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Published in:
Climatic Change

DOI:
10.1007/s10584-009-9553-y

Publication date:
2009

Climatic Change (2009) 94:169–188
DOI 10.1007/s10584-009-9553-y

Renewable and low-carbon energies as mitigation options of climate change for China

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Received: 22 February 2008 / Accepted: 29 December 2008 / Published online: 5 March 2009

Abstract This article discusses how renewable and low-carbon energies can serve as mitigation options of climate change in China's power sector. Our study is based on scenarios developed in PowerPlan, a bottom-up model simulating a countries' power sector and its emissions. We first adjusted the model to China's present-day economy and power sector. We then developed different scenarios based on story lines for possible future developments in China. We simulated China's carbon-based electricity production system of today and possible future transitions towards a low-carbon system relying on renewable and low-carbon energies. In our analysis, we compare the business-as-usual scenarios with more sustainable energy scenarios. We found that by increasing the share of renewable and nuclear energies to different levels, between 17% and 57% of all CO_2 emissions from the power sector could be avoided by 2030 compared to the business-as-usual scenario. We 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.

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

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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, we therefore study the possibilities and limitations of implementing renewable and low-carbon energy sources as mitigation options in the Chinese power sector 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" (Urban et al. 2007). 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 energies can partially replace fossil fuels in the Chinese power sector and thereby serve as mitigation options. We aim to assess the implications of this energy transition 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 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 energies 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 energies 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 energies. 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.

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, we developed story-lines for the future development of China. Third, we made scenarios for future transitions to sustainable energies.

2.1 Description of PowerPlan

PowerPlan is a dynamic and interactive simulation model that can answer '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 energies do 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 adjusted, 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.

The PowerPlan model consists of four modules (see Fig. 1):

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

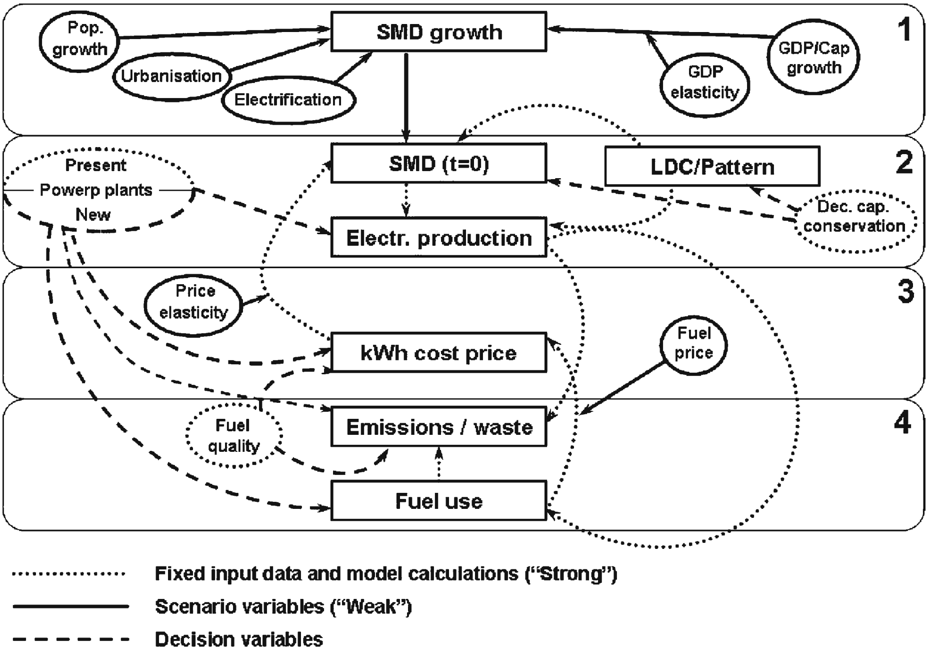


Fig. 1 Schematic overview of the PowerPlan model and its four modules, including input data, scenario variables and decision variables

- 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 and 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 and 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 and de Vries (1989), Benders (1996), Benders and Biesiot (1998) and de Vries (1990), de Vries et al. (1991), de Vries and Benders (1994).

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 (van der Werff and Benders 1987) and Taiwan (de Vries 1990). Since the energy systems and economies of developing and developed countries differ greatly (Urban et al. 2006, 2007), we adjusted PowerPlan 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 1. 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 (2007a) 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.

In 2005, China's central electricity production was about 2,500 TWh with an average growth rate of 5.5% in the last 5 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 Mt of SO_2, 0.7 Mt NO_x, 2,050 Mt CO_2 and 0.3 Mt 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 2007a). Low-carbon technologies in the power sector, such as renewable energies, nuclear energy, natural gas, coal liquidation and coal gasification technologies are thus of growing importance. In the past, renewable energies 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,

Table 1 Key starting variables for 2005 for modelling the Chinese energy setting and data sources

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)

diversify energy supplies, safeguard energy security, protect the environment, and realize the sustainable development of the economy and society" (National People's Congress of China 2005). 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 energies 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).

2.3 Story-lines and scenario-making

After adjusting 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.

We developed three story-lines: business-as-usual (BAU), renewable energy future (RE) and nuclear future (NUC). Other low-carbon energies, like natural gas and coal gasification 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 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 2).

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

Table 2 Overview of the developed scenarios and their underlying assumptions on economic and population growth, technological change and policy targets

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

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 technologies used (see also Section 3.2)

renewable energy policies; the share of renewable energies 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 energies (biogas, geothermal, SHP, solar PV, tidal, wind), while the RE(PVwind) and RE(SHPbiogas) scenarios focus mainly on two renewable energies. Wind and solar energy contribute to the major share of renewables in the RE20%(PVwind) scenario, while biogas and 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 energies among the total installed capacity in 2030 as indicated by the policy goals which the NRDC foresees for 2020, while RE30% and RE30%(SHPbiogas) aim at an implementation of 30% renewable energies 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 energies 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 our modeling approach is a simulation study only and not a policy prediction study, we do assume the same share for nuclear and renewable energies for reasons of comparability. 'What if' questions can thus be answered 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, we assessed how to quantitatively model these 'stories'. We translated the qualitative input 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

2006). In the line of this reasoning, we developed three BAU scenarios, four RE scenarios and one NUC scenario as indicated in Table 2.

3 Results

3.1 Results of the business-as-usual scenarios

We ran the developed scenarios for a simulation length of 25 years. The results for the BAU scenario are as follows: The three 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 3 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 3 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 energies among the total installed capacity does not exceed 5%. The share of nuclear power installed stays stable at around 1% to 2%.

Table 4 indicates the effects of the business-as-usual approach on the installed capacity, electricity generated, generation costs and CO_2 emissions for the future.

Figure 2 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.

3.2 Results of the renewable and low-carbon energy scenarios

The RE and NUC scenarios simulate what happens if China will undergo a transition towards renewable or nuclear energy sources within the next 25 years. Such a transition requires 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 5, 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 are renewable energies, while for the RE30% and RE30%(SHPbiogas) scenario 30% of the total capacity installed are renewable energies in 2030. It can be seen from Table 5, that the share of fossil fuels and large hydro power decreases for all five scenarios.

Table 3 Share of different types of energy among the total installed capacity for the BAU scenarios

Share (%)	Fossil fuels				Large hydro power				Nuclear power				Other renewable energies			
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 4 Installed capacity, electricity generated, generation costs and CO_2 emissions for the BAU, BAUhigh, BAUlow scenarios

	Capacity (GW)				Electricity (TWh)				Costs (CNY/kWh)				CO_2 emissions (Mt)			
Scenario/year	2005	2010	2020	2030	2005	2010	2020	2030	2005	2010	2020	2030	2005	2010	2020	2030
BAU	550	761	1,121	1,546	2,479	3,140	4,621	6,628	0.38	0.41	0.44	0.47	2,034	2,413	3,117	4,082
BAUhigh	550	836	1,491	2,051	2,479	3,403	5,796	8,699	0.38	0.41	0.45	0.47	2,034	2,649	4,081	5,718
BAUlow	550	705	933	1,119	2,479	2,956	3,793	4,675	0.38	0.41	0.45	0.48	2,034	2,259	2,416	2,581

Fig. 2 Increase of power supply between 2005 and 2030 in the BAU scenario: contribution of different power plants to installed capacity

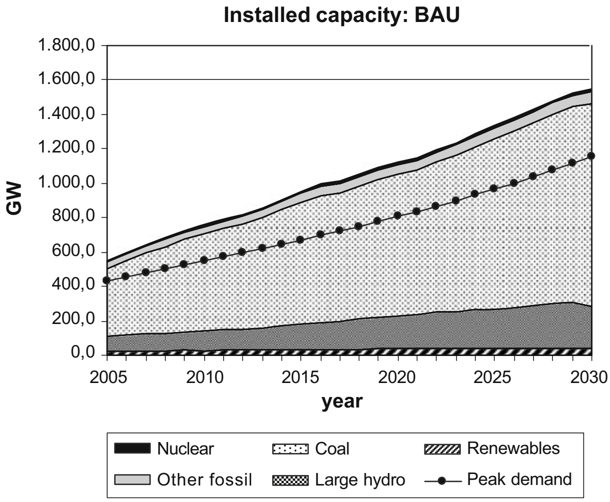


Figure 3 indicates the different types of power plants contributing to power generation in the RE30% scenario (30% renewables). It can be seen that—as in the BAU scenarios—between 2005 and 2030, the peak demand is likely to increase by factor 2.7.

Table 6 shows the effects of the transition towards renewable and nuclear energies on the installed capacity, electricity generated, generation costs and CO_2 emissions for the future.

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, because the load factor of renewable energy systems is lower than for fossil and nuclear power stations, so extra capacity is needed. Figure 4 indicates the increase in installed capacity 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 a transition towards sustainable energies is the possibility to mitigate CO_2 emissions. Our results show that the CO_2

Table 5 Share of different types of energy among the total installed capacity for the renewable energy and nuclear scenarios

Share (%)	Fossil fuels				Large hydro power				Nuclear power				Other renewable energies			
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

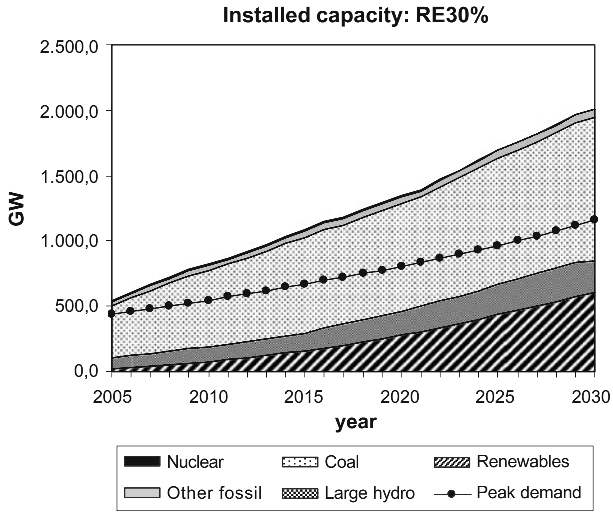


Fig. 3 Increase of power supply between 2005 and 2030 in the RE30% scenario: contribution of different power plants to installed capacity

emissions from the power sector vary significantly between scenarios as indicated in Fig. 5.

CO_2 emissions could increase up to 5,718 Mt/year in 2030 in the BAUhigh scenario, while they could reach 4,082 Mt/year in the BAU scenario and 2,581 Mt/year in the BAUlow scenario. In the RE and NUC scenario, the CO_2 emissions could remain lower with 3,392 Mt/year for the RE20%(PVwind) scenario, 2,988 Mt/year for the RE20% scenario, 2,315 Mt/year for the RE30% scenario and 1,777 Mt/year for the RE30%(SHPbiogas) scenario in 2030. Conclusively, a share of 30% renewable energies 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. A share of 20% renewable energies 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. Implementing a share of 20% nuclear energy among the total installed capacity in 2030 could reduce CO_2 emissions to up to 38% compared to the BAU scenario, but a high amount of nuclear waste would 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 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 increase by 8% by 2030. Also, about 97,700 kt 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 in local air pollution. Concerning the cost factor, in average electricity costs will rise until 2030 as indicated in Fig. 6, 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 price of about 0.38 CNY/kWhe to between 0.47 and 1.42 CNY/kWhe. The highest electricity costs are expected to arise from the RE30%(SHPbiogas) scenario, followed by the

Table 6 Installed capacity, electricity generated, generation costs and CO_2 emissions for the BAU, NUC, RE30%, RE20%, RE20%(PVwind), RE30%(SHPbiogas) scenarios

Scenario/year	Capacity (GW)				Electricity (TWh)				kWh costs (CNY)				CO_2 emissions (Mt)			
	2005	2010	2020	2030	2005	2010	2020	2030	2005	2010	2020	2030	2005	2010	2020	2030
BAU	550	761	1,121	1,546	2,479	3,140	4,621	6,628	0.38	0.41	0.44	0.47	2,034	2,413	3,117	4,082
NUC	550	759	1,124	1,556	2,479	3,138	4,617	6,627	0.38	0.47	0.68	0.80	2,034	2,234	2,233	2,536
RE30%	550	829	1,347	2,014	2,479	3,142	4,628	6,650	0.38	0.55	0.78	0.96	2,034	2,185	2,231	2,309
RE20%	550	808	1,342	1,902	2,479	3,140	4,628	6,648	0.38	0.49	0.74	0.86	2,034	2,342	2,475	2,980
RE20%(Pvwind)	550	824	1,326	1,864	2,479	3,141	4,627	6,643	0.38	0.46	0.54	0.64	2,034	2,316	2,742	3,385
RE30%(SHPbiogas)	550	837	1,344	2,017	2,479	3,147	4,635	6,662	0.38	0.65	1.06	1.42	2,034	2,112	1,995	1,738

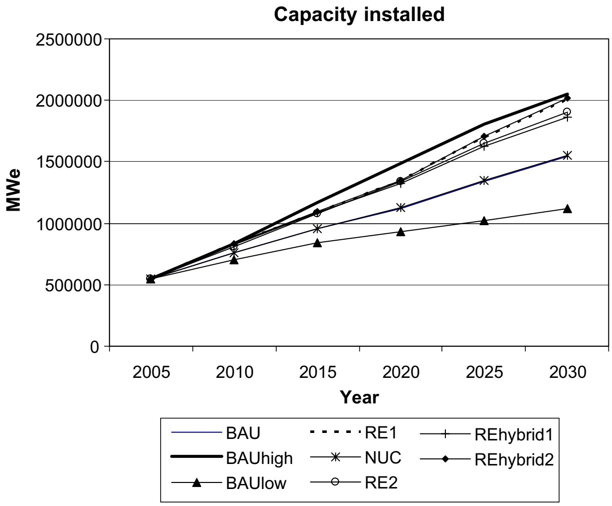


Fig. 4 Capacities installed in MWe in China between 2005 and 2030 for all scenarios

RE30%, RE20% and NUC scenario. The lowest prices can be found in the BAU, BAUlow, BAUhigh and RE20%(PVwind) scenario.

4 Discussion

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

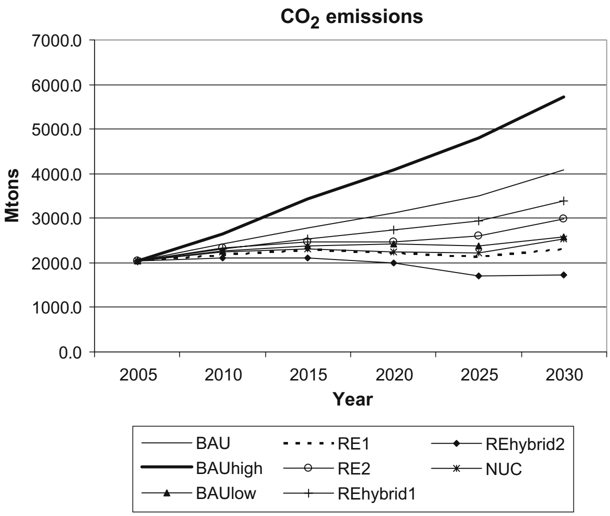
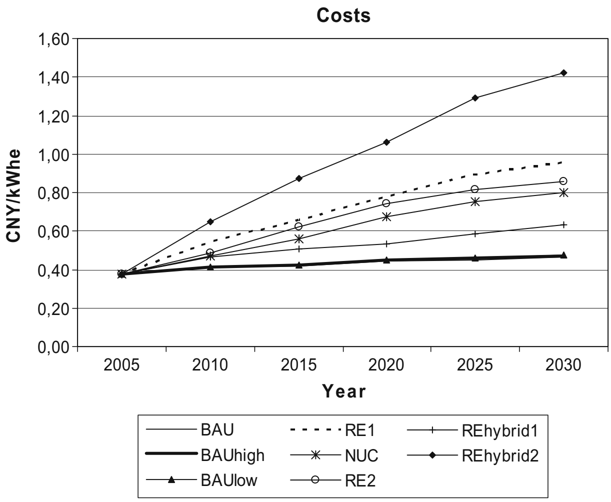


Fig. 5 CO_2 emissions in Mt/year from the Chinese power sector between 2005 and 2030 for all scenarios

Fig. 6 Electricity generation costs in CNY/kWhe in average for China between 2005 and 2030 for all scenarios



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). We also oriented our scenarios on earlier studies on the Chinese power sector, but found 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 is hard to obtain, as often data from international organisations such as the IEA or the WEC differs from the data published in China e.g. in the Statistical Yearbooks. To decrease the bias for one source of data, we therefore compared data from both sources (mainly based on LBNL 2004; IEA 2007a) and used data which was the same or similar.

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 our study, economic growth is represented as GDP growth/capita and GDP elasticity, 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 function 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 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 lack of energy security. Alternatives to a mainly coal-dominated power sector have to be implemented. Our research shows, that it may be possible for China to install up to 30% renewable energies 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 energies is that they are not constantly available, but that back-up capacity will be needed, so more capacity has to be installed (see Fig. 5). This can increase the costs as indicated in Fig. 6. However, the effects on the electricity system reliability are positive, as the LOLP (Loss Of Load Probability) for the RE scenarios decreases 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 energies 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 renewables is installed, but a lower share of electricity from renewables is 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 answer 'what if' questions and to enable a comparison with an installed capacity of 20% renewable energies. This simulation is not a policy scenario, even though nuclear energy is on the rise in China. The World Nuclear Association (2008) 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 increases 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 energies and policies which increase energy efficiency. Other useful measures could be energy-saving programmes and energy-efficient technologies etc.

The results of our 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 question who will pay for the investments necessary for a sustainable energy transition.

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 (2007b) assumes that China will 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 energies will have to be used. Alternatives are renewable energies 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 (2007b) also mentions options for hydrogen, which however is also not yet commercially used. Since China is endowed with rich renewable resources like hydropower, wind, biomass and solar they seem to be feasible alternatives.

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 could increase to about 2,600 Mt/year (BAUlow), 4,100 Mt/year (BAU) and 5,700 Mt/year (BAUhigh) until 2030. Low- and zero-carbon energies, such as renewable and nuclear energies, are 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. We found that implementing a share of 30% renewable energies 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. We also found that implementing a share of 20% renewable energies 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 is expected to increase 126 times. An increase of nuclear power plants would 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 energies are abundant in China and do not raise any safety or human health related concerns. Our study suggests that renewable energies are the most feasible option of climate change mitigation in the Chinese power sector.

There are thus several possibilities and several cost options for a transition towards a more sustainable power sector in China. China has 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 do have a responsibility in contributing to climate change mitigation in China considering their financial means, technological advancement and their own current and historic contributions to climate change.

Acknowledgements We would like to thank the Stichting Groninger Universiteitsfonds for the funding, the INET at Tsinghua University for using their premises, Wang Y. for the fruitful discussions and correspondence, A.J.M. Schoot-Uiterkamp and two anonymous reviewers for the valuable comments on this paper.

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