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Energy and emission scenarios for China in the 21st century—exploration of baseline development and mitigation options

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Abstract

In this paper, we have used the simulation model IMAGE/TIMER to develop a set of energy and emission scenarios for China between 1995 and 2100, based on the global baseline scenarios published by IPCC. The purpose of the study was to explore possible baseline developments and available options to mitigate emissions. The two main baseline scenarios of the study differ, among others, in the openness of the Chinese economy and in economic growth, but both indicate a rapid growth in carbon emissions (2.0% and 2.6% per year in the 2000–2050 period). The baseline scenario analysis also shows that an orientation on environmental sustainability can not only reduce other environmental pressures but also lower carbon emissions. In the mitigation analysis, a large number of options has been evaluated in terms of impacts on investments, user costs, fuel imports costs and emissions. It is found that a large potential exists to mitigate carbon emissions in China, among others in the form of energy efficiency improvement (with large co-benefits) and measures in the electricity sector. Combining all options considered, it appears to be possible to reduce emissions compared to the baseline scenarios by 50%. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: China; Scenarios; Mitigation

1. Introduction

As China is the world's most populous country with a rapidly growing economy, trends in China's energy future will have considerable consequences for both China and the global environment. Two important trends characterise China's energy use over the last two decades: on the one hand energy intensity has fallen dramatically (by around 4% per year), on the other its primary energy consumption has more than doubled (Zhang, 2001). Greenhouse gas (GHG) emissions have increased at a similar rate. While per capita emissions are still very low, it is possible that China could become the world's largest carbon dioxide emitting country somewhere in the first half of the 21st century. In view of this, there has been considerable attention to potential development of Chinese emissions from both scientists and policy-makers (see e.g. Müller, 2001). Despite the fact that China currently still has no obligations to limit its emissions, it does seem necessary to explore the policy options for reducing GHG emissions in China. Crucial questions are, for instance, what could be the trends in China without explicit climate policies? Is it possible to significantly reduce China's emissions during the first half of this century and how? What are the costs of such policies, what could be the co-benefits? In this paper, we explore these questions using the IMAGE/TIMER integrated assessment model and a set of newly developed storyline-based scenarios.

Future GHG emissions are the product of complex dynamic processes determined by driving forces such as demographic development, socio-economic development, and technological and institutional change. The future of these factors is highly uncertain. Various development patterns could introduce very different futures. New scenario approaches using storyline-based and multiple scenarios intend to identify some of these possible futures, by developing alternative images of how the future might unfold. These images (scenarios) can function as appropriate tools for analysing how

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driving forces may influence future emissions and for assessing the associated uncertainties. Such an approach has been used in IPCC's recently published *Special Report on Emission Scenarios* (SRES) (Nakicenovic, 2000). Using the SRES approach, we have developed in this study several baseline and policy scenarios to explore the possible development in the energy system in China and related environmental pressure. The scenarios enable us to analyse the strategic decisions involved in the different types of development, the possible impacts of climate change and possibilities for mitigation and adaptation.

In this paper, we will first briefly discuss the process and the methodology of the research, followed by a presentation of the key aspects of baseline scenarios for China, both in terms of storyline and of quantitative simulation results from the IMAGE-TIMER energy model. The next section will discuss several options and scenarios aimed at mitigating the Chinese GHG emissions between 2000 and 2050. Finally, the paper will be rounded off with conclusions.

2. Process and methodology

In this analysis, we have used the IMAGE-TIMER[1] model developed at RIVM. It is able to describe changes within the energy system well, including some of the relevant dynamics such as fuel substitution and technology development. Moreover, the energy model TIMER is directly linked with the larger framework of the integrated assessment framework IMAGE, which enables us to analyse the chain of relevant changes from driving forces to impacts of climate change.

The Integrated Model to Assess the Global Environment (IMAGE) has been developed at the National Institute of Public Health and the Environment (RIVM) in the Netherlands over the past 12 years to study the long-term dynamics of global environmental change, in particular, changes related to climate change. The present version of IMAGE 2.2 consists of a set of coupled submodels (IMAGE-team, 2001). It includes submodels related to food demand and land-use changes (Terrestrial Environment System, TES), to energy demand and supply, and energy and industrial GHG emissions (Energy-Industry System, EIS), and to the role of various GHGs in the ocean and atmosphere (Atmosphere–Ocean System, AOS). IMAGE 2.2 is linked with a world economy model (WorldScan; CPB, 1999) and a world population model (Phoenix; Hilderink, 2000).

TIMER forms the energy submodel within the Energy-Industry System. An extensive description of the model can be found in De Vries et al. (2001) and various applications have been published (Janssen and De Vries, 2000; Van Vuuren and De Vries, 2001). The TIMER model is a system-dynamics simulation model at an intermediate level of aggregation: 17 world regions, 5 energy-demand sectors (Industry, Transport, Residential, Commercial and Other) and 6–8 energy carriers (Fig. 1). The model is a simulation model: it does not optimise scenario results on the basis of perfect foresight, but instead, simulates year-to-year investments decisions based on a combination of bottom-up engineering information and specific rules about investment behaviour, fuel substitution and technology.

The time horizon in the present analysis is the period from 1995 to 2100—although for the policy options we will focus mainly on the 1995–2050 period. The model calibration is based on historical data for the period 1971–1995. This time horizon is in accordance with many other scenario studies, notably the SRES report (Nakicenovic, 2000). It puts short-term options in a long-term perspective. It should, however, be noted that in time the future becomes inherently more uncertain, and beyond the scope of current policy-makers. In this study, only GHG emissions from energy use have been considered, which means that emissions and uptake from forestry and land use are not included. We will describe our scenarios mostly in terms of their carbon dioxide emissions. However, in the IMAGE model emissions of other (greenhouse) gases such as methane, nitrous oxide and sulphur dioxide are also calculated (Fig. 1).

We have gone through various process steps to develop our emission scenarios:

1. First, we have developed storylines for China on the basis of existing global storylines from other IMAGE-TIMER projects (IMAGE team, 2001). The storylines, reviewed by various Chinese experts, have been adjusted to achieve a degree of consensus.
2. Second, we have developed a set of quantified scenarios using the IMAGE-TIMER energy model. The model serves as a means to translate qualitative storylines into consistent scenarios of quantified system variables.[2]
3. Third, several mitigation scenarios have been developed. These scenarios aim to identify the potential of different policy options to abate GHG emission in China.

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[1] The model is called Targets IMage Energy Regional model (TIMER) because it has been partially developed as part of the IMAGE 2.1 model (Alcamo et al. 1994;1998) and the TARGETS model (Rotmans and De Vries, 1997).

[2] For this purpose, we have adjusted the existing TIMER 1.0 model to describe mainland China, instead of the East Asia region included in the normal TIMER model used at RIVM. The East Asia region of IMAGE 2.2 includes, in addition to China, North and South Korea, Taiwan, Mongolia, Hong-Kong and Macau.

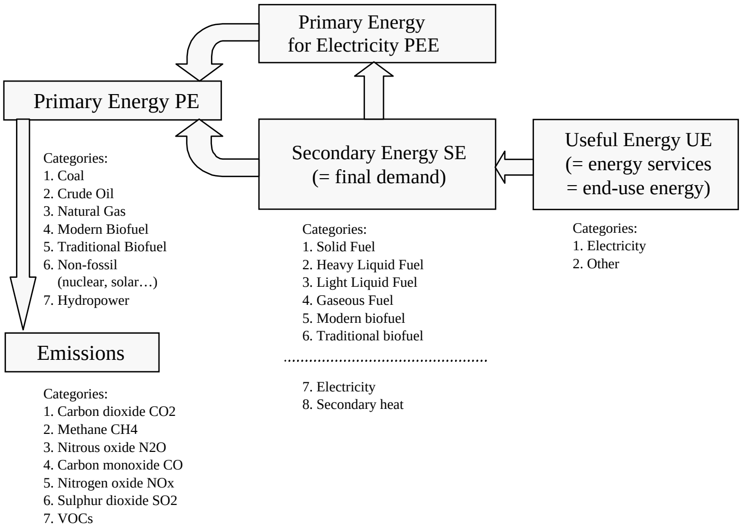

Fig. 1. Overview of categories and calculation flows in the TIMER model/IMAGE Energy Industry System (EIS).

More information on the scenarios and the assumptions made can be found in a separately published background report (Van Vuuren et al., 2001).

3. Baseline scenarios for China

The global IPCC SRES scenarios are based on the development of narrative ‘storylines’ and the quantification of these storylines using six different integrated models from different countries. The storylines describe many different developments in social, economic, technological, environmental and policy dimensions, but not all possible developments. They do, for instance, not include ‘disaster’ scenarios. Moreover, none of the scenarios include new explicit climate policies. The names of the IPCC scenarios are A1, B1, A2 and B2.

On the basis of the existing global SRES scenarios, we have developed four new scenarios specifically oriented to China. Two of the scenarios are described here in detail, while the other two are essentially used to indicate the larger range of uncertainties related to baseline development. The new scenarios do represent some main stream views in China and provide sufficient contrast for policy evaluation. None of the scenarios includes explicit climate policies.

In the next section we will discuss the scenario assumptions and results. Appendix A gives an overview of the major assumptions made within the IMAGE-TIMER model for the Chinese baseline scenarios. The assumptions made for the other global regions have been maintained as given in the SRES scenarios (see IMAGE team, 2001). Table 1 summarises some of the results, comparing China with Western Europe and USA.

3.1. A1b-C Scenario: an ‘open’ China in a globalised world

The first scenario follows the storyline for the SRES A1b scenario,[3] describing a case of rapid and successful economic development both in China and the rest of the world. Globally, the fast economic development is driven by factors as human capital (education), innovation and free trade. We assume that China will continue to pursue its open-door policies, thus enabling strong technology development. By the end of the 21st century, China will almost have caught up in income with the OECD countries, the service sector (tertiary sector) showing the largest growth, with the size in the total economy increasing from about 34% in 2000 to about 60% in 2050 (see also Table 1). The population growth path in China follows the current expectations of the planning commission—in which population reaches a level of around 1.6 billion by 2050 and then decreases to around 1.5 billion in 2100. The economic development in the A1b-C scenario provides support for technology R&D and innovation. As globalisation allows for rapid spread of technologies, renewable energy and other clean energy technologies will become available on a large scale.

As a result of economic growth and the orientation towards material-intensive lifestyles, the demand for energy increases rapidly. Per capita consumption of primary energy increases from 37 GJ per capita in 1995

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[3] There are three subfamilies in the A1 group; these are based on assumptions regarding the energy system. The A1b-C scenario describes a world with balanced energy technology, developed in terms of supply options; the other two sub-families describe a technology development that is either geared towards fossil fuels (A1f) or new technologies (A1t).

Table 1
Kaya indicators for China and selected regions under scenario A1b-C and B2-C

		Historic		A1b-C			B2-C		
		1990	1995	2010	2030	2050	2010	2030	2050
Population (million)	China	1158	1211	1389	1525	1598	1389	1525	1598
	(AAGR)		0.9%	0.9%	0.5%	0.2%	0.9%	0.5%	0.2%
	USA	257	267	305	352	386	305	352	386
	Western Europe	379	384	407	425	426	407	425	426
	World	5281	5601	6897	8235	8905	6897	8235	8905
GDP per capita (US$1995)	China	357	578	1611	4461	10,228	1495	3594	7486
	(AAGR)		10.1%	7.1%	5.2%	4.2%	6.5%	4.5%	3.7%
	USA	24,727	26,316	38,812	52,704	72,531	37,613	46,977	58,274
	Western Europe	20,122	21,636	29,563	44,332	62,065	28,308	37,547	46,126
	World	4705	4830	6388	10,866	20,789	6084	8681	12,945
Energy intensity (MJ/ppp$)[a]	China	34.4	27.8	18	13.4	10.7	17.2	12.1	9.8
	(AAGR)		−4.2%	−2.9%	−1.5%	−1.1%	−3.2%	−1.7%	−1.0%
	USA	11.9	11.4	9.2	7.5	5.6	9.1	6.8	4.8
	Western Europe	7.7	7.4	6.9	6	4.9	6.6	5.2	3.9
	World	12.2	11.6	10.1	8.4	6.3	9.8	7.7	5.8
Carbon intensity (Kg-C/GJ)	China	18.8	19.1	19.8	18.9	17.6	19.8	19.2	18.6
	(AAGR)		0.3%	0.2%	−0.2%	−0.4%	0.2%	−0.2%	−0.2%
	USA	18.4	18.3	17.9	16.9	15	17.7	15.3	12.5
	Western Europe	17.4	17	16.6	15.6	13.9	16.4	14.6	11.2
	World	16.4	16.2	16.8	16.8	14.9	16.6	16	14.1
CO_2 (billion tonnes)	China	0.7	0.9	1.6	2.6	3.8	1.4	2	2.7
	(AAGR)		5.2%	3.9%	2.5%	1.9%	3.0%	1.8%	1.5%
	USA	1.4	1.5	2.1	2.5	2.5	1.9	1.8	1.4
	Western Europe	1	0.9	1.3	1.6	1.6	1.2	1.1	0.8
	World	5.7	5.9	9.6	16.4	20.9	8.8	11.6	11.9
CO_2 per capita (tonne)	China	0.6	0.7	1.1	1.7	2.4	1	1.3	1.7
	(AAGR)		3.1%	3.1%	2.2%	1.7%	2.4%	1.3%	1.4%
	USA	5.6	5.7	6.8	7.1	6.4	6.3	5.1	3.6
	Western Europe	2.5	2.5	3.2	3.8	3.8	2.9	2.6	1.9
	World	1.1	1.1	1.4	2	2.4	1.3	1.4	1.3

Source: TIMER model results, based on underlying data from ERI (China) and RIVM's international database (other countries).

[a] Energy intensity has been expressed in terms of purchasing power parity dollars. By correcting for differences in purchasing power, energy intensity better reflects real differences in energy efficiency–although energy intensity is still also influenced by other factors such as the structure of the economy.

AAGR = annual average growth rate.

to more than 150 GJ per capita in 2050. The latter is equal to the current energy consumption of many OECD countries. Energy demand grows fastest in transport—still a small sector in 1995 but representing 25% of total energy use in 2050. In terms of end-use, traditional biofuels and coal, rapidly lose market shares. Traditional biofuels are replaced as a consequence of the 'modernisation' process. Coal is under pressure in the residential and service sectors due to its inherent environmental and comfort inconveniences. Electricity and natural gas, with their grid-character, wide applicability and local cleanliness, rapidly gain market shares. Oil also gains market shares, along with the growing transport sector, but starts to feel competition from both natural gas (LNG) and biofuels from 2020 onwards (Fig. 2).

At the moment, electricity generation in China is dominated by coal-fired power plants. In the A1b-C scenario, this situation changes only slowly, with natural gas and later zero-carbon options making inroads. The reason for this is the strong competitive position of coal in China. Increases in the use of nuclear power and hydropower are substantial—but both energy sources still cover only 5–10% of total primary inputs in 2050.

The current energy intensity (GJ/ppp$) in China is considerably higher than the other regions caused by, among others, China's reliance on heavy industry and energy inefficiency in industry and electric power

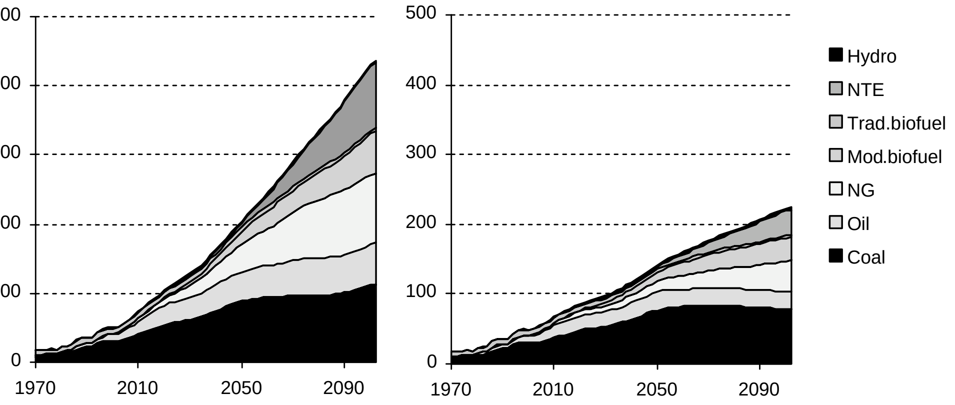

Fig. 2. Primary energy use following the A1b-C (left) and B2-C (right) scenario.

generation (see Table 1; 27.8; versus 7.4 GJ/ppp$ in Western Europe. In the A1b-C scenario, rapid technology transfer spurred by free trade allows China to close the gap in energy efficiency to OECD countries by about a factor of 2. As a result, primary energy use grows at rates slightly lower than those in the past (2.8% per year in the 2000–2050 period versus 4.0% over the last 10 years) (Figs. 2–5). Gradually, energy use will become less dominated by coal. In this scenario, the huge demand for energy, the relative shortage of energy resources and the open markets imply that China will depend more and more on international energy resources. More than 20% of the domestic demand will have to be met by the imported energy by the middle of this century. For oil and natural gas, these percentages are far higher: 80% and 50%, respectively, in 2050.

Investments in energy will increase gradually; they will reach about US$ 200 billion in 2020 and increase to 520 billion in 2050 and 1660 billion in 2100. It will clearly be a challenge for China to be able to realise these investment rates—certainly in the first part of the century. The ratio of investment in energy to GDP is about 4.5% in 2000, slightly increasing to 4.7% in 2020, decreasing to 3.1% in 2050 and further decreasing to 1.8% in 2100. This trend reflects the decreasing relative role of energy in the economic development.

Several factors will have an impact on fuel prices. On the one hand, energy resources will become less abundant and more difficult to develop, which raises the price, while on the other, people have more experience and more advanced technologies, which reduces the price. In the case of A1b-C, the prices of oil and natural gas are relatively stable at US$4 per GJ up to 2015; due to slow depletion of cheap Middle East oil and gas prices increase slowly afterwards to US$7 per GJ in 2050. The price of coal will continue to increase in the whole simulation period; however, its costs are much lower than those of oil and gas.

3.2. B2-C Scenario: China geared to solving regional environmental problems

This scenario follows the SRES B2 storyline. It assumes a slightly lower economic growth (see Table 1) with limited trade and technology transfer among world regions. The basic consideration in this scenario for China is that economic development will utilise domestic resources so as to maintain equity for the future, while maintaining balance among regions as well as between urban and rural areas. Environmental issues—food and water, air pollution and the like—are recognised as serious problems and make environmental sustainability an important priority. This scenario can be described as regional stewardship. The growth of the population is assumed to be the same as in the A1b-C scenario. The energy system will to a larger extent rely on domestic resources, while technological progress is lower for both energy production and end use because of limited trade and transfer. Coal use in this scenario will be based on clean coal technology.

The assumption of the B2-C scenario is that development in China will be oriented at solving regional problems, using predominantly domestic resources. As the main energy resource of China is coal, the strong focus to preserve local environmental resources requires the development in this scenario of clean coal technologies. In addition, energy efficiency will be important to prevent demand for oil and natural gas growing too fast. Thus, an important difference between the B2-C and A1b-C scenarios is the energy demand, which, by the end of the century, is only about half of that in the A1b-C scenario. The structure of end-energy use per sector follows a similar path to that in the A1b-C scenario: the share of industry decreases while the share of transport increases. However, the changes are slower than that in A1b-C scenario. Although the share of industry will

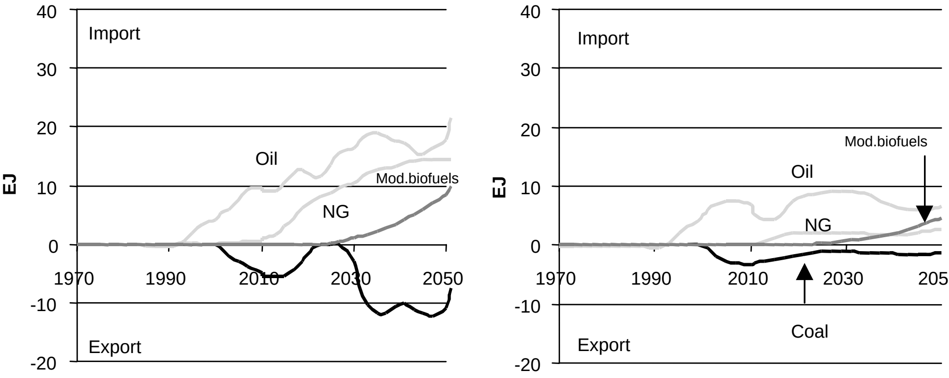

Fig. 3. Net trade in energy carriers following the A1b-C (left) and B2-C (right) scenario.

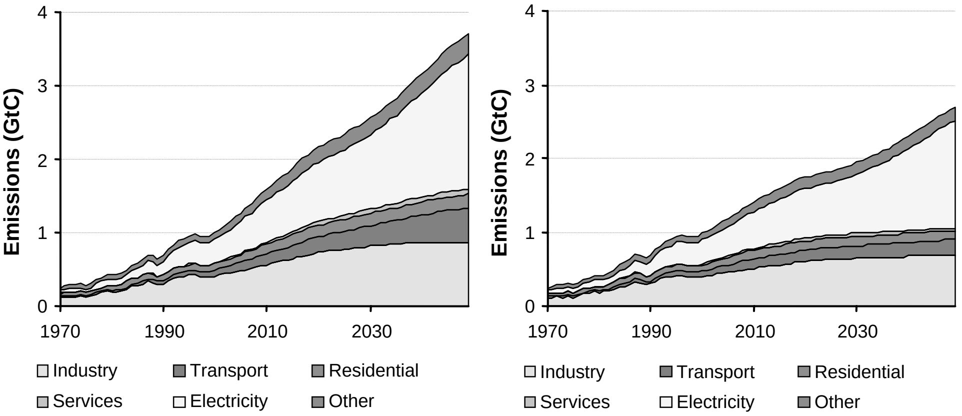

Fig. 4. Carbon dioxide emissions following the A1b-C (left) 1and B2-C (right) scenario.

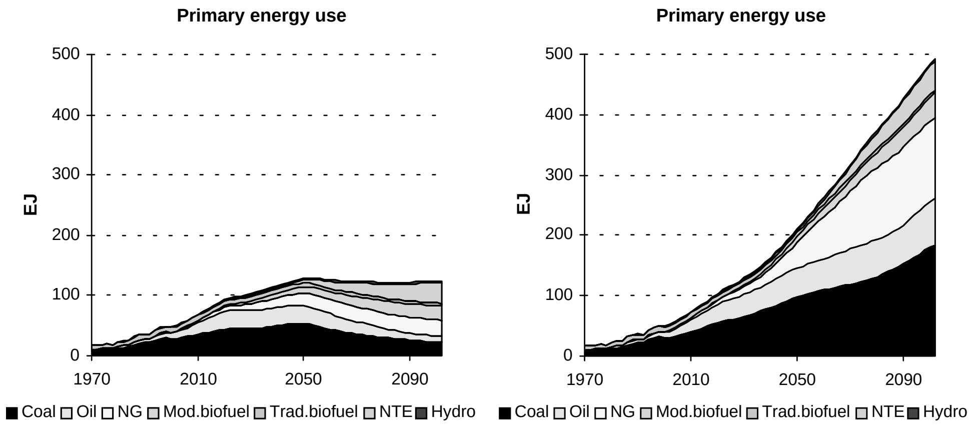

Fig. 5. Primary energy use in the alternative B1-C (left) and A1f-C (right) scenarios. Note: NTE = Non thermal electricity (Nuclear, solar, wind).

slowly decrease to 38% by the end of the century, it will still be the largest energy consumer.

Regarding the structure of primary energy demand by energy carrier, the share of natural gas, modern biomass, solar and wind energy will increase. However, compared to A1b-C scenario, China will depend on domestic energy resources, which means that coal will continue to be the most important energy source in China even though its share will gradually decrease to 53% in 2050 and 34% in 2100. Fuel trade is smaller in terms of both the absolute value and the ratio to total primary energy use compared to that in the A1b-C scenario, although some imports of oil and natural gas seem to be inevitable.

In this scenario, investment in energy are smaller than in the A1b-C scenario but the ratio of energy investment to GDP will follow the same trend as in the A1b-C scenario. The structure of energy investment will also be similar to that in the A1b-C scenario; fossil fuel will lose its share while non-thermal electricity (nuclear and/or renewables) will gradually gain a larger share. Fuel price development shows one remarkable difference. In the B2-C scenario, China depends more on domestic energy resources. Due to depletion of domestic oil and natural gas resources in the late 2010s, their prices and especially the price of natural gas will therefore rise sharply. As a result, the difference between the coal price and the oil and natural gas prices are larger than in the A1b-C scenario in the first half of the 21st century.

3.3. Energy-related carbon dioxide emissions

In 1990, carbon dioxide emissions of China were 0.68 GtC, which rapidly increased to 0.90 GtC in 1995. In contrast, between 1996 and 1999 China experienced a decrease in the emissions of carbon dioxide as a consequence of a set of short-term trends (reduction in economic growth, improvement in coal quality) and longer-term trends (e.g. efficiency improvement) (e.g. Sinton and Fridley, 2000). We have captured some of the relevant factors in our model simulations, for example, as strong improvements in autonomous energy efficiency. In both scenarios, however, the decline in emissions has only a temporary effect. Emissions increase up to 2050 by a factor of 2.7 and 3.8, in B2-C and A1b-C, respectively. For the mitigation scenarios discussed further in this paper, it is important to know where the emissions come from. In both scenarios, electricity generation—based on coal-fired power plants—will become the most important source of emissions (around 50% of all emissions in 2050). The second important source is represented by emissions from (coal use in) industry. Although transport is projected to become a much more important sector in total energy use in China, its share in carbon emissions still remains relatively low.

In both scenarios Chinese carbon dioxide emissions will be close to the USA's in 2030 and further increase to 2.7 billion tonne carbon under B2-C and 3.8 billion tonne carbon under A1b-C in 2050 (Table 1). It should be noted, however, that the carbon dioxide emissions per capita in China are still very low. Per capita emissions will be close to the world average around 2030 and 2050 under B2-C and A1b-C, respectively. Compared to GDP per capita, the relative convergence of China's carbon dioxide emissions per capita to global averages is more rapid. This is because China relies more on carbon-intensive energy resources, especially under the B2-C scenario.

3.4. Alternative scenarios: A1f-C and B1-C

The two scenarios described above are only two of many possible developments in China. Two other scenarios in the SRES set, elaborated upon for China, might be interesting here. These are the B1 scenario, a scenario based on globalisation but time-oriented towards sustainable development, and the A1F scenario—which shares many of its assumptions with the A1b-C scenario but assumes stronger technology development for fossil fuels and less development for new technologies.

The B1 scenario describes a world dominated by high levels of environmental and social consciousness and successful global cooperation. Compared to A1b-C, economic development is slightly slower and there will be a much stronger trend towards that of a service economy. In B1-C scenario, we assume China will not adopt the current energy- and material-intensive lifestyles of the Western world, but choose for a less material, more service-oriented lifestyle (also the Western countries will move in this direction in B1). In such a scenario we see a rapid improvement in efficiencies. The 2100 energy consumption of 70 GJ per capita is relatively low but comparable to the projected OECD average in that year and based on its efficiency, this energy consumed is able to facilitate a much higher level of welfare. The environmental consciousness assumed means that in the scenario, coal use declines and more environmentally friendly fuels such as natural gas and modern biofuels gain market shares. Technology development will also enable extensive use of solar and wind power.

The A1f-C scenario describes a world with strong economic growth and a supply orientation in the energy system. This implies a strongly growing energy demand and large investments in energy supply. Penetration of alternative fuels to fossil fuels is slowed down significantly as we assume more rapid technological development for the latter and slower development for the former. As a result, over the whole century the energy system remains dominated by coal, and later on, also by oil and natural gas, which will take over the use of coal in the transport and building sectors.

Fig. 6 summarises the four scenarios under three main characteristics, energy use per capita, carbon emissions per unit of energy use (carbon factor) and carbon dioxide emissions. In the A1f-C scenario Chinese carbon dioxide emissions are shown to increase to 8 GtC, a level about 30% higher than the current global emissions, caused by large energy use and a very high carbon factor. In the A1b-C scenario emissions reach a level of 30% below those in the A1f-C scenario, the difference mainly being caused by differences in the energy mix (the carbon factor)—with non-fossil based fuels gaining a significant market share in the second part of the century. The B2-C scenario results in carbon dioxide emissions that are about a factor 2 lower than in A1b-C, pushed by its lower energy use. In fact, the relative share of coal in B2-C is higher than in A1b-C (reflected in a

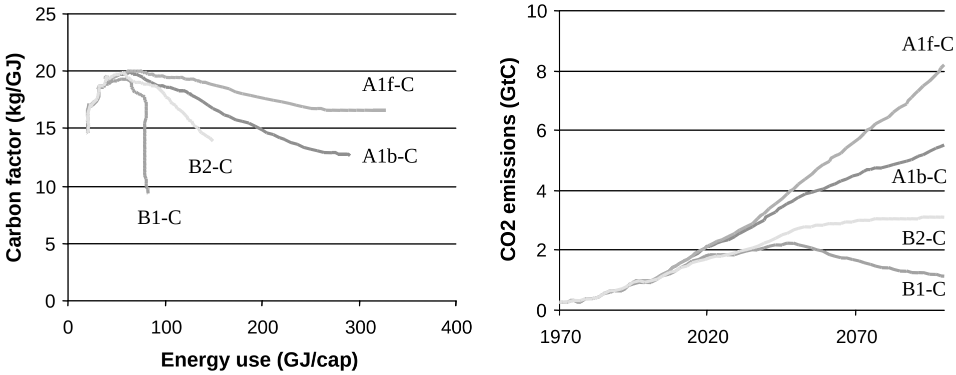

Fig. 6. Trajectory of energy use (GJ per capita) and carbon factor (tC/GJ) (left) and CO$_2$ emissions (right) in the four scenarios developed for China in this analysis.

higher carbon factor). Finally, the B1-C scenario sees emissions doubling in the first half of the century—but consequently declining to slightly above the present level in the second half. This decline compared to A1b-C is caused by both low energy use per capita (efficiency and structural change) and major changes in the energy supply.

The current level of sulphur emissions in China (around 18 Tg SO$_2$) contributes to both regional air pollution (in particular, acidification) and urban air pollution. In addition, sulphur emissions can have an important impact on climate change. Therefore, it might be worthwhile to have a look at trends in these emissions. In all scenarios, we have assumed that the Chinese government will intensify its effort to reduce sulphur emissions. However, the level of effort paid is different—and obviously also the energy mix is different. In Fig. 7 we have plotted the carbon emissions of the scenarios against the sulphur emissions. The main differences between the scenarios are caused by the high level of environmental protection in B1-C and B2-C and the less strict protection levels in A1b-C and A1F. In addition, however, we can see that sulphur emissions are also a function of the changes in energy mix—B1-C has fewer sulphur emissions than B2-C; A1b-C has fewer emissions than A1F. In other words, lower carbon emissions coincide with lower sulphur emissions. The sustainability oriented B1-C scenario benefits in particular from this.

3.5. Comparison with other scenario studies

The scenarios presented here can be compared to other baseline scenarios. Fig. 8 shows a set of recent baseline scenarios taken from various studies, in addition to the historic trend between 1990–1999 (IEA, 2000; EIA, 2001; Weyant, 2001; Sands and Jiang, 2001). All scenarios shown expect emissions to increase—with growth rates ranging from 2.5% to 4.5% per year. Both the A1b-C and B2-C scenarios lie within the range drawn up by these baseline scenarios. Until 2020, A1b-C follows the emission trend of the World Energy Outlook, while B2-C end's up very near to the projection of Sinton and Fridley (2000). Both scenarios tend to be slightly high compared to other scenarios in 2050 reflecting the storylines of the two scenarios (high energy demand in A1b-C and reliance on domestic coal resources in B2-C).

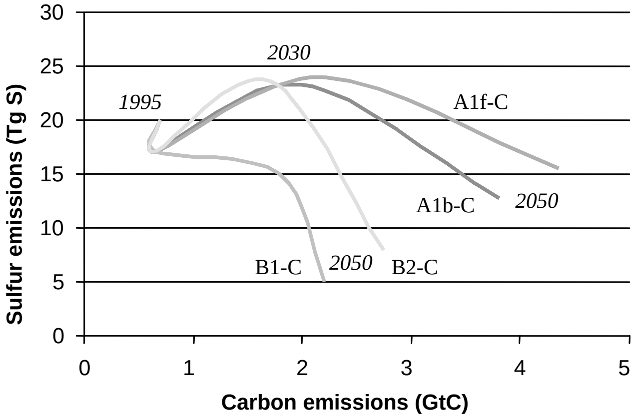

Fig. 7. Carbon and sulphur emissions under four scenarios.

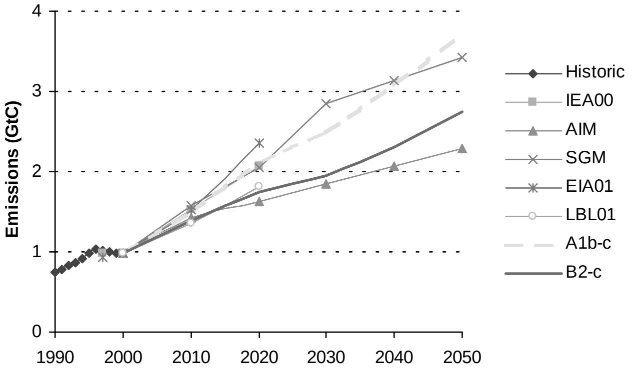

Fig. 8. Carbon dioxide emissions in different baseline scenarios. *Sources:* IEAOO = IEA, 2000; AIM = Jiang et al., 1999; SGM = Sands and Jiang, 2001; EIA01 = EIA, 2001; LBL01-Müller, 2001.

4. Mitigation scenarios for China

4.1. Policy needs for China

In the previous section we have seen that baseline developments are likely to lead to considerable emissions of carbon dioxide and thus to impacts on the global climate. Although developing countries have no obligations so far, the required reductions to prevent severe climate impacts need, in the long-run, participation from both developed and developing countries. In the next section we will attempt to explore the possible policy options for GHG emission reduction by matching sustainable development paths in China and their effects.

4.2. The context for and content of climate change policies in China

China is presently in a stage of rapid industrialisation, with rising incomes, increasing urbanisation and a decline in the share of the agricultural sector in the economy. Although these societal changes can be associated with a more general process of 'modernisation', there are also various circumstances that are specific for China. Hence, one has to carefully investigate the energy and associated systems in China, if one is to recommend policies to reduce GHG emissions. Increasingly, the need for a more sustainable development pattern than the one taken by presently industrialised countries is felt in the less industrialised regions of the world. This is as much a consequence of the perceived local environmental threats as of the possible global consequences of unsustainable practices. China has recognised the necessity of climate change abatement action in response to UNFCCC, which was ratified by China in 1992. In fact, climate change could be an important factor for the Chinese government in designing future environmental development in the framework of sustainable development, a long-term strategy set up by government. Many elements of climate policy could support such a longer-term strategy in the form of co- or ancillary benefits.

For the sake of convenience, we distinguish the following components of climate policies:

- (*Climate change*) *policies*: refers to any action which interferes with the development path in the baseline scenario under discussion;
- *Measures*: the physical changes within the energy system (in fuel use, technology, reduction of energy demand, emission control, etc.) which influence the GHG emissions;
- (*Policy*) *instruments*: the political actions and mechanisms (such as subsidies, low-interest loan provision, educational campaigns, etc.) that are instrumental in implementing and realising the policy measures. The set of policy instruments can be subdivided in several clusters, including economic instruments, regulation, technology support and so-called 'social instruments' (e.g. information campaigns).

Within each of the scenarios outlined in the previous section, there is a range of possible options and measures for GHG emission reduction that could be part of a longer-term climate change mitigation plan or strategy. Some of such options and measures are conceivable within both scenarios from the perspective of economic, political and societal feasibility and desirability. Others are not, in the sense that they will be attractive in the one scenario and unattractive, ineffective or hard to imagine in the other. For their global analyses, the 'SRES' modelling groups did indicate possible storylines for mitigation scenarios, but in the quantified scenarios the storylines seem to have played only a minor role (IPCC, 2001; Morita et al., 2000). Here, we have followed a similar approach. Table 2 indicates the various policy options, measures and instruments that we explored with the TIMER energy model within the context of the two baseline scenarios. For each instrument, we have indicated how likely we considered the implementation of this instrument under each of the scenarios, but in our quantitative exercises we have nevertheless considered all options.

A few important features of these simulations with the TIMER model should be noted:

- Population and economic activity trajectories are exogenous and taken from the baseline scenarios without any feedback from the energy system being taken into consideration.
- The TIMER model is not an optimisation model. It simulates a complex interplay of decisions within the energy system. Hence, the analysis is often based on expert judgements about which policy options and measures are interesting to explore, separately or in combination. The evaluation of the results is not in terms of an objective function but of various relevant system variables such as (changes in) investments, user costs and emission reduction.
- TIMER includes endogenous technology dynamics that have important cost-reducing effects if a technology is pushed by subsidies, demonstration projects and/or standards. For instance, use of energy efficiency measures, lowers the cost of such energy-saving measures through learning-by-doing from accumulated energy-efficiency investments.
- As for all models, the quantification of policies is constrained by the characteristics of the TIMER model. Many of the complex, region-specific social dimensions of the determinants of GHG are absent

Table 2
Overview of policy options/measures, instruments and applicability

Policy measure	Possible policy instruments	Applicability		Implementation explored in modelling experiment
		A1b-C	B2-C	
(1) Incentives for energy-efficiency investments	Taxes/subsidies	±	+ +	Reducing the gap in final energy intensity between Western Europe and China in 2050 by another 30% beyond the baseline
	Low/zero-interest loans	+	+ +	
	Information campaigns	—	+ +	
	Appliance labels/ standards	+	+ + +	
	Investment in public transport systems	+	+ +	
	Voluntary agreements with industry	+ +	+ +	
(2). Energy taxation inducing a series of responses	Tax on gasoline/kerosene, as part of 'greening tax' policy	+	+ + +	Adding an energy tax –equal for all fuel types—for industry and transport equal to current Western European tax levels for oil and gas
(3) Influencing market penetration of secondary energy carriers	Taxes/subsidies e.g. on natural gas or biofuels	+/−	+	Reducing the use of coal in the building sector to zero
	Emission standards	+	+ + +	
(4) High-efficiency, gas-fired combined-cycle (CC) in central electric power generation	Technology and emission standards	+ +	+ +	In 2050, 15–20% of all electricity is generated by gas-fired combined cycle
	Institutional reforms	+ +	+ +	
(5) Advanced clean coal (ACC) options including integrated gasification combined cycle	RD&D projects	+ +	+ +	All new coal power plants from 2010 onwards are highly efficient.
	Investments			
(6) Reduce transmission losses		+ +	+ +	Losses in distribution and transmission of electricity are reduced in 2050 to the level of OECD countries (8%)
(7) Increasing the share of nuclear power generation	Technology and emission standards	+ +	+	Use of nuclear power is increased from 10% (A1b-C) and 7% (B2-C) to 20% of all electricity generated
(8) Increasing the share of renewables such as solar and wind in electric power	portfolio standards/renewable energy obligation	+ +	+ +	Use of new renewables in electric power generation is increased from 7% (both A1b-C and B2-C) to 20% of all electricity generated. In 2020, the required share is 10%
	institutional reforms	+ +	+	Use of hydropower is increased from 68% to 90% of maximum potential of 378 GW
(9) Increasing the share of hydropower generation	RD&D projects	+	+ + +	Overrule market dynamics with expansion targets; 10% market share in oil/gas market 2020, 20% market share in 2050
	Investments			
(10) Accelerating the penetration of biomass-derived fuels	RD&D projects			
(11) Carbon taxation inducing a series of responses	Tax exemption/subsidies to farmers			
	Low/zero-interest loans			
	Portfolio standards/renewable energy obligation			
	Carbon tax on fuel use in all sectors	+ +	+ +	Implementation of a US$30 carbon tax

+ + +: Very well applicable, + +: well applicable; +: applicable; ±: might be applicable; −: poorly applicable.

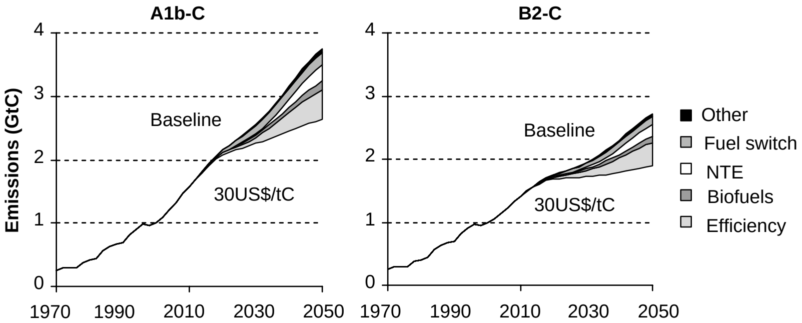

Fig. 9. Attribution of carbon savings induced by US$30 per tC carbon tax in baseline scenarios.

so one has to rely on proxy variables and on storyline related interpretations.

- A method to induce different abatement measures in TIMER is to attach a price to carbon emissions (by means of carbon levy or tax). Such a price generates a range of responses, such as investments in energy efficiency, fuel substitution and investments in non-fossil options. In TIMER, such a tax does not have any impact on the economic activity trajectory.

It should be kept in mind that these policy options and measures have to be introduced and implemented in a large field of competing policy interests. Sometimes, such other policies—for instance, population, employment, or health—have large impacts on the GHG emission path and are as such part of the baseline storyline and scenario.

5. Results for policy scenarios

This study dealt with three types of model experiments:

1. Exploring the system response by introducing a carbon tax during a certain period and at various levels.
2. Exploring the system sensitivity for specific options and measures.
3. Exploring a mitigation scenario by calculating the carbon emission reduction for an increasingly extensive package of the policy options and measures mentioned under point 2.

5.1. Responses to a carbon tax

One of the policy instruments that could be used to reduce carbon emissions is a carbon tax. Many studies have indicated that attaching a price to carbon emissions (for instance by carbon taxation) could be a very cost-effective instrument for inducing a series of measures to be taken in the energy system. The use of a tax allows for a large flexibility among end-users and investors in the choice of the actual measures taken. In models, applying a carbon tax in the system is often also used to get an indication of the possibilities of other instruments.

Fig. 9 shows that a carbon tax, gradually introduced from 2015 and reaching a maximum value of US$30 per tC up in 2030, reduces the Chinese carbon dioxide emissions by 30% in both scenarios. To show the contribution of various reduction measures, we have allocated all avoided carbon emissions to four different clusters: the effects of energy-efficiency improvement, the effects of additional use of modern biofuels, the effects of additional use of non-thermal electricity (in particular, solar and wind) and the effects of fuel switching among fossil fuels.[4]

In the first 15 years after the introduction of the tax in the A1b-C scenarios, reductions are dominated by fuel switch from coal to other fossil fuels; to a slightly lesser extent this is also the case in the B2-C scenario. However, after this period the role of the tax declines rapidly as fossil fuels, including natural gas, are being replaced by non-fossil options. Over the whole period 2015–2050, energy savings contribute most to avoided carbon dioxide emission. From 2030, the effect of renewable mitigation options starts to become more and more important. Other indirect impacts of the carbon tax are discussed further in this paper.

We can obtain some idea of the marginal abatement costs of emission reductions in China by exploring the system's response to different levels of carbon tax. Fig. 10 shows the response in two regions (China and Western Europe) for a hypothetical carbon tax introduced in 2000 for two different sight years, 2010 and 2030 within the A1b-C scenario. The figure shows that significant emission reductions can be achieved in China

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[4] It should be noted that the allocation, particularly the order, will depend somewhat on the methodology chosen. Here, first energy savings have been allocated, next biofuels and non-thermal electricity and finally fuel-switch. Because of the sequence chosen, the effects of the latter are limited only to the changes in the remaining use of fossil fuels, after energy savings and additional non-fossil options have been accounted for.

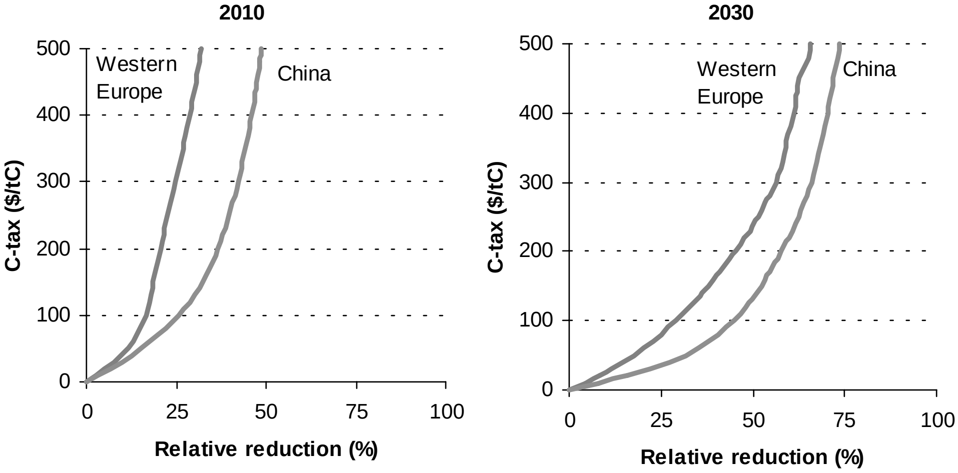

Fig. 10. Relative emission reduction as a function of carbon tax applied for 2010 and 2030 in scenario A1b-C.

at relatively low taxes—certainly in comparison to Western Europe. The figure also shows that significantly larger emission reductions can be achieved in 2030 with the same energy tax (introduced in 2000) as in 2010. This is a function of two important mechanisms within TIMER. First of all, delays within the systems in terms of capital turnover and response time prevent the system from responding immediately to price pressure. Secondly, action taken in response to the tax is assumed to accelerate technology development by means of learning-by-doing, which enlarges the potential for reduction in later periods.

The comparison of the carbon tax response curve of the two regions gives us some idea of the potential for use of the Clean Development Mechanism to meet the required emission reductions of Annex-I countries through actual reductions in non-Annex-I countries. Under the Kyoto Protocol, Western Europe has to reduce its emissions by 8% compared to 1990, which is about 20–30% compared to the baseline.[5] Some current European studies expect that the final carbon price will be around US$50 per tC (e.g. RIVM et al., 2001) (these costs are relatively low as a result of non-CO_2-mitigation options and trading among Appendix A countries). In China, projects corresponding to a shadow carbon price of US$50 per tC could reduce emissions by 15–20% compared to its baseline—or in other words reduce emissions by 0.2–0.3 GtC. This is an enormous potential for emissions reduction making China potentially very attractive for CDM projects.

5.2. Carbon emission reduction: policy options and measures

To get a better idea of the potential impacts of different policies between 2000 and 2050 in China, we have implemented a series of modelling experiments. In most cases we have chosen measures that we regard as ‘moderate’ since they are based on energy policies that are under discussion for the coming decade(s) in Western Europe. The explored measures are discussed in Table 2. The exact implementation in the model is indicated in Appendix B.

Table 3a and b show the mitigation effectiveness and cost aspects of these 11 policy options and measures, for the A1b-C and the B2-C baseline scenarios. Each policy option/measure can be characterised along four axes for an overall evaluation of effectiveness, financial feasibility, political feasibility and strategic consequences. Here, we used the following indicators:

1. *effectiveness*: emissions reduction with respect to baseline;
2. *financial feasibility*: increase in energy system investments;
3. *political feasibility*: additional user costs;
4. *strategic consequences*: changes in total net costs on imported fuels.

The tables show most of our explored measures to have similar results and dynamics in both baseline scenarios. It is interesting to see that many of them differ strongly in the type of response within the system.

One of the most effective and promising options in reducing carbon dioxide emissions is clearly improvement of energy efficiency, reducing carbon emissions by 10–15% in 2050 compared to baseline. The option, however, requires considerable investment from end-users (whom might be covered by subsidies or

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[5] After the 2001 Bonn Agreement and the Marrakesh Accords, the actual reduction target of the EU compared to 1990 is somewhat less, but reductions compared to baseline remain of the same order of magnitude.

Table 3

Measure/instrument (cf. Table 5/ Appendix B)	Carbon emissions (compared to baseline)		Energy investments (compared to baseline)		User costs (compared to baseline)		Fuel balance of trade (compared to baseline)	
	2020	2050	2020	2050	2020	2050	2020	2050
(a) Introducing policy options/measures in China using the A1b-C baseline scenario								
Demand side								
(1) Energy efficiency	−6.2%	−10.8%	6%	9%	2%	3%	−15%	−28%
(2) Energy taxation.	−2.0%	−3.8%	2%	1%	11%	15%	4%	5%
(3) No coal use in buildings	−1.4%	−0.4%	1%	0%	3%	1%	7%	3%
Fossil based electricity								
(4)Combined cycle	−0.5%	−4.9%	0%	2%	0%	2%	2%	10%
(5) IGCC	−5.3%	−9.4%	4%	8%	1%	3%	0%	0%
(6) Improved distribution	−1.0%	−1.0%					0%	0%
Non-fossil fuels								
(7 Nuclear	−0.4%	−9.6%	1%	6%	0%	2%	0%	−4%
(8) Solar/wind	−2.3%	−6.2%	7%	4%	2%	2%	0%	−2%
(9) Hydro	−2.8%	−2.9%	−1%	−1%	0%	0%	−1%	−2%
(10) Biofuels	−0.2%	−0.7%	0%	−1%	0%	1%	0%	6%
Carbon tax								
(11) 30 US$ per tC	−6.5%	−30.6%	6%	16%	20%	20%	28%	30%
(b) Introducing policy options/measures in China using the B2-C baseline scenario								
Demand side								
(1) Energy efficiency	−7.6%	−14.4%	7%	12%	2%	1%	−17%	−28%
(2) Energy taxation	−2.0%	−3.6%	1%	3%	15%	20%	4%	0%
(3) No coal use in buildings	−0.9%	−0.5%	1%	1%	2%	1%	5%	1%
Fossil based electricity								
(4) Combined cycle	−0.3%	−4.5%	0%	1%	0%	1%	0%	5%
(5) IGCC	−3.7%	−9.3%	4%	9%	2%	2%	1%	−1%
(6) Improved distribution	−1.0%	−1.0%					0%	−1%
Non-fossil fuels								
(7) Nuclear	−0.4%	−7.1%	1%	5%	0%	1%	0%	−5%
(8) Solar/wind	−2.2%	−5.0%	7%	4%	1%	1%	0%	−3%
(9) Hydro	−2.4%	−1.9%	−1%	0%	0%	0%	−1%	−2%
(10) Biofuels	−0.3%	−2.0%	−1%	−1%	1%	2%	3%	9%
Carbon tax								
(11) 30 US$ per tC	−6.7%	−29.8%	4%	16%	21%	15%	31%	18%

Note: IGCC = integrated gasification combined cycle.

soft-loans). An important co-benefit of this policy is the sharp reduction in reliance of China on imported natural gas and oil.

The energy taxation measures explored (raising or introducing fuel taxes in industry and transport) have a modest impact on carbon dioxide emissions. Fuel taxes, however, might have an important ancillary benefit in that it can generate the finance required for investment and maintenance of energy and transport infrastructure. Obviously, the taxes lead to increases in user costs. Some of these might be compensated by recycling tax revenues (for instance, reducing the current road construction fee on cars). At the moment, many of the OECD countries are reformulating their tax policies, lowering the taxes on labour and increasing them on resource extractive activities. There might be a potential here for countries such as China to leapfrog this development.

The impacts of banning coal use from buildings has relatively little impact in overall emissions compared to baseline: most of the coal use in these sectors has already been phased out as a result of environmental policies and other trends in the baselines. Nevertheless, further reduction of coal use—where possible, given limited access to other fuel types in rural areas—might have important ancillary benefits for other environmental problems. Obviously, reduction of coal use leads to larger oil and gas imports.

Highly efficient power plants such as combined cycle and IGCC are able to considerably reduce emissions in China. This is particularly the case for IGCC if coal remains the dominant fuel in electric power. The strategy to develop coal-based clean technology could have both environmental and economic benefits, especially if China could become a leader on this technology. It should be noted that improvement of electricity distribution can further reduce emissions by 1%.

In China until 2050, alternatives for fossil fuel in the power sector are likely to remain poor competitors of thermal power plants with large supplies of very cheap coal. Thus, policies aiming to bring down costs of these alternatives (either nuclear, wind or solar) to improve their competitive position are unlikely to be very successful. Additional measures are required, such as long-standing renewable energy obligations or combination of policies to promote non-fossil based alternatives and carbon taxes. The relatively modest policies explored here can reduce emissions by 5–10% for both nuclear and solar/wind power. The contribution of additional hydropower is modest as most of the existing resources are already used in the baselines. Biofuels (as an alternative to natural gas and oil) can reduce emissions to some extent—but will probably need to be imported.

Finally, as indicated earlier, a carbon tax of US$30 per tonne carbon introduced slowly in the 2015–2030 period induce a set of measures, which combined, reduce emissions by 30% in both scenarios. It requires considerable additional investments to be made and increases user costs. As the funds raised by the tax itself can in principle be recycled, the net increase of user costs is 10 to 15%. As the carbon tax induces a large shift from coal to oil and natural gas use, the tax increases the fuel import costs by 20–30%.

5.3. Combining different measures into mitigation scenarios

The energy system is complex and there is a difference between the effectiveness and costs of a single option/measure in isolation or the same option/measure in combination with others. Here, we will present the results of a mitigation scenario based on a combination of the policy options discussed in the previous section. We have grouped them into four different categories: (1) demand side measures, (2) measures for fossil-based electricity, (3) non-fossil technologies and (4) a carbon tax of US$30 per tC, fully effective after 2030.

Fig. 11 (left) shows the carbon emission profile for the sequence of these different options starting from the A1b-C baseline. Demand-side measures form a very important part of the emission reductions obtained in these scenarios. If all options/measures are implemented, emissions are reduced by 50%—leading to a level of 2 GtC in 2050. The type of policies explored should certainly be regarded as feasible. Fig. 11 (right) shows the same results, but now with the B2-C scenario as the baseline. Also here, the carbon emissions can be reduced by around 50%—and the final emissions come to about 1.3 GtC per year (stabilisation after 2020/30). A large potential for GHG emission reduction was also identified in other studies (e.g. Jiang et al., 1998).

5.4. Kaya-factor accounting

The results can also be expressed in terms of the so-called Kaya-identity. Fig. 12 shows the changes in carbon emissions for 1970–1995, 1995–2020 and 2020–2045 for the baseline and the combined mitigation scenario (black bars). In addition, the stacked bars on the left of the black bars indicate which factors have

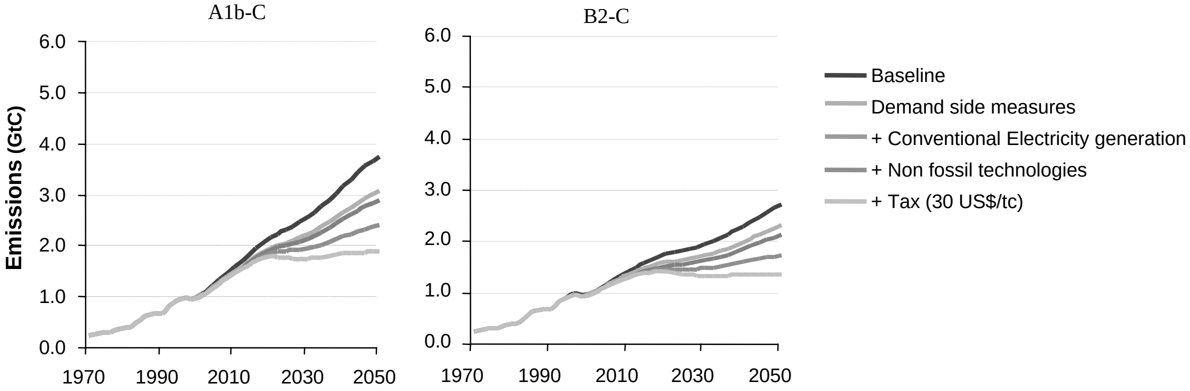

Fig. 11. Carbon emission reductions achieved by a combination of policy measures.

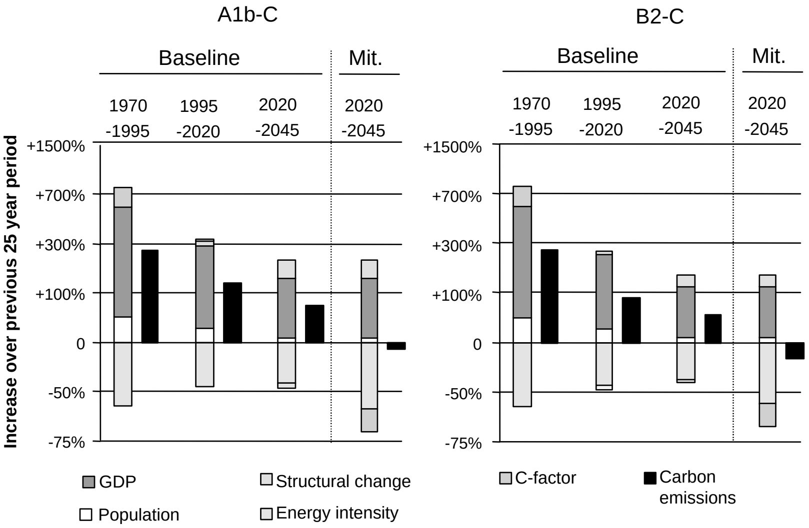

Fig. 12. Changes in carbon emissions in 25 year periods and allocation of these changes to changes in Kaya-factors.

contributed to these changes ('Kaya' factors). The figure shows that not only in the mitigation scenario, but also in the baseline scenario, several factors contribute to emission reductions. Between 1970 and 1995, emissions would have increased by a factor of 8 driven by population and economic growth, and a shift towards commercial fuels, if not for a strong improvement in energy efficiency. Taking this improvement into account, the net increase is slightly less than a factor 4. In the future too, reduction of energy intensity—based either on deliberate policies to improve energy efficiency or autonomous changes—continues to be an important force preventing the Chinese emissions from doubling or even quadrupling in 25 year periods. Reduction in the carbon factor caused by shifts from coal to natural gas in residential areas also plays an important role in this. The mitigation scenarios push the contribution of these factors considerably further. In both the A1b-C and B2-C scenario, the mitigation scenario is successful in actually stabilising emissions after 2030.

6. Conclusions and suggestions

6.1. Conclusions from the scenario analysis

Our scenario analyses suggest a number of trends and options with regard to future GHG-emissions in China. Given economic and population growth scenarios, carbon emissions can be expected to increase with a factor 3–4 in the first half of the century. In absolute terms, the increase will be largest in electric power generation and industrial production. The high growth in electricity demand and the competitive position of Chinese coal in this sector make electricity generation the fastest growing and, from 2015 onwards, largest carbon emitting activity. Industry is also expected to rely heavily on coal for the first decades of the century, but the increasing market share of oil and gas in combination with a decline in the energy-intensity of new industries may well lead to stabilisation in industrial carbon emission before 2040. The fastest growth in energy use is in the transport sector; however, it remains rather small in absolute terms and will mainly rely on oil and natural gas with a lower carbon content. Consequently, the sector is one of the driving forces behind rapidly growing oil and gas imports. In the residential and services sector, a phase-out of traditional fuels and, especially in urban regions, of coal can be expected. Carbon emissions are expected to grow only slowly in these sectors.

Given these trends, China with its coal remaining the dominant energy carrier will contribute an even larger part to global carbon emissions—becoming the largest emitter in the third decade of the century. The IMAGE 2.2 model indicates that both scenarios are expected to lead to an increase in global temperature of about 3–4°C by the end of the century (IMAGE-team, 2001). China is expected to experience temperature increases similar to this overall global increase.

Longer-term carbon emission trends, in the second half of the century, will be largely determined by—uncertain—developments in the economic and social feasibility of non-carbon options such as solar/wind and biomass-derived fuels. It is also in the longer term that the difference between the various scenarios—in terms of sustainable development orientation, openness to fuel trade and the like—starts to make a large difference. For instance, by 2100 primary energy demand may differ up to a factor 4 and carbon emissions up to a factor 8. An important dynamic factor here is the assumed learning-by-doing which induces important cost decreases for non-carbon options as result of R&D and investment programs in the sustainable development oriented future. However, our analyses clearly indicate the large benefits of an orientation on sustainable development, especially in the longer term, for both China—lower urban air pollution, for instance—and the world.

Our exploration of emission reduction options suggest that there is a large potential at costs which are low as compared to international standards. Not all options will be equally attractive and feasible across the various scenarios. In the first decades, a strengthening of energy conservation policies is most beneficial and cost-effective. However, energy efficiency improvements are often confronted most with institutional and financial barriers, especially in rapid growth periods in low-income countries.

Under both baselines, coal is expected to remain a dominant fuel in electricity generation. There are several specific measures to reduce GHG emissions in the electric power sector. First of all, introduction of clean coal use techniques (highly efficient IGCC, for instance) and an accelerated substitution away from coal to natural gas (with concomitant rise in gas imports) can be key options in the electricity sector (*see also* Zhang, 1998). Accelerated expansion of hydropower has only a marginal reduction potential—some 2% by 2050. Other non-fossil fuels, such as nuclear, wind and solar energy can be important to reduce carbon dioxide emissions further, certainly on the longer term. However, in view of the strong competitive position of coal, these fuels can only play an important role when they are supported by a lasting policy-guided effort (e.g. renewable energy obligation targets or carbon taxes). In all cases, the required investment fluxes may pose the largest challenge.

The analyses also show important trade-offs between the different options in terms of investments, increase of user costs, impacts on the balance of trade and emissions. For instance, policies that rely on a fuel switch from coal to oil might be cheap in terms of required investments but increase the costs of fuel imports.

Finally, the model simulations suggest that many of the options would benefit from introduction of a relatively low carbon tax. It was also found that, in view of the differences in costs with Annex-I regions, there could be a considerable potential for CDM projects that could lower some of the financial barriers (see also Sands and Kejun, 2001; Li, 2000).

6.2. *Suggestions for policy implementation*

These policy measures discussed above need to be implemented in the context of existing (environmental) policies and development strategies in China. Below, we will make some suggestions how this could be done, based on knowledge of the Chinese situation, international experience and the results of our analysis.

First of all, policy to reduce GHG emissions could be combined with already existing plans, in particular a domestic sustainable development strategy and the national energy development plan. Sustainable development is already recognised as an important factor for both short- and long-term plans. Agenda 21 for China, announced by the Chinese government in 1994, addresses the sustainable path into the future, which covers many energy activities. Policy options assessed in this study, such as clean energy utilisation, including natural gas, and non-fossil based energy, could well match the targets described in these national plans (see also Zongxin and Zhihong, 1997).

Secondly, it will be important to focus on no-regret opportunities. Much of the potential emission reductions discussed above can be implemented even with finding benefits larger than costs, certainly when taking into account the co-benefits (reduction of air pollution) (Wang and Smith, 1999). International technology collaboration to respond into climate change could provide an essential basis for developing countries to reach their sustainable development goal, such as CDM and technology transfer (see also Jiang et al., 1999).

In terms of instruments many options are available. International cooperation could focus on GHG emission reduction and domestic sustainable development and could help reducing some of the political and financial barriers to GHG mitigation in China. Tax reform in China started 10 years ago: energy subsidies have been reduced and a fuel tax for transport will be established soon. In most OECD countries, energy taxation has originally been implemented for revenue consideration. In view of the different time period, it may be wise for China to consider not only revenue but also environmental concerns in its current tax reforms. Such taxes (either carbon tax or a mixed energy tax) could discourage the use of environmentally harmful energy types and cover so-called externalities. For other issues, a focus on physical planning and performance standards can be more effective than economic instruments.

To conclude, in this paper we have seen that the emissions of carbon dioxide are expected to grow rapidly under different assumptions for the baseline scenario. The rate of increase is determined by several factors, such as economic growth, energy efficiency but also the orientation towards environment and sustainable development values. We have also indicated the potential for emission reduction is considerable, often at low costs. Most options have important trade-offs between different types of policies in terms of investments, user costs, import costs and environmental effectiveness.

Table 4

Demand	A1b-C	B2-C	A1F	B1
Population	In all scenarios, we have assumed population to increase to 1.6 billion in 2050 and afterwards to decrease to 1.5 billion in 2100.			
GDP growth	Very fast (2050: 10230 US$/cap; 5.3% p.a. 1995–2050)	Strong (2050: 7490 US$/ cap; 4.8% p.a. 1995–2050)	Very fast (2050: 10230 US$/ cap; 5.3% p.a. 1995–2050)	Fast (2050: 10230 US$/ cap; 5.3% p.a. 1995–2050)
Lifestyle	Material-intensive lifestyles (relevant parameter reaches a value of 50% above default)	Moderate trend to dematerialisation (relevant parameter reaches a value 10% above default)	Material-intensive lifestyles (relevant parameter reaches a value 50% above default)	Strong dematerialisation (relevant parameter reaches a value 20% below default)
Autonomous efficiency improvement	Fast efficiency development, pushed by private investment	Normal efficiency improvement	Fast efficiency development, pushed by private investment	Fast efficiency development, pushed by private investment and technology transfer
Price-induced efficiency improvement (accepted pay-back times)	Accepted pay-back times reach current OECD levels (e.g. 3 years in industry)	In between A1b-C/ A1f and B1	Accepted pay-back times reach current OECD levels (e.g. 3 years in industry)	Accepted pay-back times reach levels of twice current OECD levels (e.g. 6 years in industry)
Fossil fuel resources	In all scenarios, we have assumed extensive fossil fuel resources in China—with both resources and production costs based on Rogner (1997). These resources also cover undiscovered and unconventional types such as methane hydrates and unconventional oil.			
Energy taxes	Energy end-use taxes converge to current USA levels in 2100 (e.g., 4–6 US$4–6 per GJ in transport)	In 2100, end-use taxes reach a level in between the final B1 level and the current regional level	Energy end-use taxes converge to current USA levels in 2100 (e.g., 4–6 US$/GJ in transport)	Energy end-use taxes converge to current Western European levels in 2100 (e.g., 14–16 US$/GJ in transport)
Preference levels for end-use fuels	Strong aversion to use of coal for health, convenience and environmental reasons	Very strong aversion to use of coal for environmental reasons	Modest aversion from use of coal; problems related to coal use are solved differently	Very strong aversion from use of coal for environmental reasons
Electricity				
Efficiency of thermal power	Increases to 0.47–0.49 for coal, 0.51–0.54 for oil and 0.56–0.58 for natural gas	Increases to 0.44–0.48 for coal, 0.49–0.53 for oil and 0.53–0.57 for natural gas	Increases to 0.48–0.50 for coal, 0.52–0.55 for oil and 0.57–0.59 for natural gas	Increases to 0.44–0.48 for coal, 0.49–0.53 for oil and 0.53–0.57 for natural gas
Preference levels for fossil fuels	No preferences or aversion to any fuel in 2100	No preferences or aversion for any fuel in 2100; only small add-on cost for clean coal.	No preferences or aversion for any fuel in 2100	Very strong aversion from use of coal for environmental reasons
Preference levels for types of production	Indifferent	Indifferent	Indifferent	Preference for renewable electricity production; modest aversion towards nuclear; strong aversion towards fossil
Fuel supply				
Technology development for fossil fuels	Default (0.90)	Default (0.90)	Fast (0.87)	Default (0.90)
Technology development for renewables	Strong till 2040 (around 0.8–0.87), default from 2040 onwards (0.90)	Strong till 2040 (around 0.8–0.87), default from 2040–2060, 2060–2100 slower (0.92)	Slow to very slow (0.92–0.95)	Strong till 2040 (around 0.8–0.87), modestly strong from 2040 onwards (0.88–0.90)

Table 4 (*continued*)

Demand	A1b-C	B2-C	A1F	B1
Trade	No trade constraints	Trade between global regions is limited	No trade constraints	No trade constraints

Table 5

Policy option/measure	Implementation explored in modelling experiment	Changes in model parameters
(1) Incentives for energy-efficiency investments:	Reducing the gap in final energy intensity between Western Europe and China in 2050 by another 30% beyond the baseline.	Increase the accepted payback time for energy efficiency investments in such a way that the required energy intensity is reached
(2) Energy taxation inducing a series of responses	Adding an energy tax –equal for all fuel types—for industry and transport equal to current Western European tax levels for oil and gas	Increase the tax on fuels in these sectors to reach the Western European level by 2020
(3) Influencing market penetration of secondary energy carriers	Reducing the use of coal in the building sector to zero	Introduce a premium factor for coal such as to phase coal out of the residential and service sector by 2020
(4) High-efficiency, gas-fired combined-cycle (CC) in central electric power generation	In 2050, 15–20% of all electricity is generated by gas-fired combined cycle	Change the premium factor for natural gas for electricity generation and change its efficiency
(5) Advanced clean coal (ACC) options including integrated gasification combined cycle	All new coal power plants from 2010 onwards is highly efficient	Change efficiency of coal power plants
(6) Reduce transmission losses	Losses in distibution and transmission of electricity are reduced in 2050 to the level of OECD countries (8%)	Change distribution and transmission losses
(7) Increasing the share of nuclear power generation	Use of nuclear power is increased from 10% (A1b-C) and 7% (B2-C) to 20% of all electricity generated	Forced expansion
(8) Increasing the share of renewables such as solar and wind in electric power	Use of new renewables in electric power generation is increased from 7% (both A1b-C and B2-C) to 20% of all electricity generated. In 2020, the required share is 10%	Forced expansion
(9) Increasing the share of hydropower generation	Use of hydropower is increased from 68% to 90% of maximum implementable potential of 378 GW	Accelerate hydropower by forced Expansion as to reach 350 GWe installed capacity by 2050
(10) Accelerating the penetration of biomass-derived fuels	Overrule market dynamics with expansion targets; 10% market share in oil/gas market 2020, 20% market share in 2050	Forced expansion
(11) Carbon taxation inducing a series of responses	Implementation of a US$30 carbon tax	Implementation of a US$30 carbon tax, slowly building up from 2020 onwards

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Appendix A

Major assumptions within the baseline scenarios are as given in Table 4.

Appendix B. Translation of the policy options into system variables

This appendix indicates how the policy options discussed in the main text have been translated into changes in model parameters are as given in Table 5.

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