering nodig die voor ontwikkelingslanden geschikt is.

Aangezien de klimaatverandering een mondiaal probleem is, is het de verantwoordelijkheid van zowel de zich ontwikkelende landen als ook van de industrielanden om samen te werken teneinde een duurzame energietoekomst te realiseren. Een dergelijke samenwerking zou van essentieel belang kunnen zijn voor het succes van het internationale klimaatbeleid. De energiemodellen die worden aangepast aan de behoeften van ontwikkelingslanden zullen het succes van de onderhandelingen over het klimaatbeleid waarschijnlijk kunnen verhogen, aangezien het nuttige hulpmiddelen zijn om de energieplanning van ontwikkelingslanden te ondersteunen.

Kurze Deutsche Zusammenfassung:

Nachhaltige Energie für Entwicklungsländer

- Modellierung von Übergangen zu erneuerbarer und sauberer Energie in Schwellenländern

Die rasant wachsende Wirtschaft der Schwellenländer China und Indien ist sehr stark abhängig von fossilen Brennstoffen, besonders von verschmutzender Kohle. Fossile Brennstoffe sind mit einer Anzahl von Umweltproblemen verbunden, wie zum Beispiel dem globalen Klimawandel, Raubbau an Ressourcen und Luftverschmutzung. Eine Art und Weise die Abhängigkeit von fossilen Brennstoffen zu vermindern, ist der Ausbau nachhaltiger kohlenstoffarmer Energie, wie zum Beispiel erneuerbare Energie (z.B. Solar, Wind, Wasserkraft) und so genannte saubere Energie, die weniger verschmutzend ist als konventionelle Kohle und Erdöl (z.B. Erdgas, Atomenergie).

Diese Doktorarbeit befasst sich deshalb mit der Modellierung von Übergängen zu nachhaltiger Energie für die Schwellenländer China und Indien. Diese Forschung beschäftigt sich mit dem Chinesischen Elektrizitätssektor, der Wirtschaft von Peking und armen ländlichen Haushalten in Indien, die keinen Zugang zu Elektrizität haben.

Die meisten der heutigen Energiemodelle sind in und für Industrieländer entwickelt. Diese Modelle gehen daher oft nur unzureichend auf die sehr unterschiedlichen Energiesysteme von Entwicklungsländern ein. Diese Forschung hat als Ziel, von den auf Erfahrungen in Industrieländern basierenden Modellen abzuweichen und Energiemodelle für die spezifischen Konditionen in Entwicklungsländern anzupassen. Diese verbesserten Modelle werden benutzt, um Übergänge zu nachhaltigen Energien für China und Indien zu modellieren.

Diese Doktorarbeit deutet auf das hohe Potential zur Verminderung des Klimawandels hin, welches durch nachhaltige Energien ermöglicht werden kann in China und Indien. Die Ergebnisse dieser Forschung könnten nützlich sein für Energieexperten, Energiebetriebe und auch Politiker und Gesetzgeber, die sich mit diesen Themen befassen, vor allem in China und Indien. Die Ergebnisse dieser Studie könnten ebenfalls dazu beitragen, das nötige Wissen für nachhaltige nationale Energieplanung in beiden Ländern zu erhöhen. Gleichzeitig könnten die Ergebnisse notwenige Informationen liefern als Unterstützung für China und Indien für die internationalen Klimaverhandlungen.

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