

APPLICATION OF A HYBRID MODEL TO EXPLORE ENERGY EMISSIONS ABATEMENT POLICIES IN CHINA

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Abstract

Local air pollution, climate change and energy security are three key policy issues in China's energy sector. The objectives of this research project are: 1) to develop a Chinese energy-economy model which is able to estimate GHG emissions and local air pollutant emissions over time; 2) to use this model to evaluate how to design policy instrument to meet China's emissions control and energy security goals; 3) to use a hybrid model – CIMS, as this incorporates improvements to both the top-down and bottom-up approaches for energy policy modelling.

This study uses CIMS, a technologically explicit and behaviourally realistic model as the modelling tool. The outputs of CIMS can inform decision makers of the effects of different policy actions due to changes in (1) technology stocks; (2) products or energy services; (3) fuel mixtures; and (4) the associated incremental costs. The study covers China by sector (industry, commercial, urban residential, rural residential, transportation, agriculture). Forecasts of growth and structure change are based on the reference scenario defined in the MARKAL China report to the China Council for International Cooperation on Environment and Development (CCICED).

The findings show that there are plausible energy development paths that would enable China to continue economic development while ensuring security of energy supply and acceptable local and global environmental quality. Advanced technologies are identified as the key drivers to achieve ambitious emissions control and energy security targets. Thus the demonstration and commercialization of advanced technologies should be accelerated in the near future to ensure long-term sustainable development in China's energy sector. In addition, this study reveals that while the CO₂ tax can effectively reduce both CO₂ and SO₂ emissions, the SO₂ tax is a policy instrument more specifically addressing local air quality. It is essential to understand the inevitable tradeoff among different policy goals and the associated incremental costs. This study suggests that a best case energy development path can be formulated to achieve all three policy goals. However, this path will be inevitably associated with substantial incremental costs, which imposes a difficult challenge for China's energy policy makers.

Dedication

To my wife Na, with love

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1. INTRODUCTION

1.1 Background

The earth's climate is predicted to change because human activities are altering the chemical composition of the atmosphere through the build-up of greenhouse gases (GHG) – primarily carbon dioxide (CO₂), chlorofluorocarbons (CFCs), methane (CH₄), and nitrous oxide (N₂O). Although uncertainty exists about exactly how the earth's climate responds to these gases, the global average surface temperature has increased by $0.6 \pm 0.2^{\circ}\text{C}$ since the late 19th century. In light of new evidence and remaining uncertainties, most of the observed warming over the last 50 years is likely to have been due to the increase in the GHG concentration (IPCC 2001).

In anticipation of this phenomenon, the United Nations commissioned the International Panel on Climate Change (IPCC) in 1988 to respond to the growing pressure. As a result of the IPCC's deliberations, and growing political acceptance of climate change issues, 160 nations reached a “legally binding” agreement in Kyoto, Japan aiming at reducing the average national emissions of the Annex I countries by about five percent below 1990 levels over the period 2008-2012¹.

As a signatory developing nation, China² approved the Kyoto Protocol on August 30, 2002³ without quantitative commitments to reduce GHG emissions. Since Article 12 of the Kyoto Protocol establishes the Clean Development Mechanism (CDM) to foster sustainable development in developing countries and to help developed countries meet their mandated GHG emission reduction targets cost-effectively, China has attracted

¹ Kyoto Protocol: Third Conference of Parties to the United Nations Framework Agreement on Climate Change. United Nations Framework Convention on Climate Change. Internet: <http://unfccc.int/>

² Hong Kong, Macau and Taiwan are excluded from the historical data and projections presented in this study.

³ <http://unfccc.int/resource/kpstats.pdf>, last modified on 17 March 2004.

more attention as a key player in the global CDM market with its low cost of emissions abatement due to its dependence on carbon-intensive coal as a primary source of energy.

Like GHGs, the primary source of criteria air contaminants (CACs) is also a by-product of fossil fuel combustion. CACs include carbon monoxide (CO), nitrogen oxides (NO_x), sulphur oxides (SO_x), volatile organic compounds (VOCs), and particulate matter (PM). In comparison to GHGs, CACs differ in terms of the nature of their impact on the environment. While GHGs mix uniformly in the atmosphere, CACs behave in a more localized manner. Notably, SO₂, one of the most commonly studied CACs, contributes to the formation of acid rain and photochemical smog. Impacts associated with smog are reduced visibility and a number of health problems including increased respiratory distress. Acid rain contributes to serious environmental and structural degradation by defoliating vegetation, acidifying lakes, and damaging infrastructure. The subsequent costs of mortality, morbidity, reduced visibility, and structural damage can be quite high (Burtraw and Toman 1997).

China, the world's most populous country, has over 1.27 billion inhabitants, accounting for more than 20% of the total world population. Measured in Purchasing Power Parities (PPPs), China is the second largest economy in the world after the United States. A key player in the world energy market, China is the second largest consumer of primary energy behind the United States and the third largest energy producer after the United States and Russia (International Energy Agency 2000b). In October 2002, the Chinese government established the goal of expanding China's economy fourfold by 2020. Because China's domestic oil and gas resources are limited, it is generally believed that China needs to import more oil and gas to achieve the projected development goal, and energy security will become a serious concern in the near future (Downs 2000; International Energy Agency 2000a; Andrews-Speed et al. 2002). Table 1-1 highlights China's growing importance in the world in terms of energy consumption, associated emissions and economic growth.

Table 1-1: China's Rising Importance in the World (Percentage of World Total)

	1970	1975	1980	1985	1990	1995	2000
Primary energy consumption	4.7	5.8	6.4	7.8	8.4	10.4	8.4
Coal demand	12.7	15.5	17.3	20.7	23.6	29.3	20.9
Oil demand	1.3	2.6	3.0	3.2	3.5	5.0	6.5
Electricity generation					5.2	7.6	8.9
CO ₂ emissions				9.6	11.2	13.6	13.3
SO ₂ emission					16.4	24.2	
GDP in current PPP terms		3.0	3.2	4.7	5.7	9.1	11.2
Population	22.5	22.8	22.5	22.2	21.9	21.5	21.0

Source: BP (2003), IEA (2002), RIVM: EDGAR 3.2 (2001), World Bank (2003), United Nations (2002)

The most distinguishable feature of China's energy system is its high reliance on coal. In 1995, China alone accounted for about 30% of world coal consumption. The heavy reliance on coal consumption causes severe air pollution in China. In recent years, anthropogenic SO₂ emissions in China increased rapidly. SO₂ emissions were about 18.4 Mt in 1990, reaching to 23.7 Mt in 1995. In 1995, SO₂ concentrations in 149 cities violated the National Second Class Air Quality Standard (60µg/m³), accounting for 53.2% of the 280 cities evaluated (Hao et al. 2000). The World Bank (1997) estimated that high-level exposure to SO₂ and particulate matters together resulted in \$11.4 billion in damages to public health, accounting for 1.6% of China's GDP. The large SO₂ emissions also caused severe acid precipitation, which caused economic losses in terms of reduction in agricultural productivity, forest damage and material corrosion at around \$5 billion. The total costs of local air pollution in China were approximately 7% of China's GDP.

In 1995, the global discharge of CO₂ caused by human activities was 6.05 billion tons of carbon (tC), of which China accounted for 825 million tC, or 13.6% of the total global emissions, ranking second in the world after the United States (International Energy Agency 2002). However, China's importance in international climate policy is not solely a reflection of its sizable emissions. China also exerts considerable influence in the shaping of the developing countries' position through its involvement in the group of 77

and China (G77/China), and influences both G77 as a whole and those of other single developing countries (Tangen et al. 2001). So the potential impact on world climate change of China should not be underestimated.

In recognition of the severity of SO₂ emissions, the Chinese government acknowledges that air quality degradation represents a threat to long-term sustainable development. In 1995, the newly added Article 27 in the amended Air Pollution Prevention and Control Law requested the designation of Acid Rain Control Zones and SO₂ Pollution Control Zones (Two Control Zones), and formulated an integrated pollution control planning program between 2000 and 2010 (Hao et al. 2001).

However, fearing that future, binding, quantified GHG commitments for China will have great negative macro-economic consequences for the country, the Chinese government is unwilling to undertake any obligation of GHG emission reductions before China attains the level of a medium-developed country. The fundamental arguments China has employed in order to defend its position in the climate change negotiation can be summarized as follows:

- 1) China is still a poor country in terms of GDP per capita, so increased emissions must be allowed in order to develop China's economy.
- 2) China has low per capita emissions. Thus, the Chinese government deems its current GHG emissions as "survival emissions".
- 3) From a historical perspective, China's responsibility for global warming is lower than that of developed countries (Tangen et al. 2001).

With the expected sizable incremental emissions from China, the global GHGs stock is likely to grow even if developed countries reduce their discharge of CO₂. Without some form of cooperation from China, the goal of stabilizing (let alone reducing) global GHG emissions seems to be beyond the limits of feasibility.

During the past centuries, China experienced a temperature rise about 0.2°C higher than the global mean rise (Zhao 1994). Chinese coasts have experienced an average sea level rise of about 11.5 cm (Han et al. 1995). Chinese researchers have showed that if coastal areas are not protected, a 1 meter increase in sea levels will flood regions covering a total of 92,000 km², with 67 million inhabitants (World Bank 1996).

As global warming can accelerate the post-glacial migration rate of tree species by 5 to 50 times and lead to a major disruption of the ecosystems, China is very likely to experience desertification, soil degradation and a loss of biological diversity (Bach and Fiebig 1998). Moreover, a temperature increase of 1°C would reduce rice and wheat yields, China's most important grains, by 6% and 8%, respectively (Tao 1994).

Franhauser (1995) has estimated the total monetary losses for a doubling of atmospheric CO₂ concentration. He found that of all regions in the world, China was the one most severely affected by global warming, resulting in US\$16.7 billion or 4.7% of the GNP losses.

Currently, China is starting to recognize the negative domestic impacts of climate change. Officials in China's Meteorological Administration directly attributed the heavy flooding in 2001, which killed more than 1,000 people, to climate change. The rains occurred in normally arid areas and caused at least \$3.6 billion in damage to agriculture, transportation, power, and other infrastructure according to official estimates (Szymanski 2002). Moreover, considering the recent finding from 12 climate change models that China's average temperature is likely to increase by 2.4 °C - 3.3 °C in 2050 (Zhao et al. 2003), the potential impacts of climate change on China's economy should not be underestimated.

Therefore, along with the increasing pressure from the international community, the domestic concern for climate change in China will become more serious. If current economic growth continues, China's status as a poor developing country is likely to

change. As China's sizable emissions continue to grow, China will be held responsible for its increasing contribution to the GHG concentration in the atmosphere. Without any specified GHG emission control strategy, China's per capita emission is likely to exceed the world average, making it more and more difficult for China to maintain its fundamental arguments to defend its current position. Therefore, Chinese energy policy makers are likely to take more actions to address the challenge of climate change in the future.

1.2 Energy Economy Modelling for China

Anthropogenic GHG and CAC emissions are primarily a result of fossil fuel based energy production and consumption. Therefore, the objective of policymakers is to design policies that will induce actors in the economy to switch to technologies that are more efficient and rely increasingly on renewable or clean energy sources.

Correspondingly, policymakers rely on tools to simplify the energy-economy system, and help them understand how policies will affect the choices of actors, and induce technological change (Jaccard et al. 2002). Energy-economy models are one such type of tool used extensively in the past to evaluate climate and air quality policies, which attempt to capture the impact of energy systems on the wider economy.

1.2.1 Modelling Approach

Energy-economy models are typically classified as 'top-down' or 'bottom-up' in their approach. Each category of models produces very different estimates of the cost and effectiveness of climate policies.

Top-down method

The top-down approach suggests that energy consumption can be understood as a function of a few aggregate explanatory variables. These relationships are thought to remain stable enough that energy demand can be forecasted with a measure of

statistically-supported confidence. Top-down methodologies seek to approach a general equilibrium framework on the basis of historical market data, the parameters of top-down models can incorporate information on how consumers and firms may respond to real changes in the costs of productive and consumptive inputs (Nyboer 1997).

A key limitation to the use of top-down models is their limited depiction of the technology stock and exogenous specification of the autonomous improvements in energy efficiency (AEEI), which precludes the ability to represent potential future technology options and for policies to affect the rate of technological change (Azar and Dowlatabadi 1999). Moreover, the behavioural pattern of top-down models may be subject to the Lucas Critique (Lucas 1976) - past behaviour may no longer hold true in the light of rational expectations regarding policy actions. For instance, the historical price-consumption relationship cannot accurately indicate the likely consumer preferences for new technologies in the future.

Bottom-up method

Bottom-up analysis, most frequently applied by engineers and systems analysts, focuses on the alternative technologies that are available to provide energy services, and how increasing diffusion of these technologies can result in changes in energy use and emissions. Correspondingly, a detailed account of current and future technologies is included in the model, including cost (financial) and performance (efficiency) characteristics.

The key advantage of this approach is that, by accounting for all technologies, it is better able than the top-down method to show the potentials of energy efficiency improvement and fuel substitution to which each technology will contribute under changing regulatory and fiscal policies. However, underestimation of the transaction costs associated with implementing technologies and the failure to account for risks, consumer preferences and market heterogeneity in bottom-up models, when estimating the cost of technology

alternatives, lead to overestimation of the willingness of consumers to switch to emerging technologies. The result is that the social cost of climate policies is underestimated and a prematurely quick and inexpensive improvement in energy efficiency and emission reduction over time is predicted.

Hybrid

Hybrid models attempt to model the energy-economy system by addressing the criticisms of top-down and bottom-up models by incorporating technological detail, consumer preferences, and economic feedback. Hybridization has been approached from both the top-down and bottom-up directions. For example, bottom-up models begin with the benefit of considerable technological detail and can be enhanced with incorporating consumer preferences with the use of information from marketing research and discrete choice modelling studies. CIMS, a bottom-up hybrid model, has incorporated economic feedback with the use of energy service elasticities and integrated supply and demand between energy and production sectors. CIMS has also incorporated parameters describing consumer preferences informed with the use of discrete choice surveys, as well as revealed and stated preference surveys (Jaccard et al. 2003b).

While a hybrid approach is able to shed light on both economic and technological aspects of policy changes, it does present some drawbacks. To obtain consistent linking results between top-down and bottom-up models, a hybrid model needs to remove all the inconsistencies built into these two types of models. This often turns out to be cumbersome and time consuming (Zhang 1998).

1.3 Research Objectives and Research Questions

The preceding discussion has established the need for policy analyses to address the policy issues facing China's energy sector: local air pollution, climate change and energy

security. Correspondingly, decision-makers need a way to keep track of how policies crafted to deal with one policy issue can also affect the dimensions of another.

The climate change issue is rather remote compared to more pressing environmental threats such as local air pollution. Thus, GHG policies are considered as “co-benefits” in my research. The concept is that certain options for GHG emission reductions will simultaneously reduce local air pollution, such as the SO₂ emissions covered in this study. If the benefits of local air pollution reduction are significant, GHG emission reductions can be obtained with low additional costs. This argument is used to plead for a reduction of GHG emissions in China (Gielen and Chen 2001).

Similarly, when the Chinese government takes actions to reduce local air pollution, a tool is required to track the actions stimulated by air quality policy and the corresponding changes in GHG emissions. Hence, the objectives of this research project are:

- 1) to develop a Chinese energy-economy model which is able to estimate GHG emissions and local air pollutant emissions over time;
- 2) to use this model to evaluate how to design policy instrument to meet China's emission control and energy security goals; and,
- 3) to use a hybrid model – CIMS – as this incorporates improvements to both the top-down and bottom-up approaches for policy modelling.

The main research questions of this study are:

- 1) Are there plausible energy development paths by which China could substantially reduce local air pollution while meeting its projected demand for energy services?
- 2) Are there conceivable energy development paths by which China could meet requirements for lower carbon emissions that may arise from climate change concerns?

- 3) Are there plausible energy development paths by which China could meet its projected needs for liquid fuels, while not becoming overly dependent on imported energy?
- 4) Are there plausible energy development paths by which China could ensure the security of energy supply and acceptable local and global environmental quality simultaneously?

1.4 Report Outline

Having outlined the study background and research questions in Chapter One, Chapter Two begins with an overview of the modelling methodology of this study. Chapter Three describes the status of China's energy sector and the assumptions made by the CIMS model. Chapter Four presents the results emanating from the CIMS simulation. Chapter Five compares the marginal abatement cost curve of this study with other sources. Finally, Chapter Six discusses the policy implications of this study and makes recommendations for future research.

2. METHODOLOGY

The research objectives outlined in section 1.4 were pursued with an established hybrid energy-economy simulation model, already used to estimate GHG emissions and the costs associated with Canada's climate policy alternatives as part of the National Climate Change Implementation Process (NCCIP). Section 2.1 starts with an introduction of an energy-economy assessment report by MARKAL-China modellers. Then the rationale of choosing CIMS as the modelling tool are given in details together with the structure, function and cost algorithm of the model.

2.1 Literature Review: MARKAL Application in China

The Working Group on Energy Strategies and Technologies (WGEST) of the China Council for International Cooperation on Environment and Development (CCICED) assessed the future energy strategies for China. The China MARKAL model developed for this assessment was built as a simplified, but representative model of China's energy system. The assessment by WGEST identifies and highlights key implications of different advanced-energy technology strategies that could allow China to continue its social and economic development while ensuring national energy security and promoting environmental sustainability.

The overall conclusion from the analysis is that there are plausible energy technology strategies that would enable China to continue social and economic development through at least the next 50 years while ensuring the security of energy supply and improved local and global environmental quality. To meet all environmental and energy security goals of China, an energy development strategy that relies on the introduction of advanced technologies is essential (Wu et al. 2001).

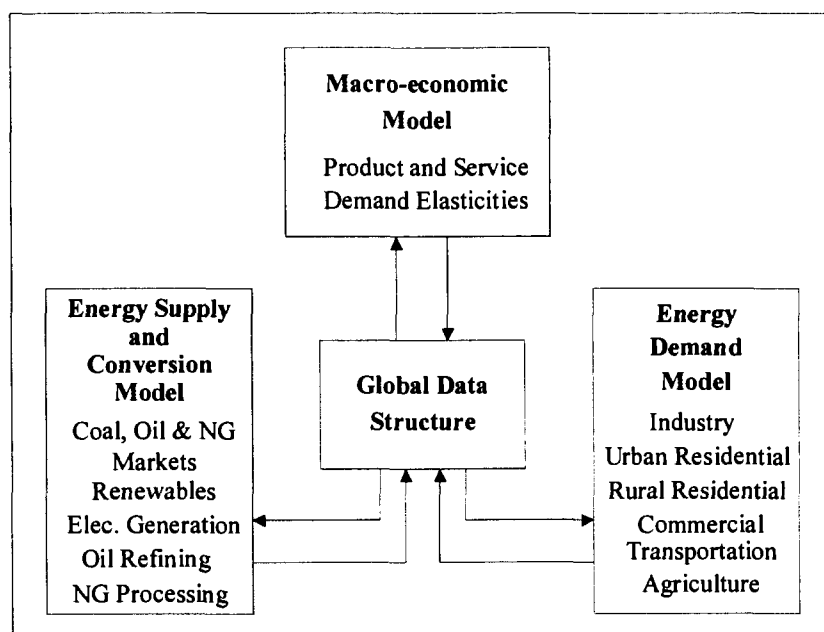
2.2 *Introduction to CIMS*

CIMS is a technology simulation model, developed by the Energy and Materials Research Group (EMRG) at Simon Fraser University. CIMS was designed to help policy makers better understand the effect of policy alternatives aimed at changing energy demands and emissions. Sometimes characterized as a hybrid model, CIMS addresses the criticisms of bottom-up and top-down models by incorporating both technological detail and consumer preferences. With the representation of the energy economy system and the capacity to estimate GHG and CAC emissions, CIMS is an ideal tool for national energy policy planning.

2.2.1 Structure and Function

CIMS represents the economy in terms of annual energy services. Energy services are as diverse as tonnes of market pulp produced, person-kilometers travelled, and square meters of heated commercial floor space. The alternative technologies for providing each service are characterized in terms of capital cost, operating costs, energy costs, energy efficiency, fuel type, lifespan, date of first availability, and intangible costs related to consumers' surplus. Other decision parameters include discount rates, dependence on related investment decisions, constraints on market penetration and cost-reducing feedbacks related to levels of market penetration. As illustrated in figure 2-1, CIMS has three major components. The energy service demand component includes the industrial, residential, commercial, transportation and agricultural sectors. The energy supply component includes conversion models of electricity generation, petroleum refining and natural gas (NG) processing, alongside supply curves for fossil fuels and renewables. The macro-economic component includes energy service elasticity parameters that relate product and energy service demands to their costs. Note that for this study, the macro-economic feedback loop was disabled to permit the isolation of the direct emission reductions in the energy sector associated with policy alternatives.

Figure 2-1: The Major Components of CIMS



2.2.2 Modelling Sequence of CIMS

For this project, a CIMS simulation involves five basic steps.

- 1) *Assessment of demand*: A forecast of growth in demand for energy services is provided for the Energy Demand module in five-year increments from 1995 to 2030.
- 2) *Retirement*: In each future simulation period, a portion of previous-period equipment stocks is retired, following a time-dependent function⁴. If the remaining technology stocks are insufficient to meet the demand for energy services, investment occurs to acquire additional technology stocks to meet the unsatisfied demand for energy services.
- 3) *Competition for new demand*: If new stocks are required, prospective technologies compete to determine which will contribute the remainder of the energy services.

⁴ Following normal retirement, if excess stock exists beyond what is required to meet forecasted growth in demand for energy services, an additional portion of stock is permanently retired.

The market shares of technologies are allocated by using a probabilistic function of life-cycle costs. Section 2.2.3 presents a detailed description of how market share is determined.

- 4) *Equilibrium of energy supply and demand*: Once all information is processed, the model iterates between energy demand and energy supply components until energy prices stabilise at equilibrium.
- 5) *Output*: The simulation ends with a summing of net energy use, net emissions and costs for each technology. The difference between a reference scenario and a policy simulation provides an estimate of the emission changes and cost of the given policy scenario.

2.2.3 Market Competition Algorithm

The equations that determine the proportion of new market share that a technology will capture are described below. In equation 1, the market share function (MS_{kt}) is a logistic relationship between the life-cycle cost of a given technology and all other technologies that compete to fulfil the same service demand.

$$MS_{kt} = \frac{LCC_{kt}^{-v}}{\sum_{k=1}^z LCC_{kt}^{-v}} \quad (1)$$

where:

- | | | |
|------------|---|--|
| MS_{kt} | = | market share of technology k for new equipment stocks at time t, |
| LCC_{kt} | = | annual life cycle cost of technology k at time t, |
| v | = | variance parameter, |
| z | = | total number of technologies competing to meet service demand. |

The slope of the logistic curve is determined by a *variance parameter*, v . The magnitude of v describes the relationship between life-cycle costs and market share for different technologies. For example, a high value for v (e.g., 100) means that the technology with the lowest life-cycle cost captures almost all the new equipment stocks. In comparison, a

very low value for v (e.g., $v = 1$) results in the market share being distributed evenly among competing technologies, regardless of their life-cycle costs.

The life-cycle cost for an individual technology is calculated using the following formula.

$$LCC_k = \left(\frac{CC_k \times \frac{r}{1 - (1 + r)^{-n}}}{SO_k} \right) + O_k + E_k \quad (2)$$

where:

CC_{kt}	=	capital cost of technology k at time t ,
SO_k	=	annual service output of technology k ,
O_{kt}	=	operating cost of technology k at time t per unit of service output,
E_{kt}	=	energy cost of technology k at time t per unit of service output,
r	=	discount rate (time preference)
n	=	equipment lifespan

Equation 2 calculates the life-cycle cost (LCC) as a function of annualized capital costs, operating, and energy costs. The discount rate (r), determines the relative importance of capital costs versus operating costs in the total life-cycle cost of a technology.

Capital costs are calculated using equation 3, which incorporates both financial and non-financial, or intangible costs:

$$CC_k = FC_k + i_k \quad (3)$$

where:

FC_{kt}	=	financial cost of technology k at time t
i_{kt}	=	intangible cost factor of technology k at time t

The intangible cost factor (i_{kt}) can be used to increase the capital cost beyond simply the financial cost of a technology to reflect one or several factors such as identified differences in non-financial preferences (e.g., differences in the quality of lighting from different light bulbs) and perceived risks (e.g., one technology is seen as more likely to fail than another) of technologies (Jaccard et al., 2003).

The parameters v , r and i are critical to the simulation of technology competition, especially with respect to the definition of cost. Sensitivity analyses are conducted for parameter v and r in section 4.5.

2.3 *Supporting Data*

To simulate technology stock change over time, CIMS needs four types of information inputs. First, as a detailed end-use model, CIMS requires data that describe technological characteristics (e.g., capital costs, fuel requirements, technology life). Second, CIMS needs macroeconomic inputs describing changes in sectoral structure and growth in energy demand for products and services. Third, CIMS requires fuel prices and other economic or technical constraints. Finally, CIMS needs inputs of discount rates for each type of decision.

Both MARKAL and CIMS contain the same detailed representation of the technologies. During the national process for estimating mitigation costs, the Canadian government employed CIMS and MARKAL for the integrated, micro-economic analysis of climate policy with the same database of inputs. EMRG has exchanged data with the MARKAL modellers in Canada and has experience with this type of operation. Fortunately, when the research was started, the MARKAL-China database was available, which not only saved the researcher tremendous time from data collection, but also made the methodological comparison between MARKAL and CIMS in Chapter 5 plausible.

2.3.1 Discount Rates

Nyboer (1997) provided a summary of the default values for discount rates used in CIMS. Table 2-1 shows that discount rates vary for the different sectors and even between sector branches, and the discount rates of residential and commercial consumers consistently

match or exceed industrial discount rates. For a detailed description regarding the discount rates used in CIMS, please refer to Nyboer (1997)⁵.

Table 2-1: Discount Rates Applied in Various Sectors and for Various Services

Sector or service	Range (%)	Source
Industrial		
Process	20 – 50	Hassett and Metcalf 1993
Discretionary	>50	DeCanio 1993
Residential		
Shell heating	7 – 21	Lin et al. 1976
	>36	Goett 1978
	6.5 – 16	Goett and McFadden 1982
	4.4 – 36	Reported in Train 1985 [‡]
	26 – 79*	Hartman and Doane 1986
Shell conservation retrofit	15 – 35	Cole and Fuller 1980
	6 – 34	Corum and O'Neal 1982
	>32	A.D. Little 1984
	10 – 32	Reported in Train 1985 [‡]
	52 – 98	Hartman and Doane 1986
Refrigerators	61 – 108	Cole and Fuller 1980
	45 – >100	Gately 1980
	34 – 58	Meier and Whittier 1983
	34 – 108	Reported in Train 1985 [‡]
Appliances	18 – 31	Lin et al. 1976
	24	Dubin 1982
	67	Goett and McFadden 1982
	30 – 70	Reported in Train 1985 [‡]
Commercial		
Shell/HVAC	30 – 50	Lohani and Azini 1992

* For middle income, middle aged groups.

‡ Train (1985) provides a summary of literature on discount rates for residential and automobile use

Source: Nyboer (1997)

The default values of discount rates set in CIMS were used in this study. This might not be appropriate for China. Using sensitivity analysis, the effects of a change of $\pm 5\%$ and $\pm 10\%$ added to the discount rate (e.g., 15%, 20%, 25%, 30%, 35%, 40%, 45%) on technology stock and energy consumption were tested. The results shows that the impacts

⁵ Available online <https://www.emrg.sfu.ca>

on energy consumption by changes in the discount rates are within $\pm 5\%$ (see section 4.5.2).

2.4 The Analysis

In this study, a preliminary forecast is required to determine the trajectory that society is currently on, thus where it is likely to be in a policy target year, from which we will be able to understand the consequences of a set of policies on energy efficiency and changes in CO₂ and SO₂ emissions. There are several terms used for a preliminary forecast. They include reference scenario, business as usual, probable forecast and baseline assumption. The term reference scenario was used in this report. This study used growth rate and structural change from the reference scenario defined in the Appendix A of the MARKAL-China report to CCICED as the reference scenario assumptions (Wu et al. 2001).

Then, alternative simulations were formulated where one (or a combination of) economic parameter (e.g., fuel prices, discount rates, taxes) or constraints in market share of a technology are changed from the reference scenario to determine the consequence of these actions on the energy sector. Each of these simulations is considered as a policy *run*.

2.4.1 Runs Defined

Table 2-2 summarises different runs proposed for China's energy sectors. Five of the simulations described below provide information on the range of possible outcomes to which the results of a set of policy runs were compared. A *reference* run was produced on the basis of the reference scenario. It reflects how the energy system would evolve if no new policies or other influences were invoked, and firms and households acted in a manner consistent with historical indicators. The *reference* run could be perceived as the

most likely trajectory if no new actions were proposed by decision makers, and no abrupt external influence occurred in the future.

Table 2-2: Comparison of Runs under Reference Scenario

Title	Conditions	Purpose
Reference (1 run)	No new policies, <i>de facto</i> Discount rate, <i>status quo</i>	Reference for comparison
SO₂ cap (1 run)	Accelerate energy conservation, coal gasification, decommission of inefficient power plants, stringent fuel standards, etc. to meet national SO ₂ control target	Answer research question 1
39GtC cap (1 run)	Accelerate energy efficient technologies, relax constraint on fuel substitution, decommission of inefficient power plants, etc. to meet national CO ₂ control target	Answer research question 2
Integrated (1 run)	Encourage renewable and efficient technologies, coal gasification and liquefaction, decommission of inefficient power plants, stringent fuel standards, etc. to meet emission control and energy security target	Answer research question 1,2,3, 4 simultaneously
CO₂ tax (6 runs)	Apply different CO ₂ emission charge (10, 20, 40, 60, 80, 100 US\$/tCO ₂)	Test the effectiveness of CO ₂ tax
SO₂ tax (5 runs)	Apply different SO ₂ emission charge (300, 600, 900, 1200, 1500 US\$/tSO ₂)	Test the effectiveness of SO ₂ tax

The *SO₂ cap* run simulates how China's energy sector would respond to national SO₂ emission control targets set by MARKAL China modellers: 22.5, 20.6, 18.5, 16.3, 14.4 and 13.0 MtSO₂ for 2005, 2010, 2015, 2020, 2025 and 2030 respectively (DeLaquil 2003) .

The *39GtC cap* run simulates how China's energy sector could meet the 39GtC cumulative CO₂ emission constraint between 1995 and 2030. The emission control target of 39GtC is consistent with China's atmospheric carbon budget in the 450 ppm CO₂ concentration stabilization profile⁶ developed by Wigley et al. (1996).

⁶ This is also commonly referred to as WRE 450 profile.

The *integrated* run was constructed to test whether it is possible for China to meet CO₂, SO₂ emission control targets and alleviate the energy security constraint simultaneously. While the SO₂ control target of the *integrated* run is as stringent as that of the *SO₂ cap* run, the allowable cumulative CO₂ emissions of the *integrated* run were set as 44GtC, a level higher than that of the *39GtC* run but still consistent with the 550 ppm CO₂ concentration stabilization profile developed by Wigley et al. (1996). Moreover, the energy security constraint in the *integrated* run is defined as follows: imported oil and natural gas account for no more than 30% to 50% of total oil and gas fuel consumption in any given year (DeLaquil 2003).

The remaining two simulations reflect the imposition of CO₂ or SO₂ emission charges. The difference between simulation outputs of a policy run and the *reference* run can provide the decision maker with information about the impact of the simulated policy instrument.

2.5 Cost Methodology

2.5.1 The Techno-economic Cost (TEC) Estimates in This Study

Technical Economic costs (TEC) is the pure financial costs of technologies at the social discount rate (10% in this study). These costs would be the change in expenditures on capital, energy and operations between the reference and policy run, and these are the usual cost estimates from conventional, first-generation bottom-up models. While provided here as single cost estimates, TEC costs in CIMS are probabilistic; they cannot be perfectly represented as a single value (TEC faced by consumers are not uniform) and should therefore be treated as a condensed estimate of a range.

2.5.2 The Expected Resource (ERC) and Perceived Private Cost (PPC)

An estimate of welfare costs has been included in this study. The welfare cost measures are expected resource cost and perceived private cost. Table 2-3 defines the relationship of different costs.

Perceived private costs (PPC) include all costs faced by the private entity. It is the cost the private entities would feel they are facing. This cost is what drives the consumer to make their choices and, thus, determines the compensation required to have consumers do something differently (i.e., move from gasoline to electric car).

Table 2-3: Types of Costs

Type of Costs	Notes
<i>Techno-economic costs (TEC)</i> : Pure financial costs of technologies at the Social Discount Rate.	Includes change in capital, energy and operations costs (with no uncertainty, no variability and no consumers' surplus). Most comparable to 'risk-free' financial cost.
<i>Perceived private cost</i> : This is based on the concept of private avoided costs; firms and households were willing to reduce X tonnes of GHGs when faced with Y shadow price and all other taxes and real prices in the economy	Established as emission reductions multiplied by shadow price.
<i>Expected resource cost (ERC)</i> : This may be conceived as the "real" cost or as the perceived private cost adjusted for risk and general inefficiency.	$ERC = (TEC + (PPC - TEC) * 0.75)$. The missing 0.25 is the estimate of the 'inefficient' resistance of the economy to price signals. ERC is TEC plus the real risk associated with actions.

Source: M.K. Jaccard and Associates (2002)

Expected resource costs (ERC) are the probabilistic financial costs the private entity would incur, including risk and cost of capital, etc. It is generally less than PPC because it does not include the less tangible component of consumers' surplus. Based on substantial literature review, M.K. Jaccard and Associates (2002) estimated $ERC = TEC + (PPC - TEC) * 0.75$. The same cost algorithm was used in this study.

2.6 Development of Environmental Indicators

Environmental indicators are key statistics which represent or summarize a significant aspect of the state of the environment, natural resource sustainability and related human activities. They focus on trends in environmental changes, the stresses causing them, how the ecosystem and its components are responding to these changes, and societal responses to prevent, reduce or ameliorate these stresses⁷.

Historically, environment indicators such as CO₂ emissions and SO₂ emissions are most frequently reported when energy policy modellers try to address the policy issues such as climate change and local air pollution, because these indicators can directly provide the trend in environmental changes, and the associated calculation and analysis could help energy policy modellers identify the stresses causing them and how to design appropriate policy instruments to respond to these stresses.

However, if energy policy makers only focus their attention on these quantitative emission indicators, they are very likely to ignore the pollutants left by fossil fuel combustion. For example, when Chinese bituminous coal is burnt, most of the sulphur will be emitted as SO₂, with a remainder of 5 to 10% of this sulphur left in the coal ash (Chen 2001). In the electricity sector, Flue Gas Desulphurization (FGD) units can substantially decrease the SO₂ emission intensity of coal power plants, but they still cannot reduce the total sulphur in coal. When the SO₂ emissions are reduced, there is more sulphur left in the power plants. If the sulphur content left is not processed appropriately, it could still cause environment degradation such as water contamination. Therefore, in Chapter 4 of this report, a new environment indicator, Sulphur Emission Ratio (SER), was reported in addition to the quantitative emission indicators. The definition of SER is as follows:

$$ER_s = \frac{S_{atmosphere}}{S_{Fuel}} * 100\% \quad (4)$$

⁷ <http://www.ec.gc.ca/soer-ree/English/Indicators/>, accessed on February 6, 2004

where:

$$\frac{S_{\text{atmosphere}}}{S_{\text{fuel}}} = \frac{\text{Sulphur content emitted to the atmosphere}}{\text{Total sulphur content of fossil fuel}}$$

Similarly, ER_c can be defined as the emission ratio of carbon content in fossil fuel. Please note that only ER_s for different SO_2 tax runs was reported in this study. However, in the future, if there was more detailed information regarding the feedstock of the non-energy fossil fuel consumption, and if carbon sequestration became a vital approach for carbon emission control, ER_c also needs to be calculated as a key environmental indicator.

3. ENERGY SECTOR STRUCTURE AND ASSUMPTIONS

China is treated as a single geographic region with six major energy service demand sectors: industrial, urban residential, rural residential, commercial, agricultural, and transportation.

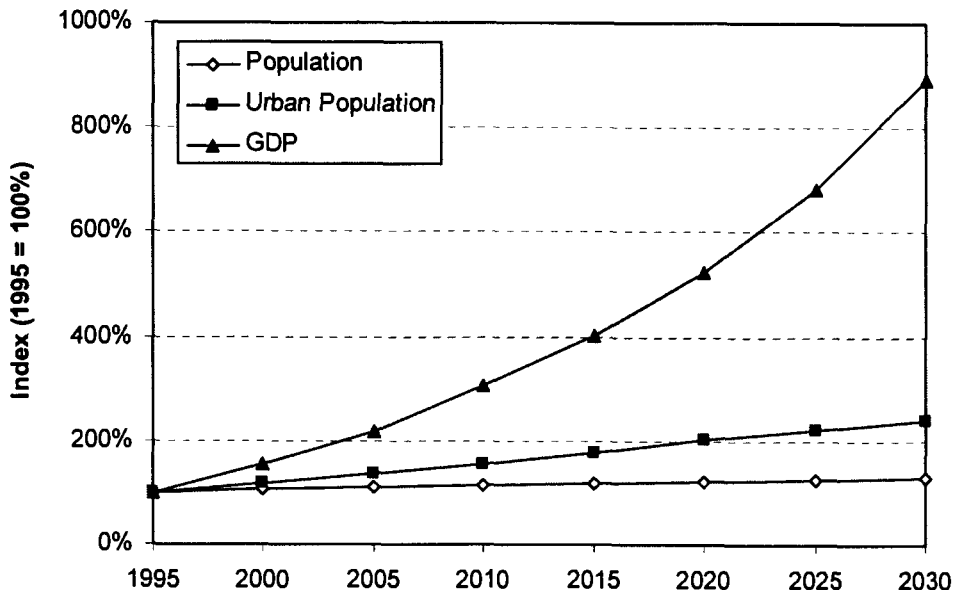
3.1 General Economic Assumptions

In 1995, China had 1.211 billion people, with 31.4% of them categorized as urban population. China's GDP was 709 billion \$⁸. Figure 3-1 presents the general economic trends underlying the energy service demand projections. The population projections and GDP projections are based on the State Economic Information Center internal report from China's State Economic Information Center, and represent their baseline population projection and their lower bound GDP growth rate projection. The urbanization trend shown in figure 3-1 should be understood in the Chinese context, where it does not mean that a person migrated to a city. Instead, it means that the person transferred from some form of land-based employment and non-commercial energy use to some form of industrial or service-based employment, and that they make commercial purchases for energy and other services.

During the 35-year modelling period, China's population will increase by 29%, but the proportion of the urban population will grow more significantly. In 2030, 0.911 billion people, or 58% of the population will live in the cities. Figure 3-1 also shows that China's economy will keep booming. In 2030, the GDP level of China will reach 6,338 billion \$ and the per capita GDP will grow to 4,063 \$ (Wu et al. 2001).

⁸ The monetary unit used in this study is 1995 US\$ unless otherwise stated.

Figure 3-1: General Economic Assumptions



Source: Adapted from table 1 of Wu et al. (2001), see also Lason et al. (2003)

3.2 Final Energy Consumption in the Chinese System

Table 3-1 displays the level of final energy consumption in Mtce⁹ in the energy demand sectors of China. The national total energy end use data were obtained from National Bureau of Statistics of China (1998).

The structure of China's energy statistics makes it difficult to ascertain the actual volume of fuels used for transport purposes. In the historical classification scheme, "transport" consumption includes only the volume used by transportation companies assigned to the transport sector of the economy. Without adjusting the numbers to account for "true" transportation usage, transport fuel demand in China appears fairly low when compared to other countries at a similar stage of development (Yamaguchi et al. 2002). Therefore, adjustment was made to reflect the true size of energy consumption for transportation.

⁹ 1 Mtce = 29.31 GJ

Table 3-1: Final Energy Consumption by Sector in 1995

	Industrial	Residential	Commercial	Agriculture	Transport	Total
Final consumption(Mtce)	682	129	29	39	98	977
Relative share (%)	70	13	3	4	10	100

There is no adjustment regarding the relative share by fuel. In 1995, coal accounted for 62% of China's final energy consumption, followed by oil with a relative share of 20%. Natural gas consumption only accounted for 2% of China's final energy consumption in 1995 due to scarce domestic resources and a lack of infrastructure.

Table 3-2: Final Energy Consumption by Fuel in 1995

	Coal	Oil	NG	Electricity	Heat	Total
Final consumption (Mtce)	608	197	22	114	36	977
Relative share (%)	62	20	2	12	4	100

3.2.1 The Industrial Sector and Assumptions

In 1995, industry consumed 70% of the total final energy consumption but only contributed 48% to the national GDP. The overall level of industrial energy intensity is 1.97 kgce/\$, which is much higher than that of most other countries. Energy service demands for the industrial sector are projected by a combination of two methods. First, industrial output for the five major energy consuming industries (steel, paper, cement, ammonia, and aluminium¹⁰) was projected, and a variety of demand technologies, providing different levels of output per unit of energy input, were modelled. Then, the "Other Industries" sector – comprised of light manufacturing, machinery, electronics, building products, and other industries – was modelled as a single entity with final energy demands for three energy carriers (electricity, process heat and non-energy feedstocks).

¹⁰ These five major energy consuming industries are categorized as "industrial sub-sector" in this study.

3.2.2 The Urban and Rural Residential Sectors and Assumptions

In 1995, the urban residential sector consumed 67.4 Mtce of total final energy. The energy demands in this sector are divided into four categories: air conditioning, cooking and water heating, lighting and electric appliances, and space heating, which were projected independently. In 1995, the rural residential sector consumed 61.6 Mtce of total final energy. The rural residential sector energy demands are divided into three categories: cooking and water heating, lighting and electric appliances, and space heating. The total per capita use of commercial energy in the rural sector was projected to grow in proportion to the GDP growth rate according to an historical elasticity of about 0.6.

3.2.3 The Commercial Sector and Assumptions

Energy demands in the commercial sector are expected to grow quite rapidly in China during the modelling period. The commercial sector floor area requirements are projected according to the ratio of commercial sector floor area to urban residential floor area, which was projected to decrease from 0.47 in 1995 to 0.40 by 2015 and then remain constant. The commercial sector energy intensity was projected to grow from the 1995 value of 13.8 kgce/m² to a value of 18.0 kgce/m² in 2030. Commercial sector energy demands are characterized according to air conditioning, space heat and water heating, and lighting and appliances.

3.2.4 The Transportation Sector and Assumptions

In 1995, the transportation sector accounted for only 10% of China's final energy consumption. However, as improvements in living standards will tremendously expand road usage, transport energy use is expected to increase significantly during the modelling period. Transport activity was projected for both freight and passengers in this study. Freight activity was projected to increase from 3,573 billion t.km in 1995 to 10,418 billion t.km in 2030, and freight transportation demands were modelled according to the following five categories: air, pipeline, ship, rail and truck. Passenger activity was

projected to increase from 900 billion p.km in 1995 to 5,508 billion p.km in 2030, and passenger transport demands are modelled in five categories: automobile, bus, rail, air and ship.

3.3 The Agricultural Sector and Assumptions

In 1995, the agriculture consumed only 4% of the total final energy, and no significant changes are expected in agricultural demand. Future final energy demands for this sector were projected from historical data that indicates an energy demand elasticity of 0.5 to the agricultural share of GDP growth. The energy demand projections were divided into four categories: electric motors, agro-processing, irrigation and farm machines.

3.4 Primary Energy Carriers

The primary energy carriers defined in this study are as follows:

3.4.1 Coal

China has 114.5 billion metric tonnes of proven recoverable reserves of coal (BP 2003) and estimated total reserves of 1,001.9 billion tonnes (Zhang 1998). In 1995, the average cost of coal in China was 0.94 \$/GJ, which is projected to increase at a constant rate of 0.5% per year to reach 1.21 \$/GJ in 2030.

The average sulphur content of unwashed coal is 1.1% (Li et al. 1998). In 1995, 18% of coal in China was washed. The fraction of coal washed in China is assumed to grow to 50% in 2030. Coal washing can remove 10-40% of inorganic sulphur (United Nations 1994b). An Environment Protection Agency study in 1983 reported that in 24 power plants that had capacities over 500 MW, burned coal with over 1% sulphur and had no FGD systems, coal washing produced an average reduction in sulphur emission of 29% (United Nations 1994a). Therefore, coal washing is assumed to be able to reduce overall sulphur content of raw coal by 25% percent in this study.

3.4.2 Oil

China's estimated proven recoverable oil reserves are 17.4 billion tonnes, and estimated total resources are about 94 billion tonnes (Gu and et al. 1999). In 1995, domestic oil production was 150 Mt. The upper bound of oil production capacity is predicted to grow slowly to peak at 190 Mt per year in 2030. In 1995, the average cost of crude oil in China was 17.9 \$/bbl. The cost is projected to increase at a rate of 1.2% annually and will be 27.2 \$/bbl in 2030. The average sulphur content of domestic crude oil is assumed to be 0.5% in 1995 (Zhang 2000).

3.4.3 Natural Gas

China's estimated proven reserves of natural gas range from 1.3 to 2.7 trillion cubic meters (Tm^3) (Qian et al. 1999; USEIA 2001), and estimated total resource are 38 Tm^3 (Zhang 1998). Moreover, an estimated 6 to 13 Tm^3 of coal-bed methane (CBM) is available from proven coal reserves in China (CCCCS 1999), and the total reserves of coal-bed methane in China are estimated at 30 – 55 Tm^3 to a depth of 2,000 m below surface (Yan et al. 2001). In 1995, domestic production of natural gas was 17.9 billion m^3 . Natural gas production capacity is predicted to grow rapidly, and the maximum production capacity could reach 150 billion m^3 in 2030. In 1995, the cost of natural gas in China was 2.3 \$/GJ, which is projected to increase by 1.4% annually to 2030.

3.4.4 Hydro Power

The economically exploitable capacity for hydro power in China is 378 GW (Yan et al. 2001). Moreover, China has an exploitable capacity of 100 GW for small hydro power plants of less than 25MW each (Tong 2003). By the end of 1995, only 13.8% of the total economically exploitable capacity had been developed. Meanwhile, the total installed capacity of small hydropower plants amounted to 16.6 GW, or 16.6% of the corresponding exploitable potential. Therefore, there is great potential for hydropower development in China.

3.4.5 Nuclear Power

Uranium deposits have been discovered in various parts of China. Total known resources are stated to be 70,000 tonnes, and the output in 1999 was 650 tonnes (World Energy Council 2001). In 1995, the installed nuclear capacity in China was 2.1GW, which currently only provides about 1 percent of China's electricity. Unlike many parts of the world, there is so far no significant objection to nuclear power plants in China, and nuclear power is considered as another proven method for the enormous potential of a large-scale generation of electricity without the parallel production of CO₂ emissions. Therefore, rapid nuclear power development is possible in China's future.

3.4.6 Renewables

Renewables cover biomass, wind, solar and geothermal energies. In 1995, their commercial use only accounted for a negligible fraction of national primary energy consumption. No attempt was made to include tidal energy, wave power or ocean thermal energy conversion. While these energy resources might be locally important for some coastal communities, they are unlikely to have a major impact on the energy system of China as a whole.

Biomass

China's annual biomass output of approximately 878 Mt comprises wood chips, firewood, maize cobs, cotton stalks, rice hulls, soy husks, coconut shells, palm nut shells, sawdust and other fuels, and nearly 50% of the biomass output is directly and inefficiently (the efficiency of traditional cook stoves in rural households is only 10-12%) burned as fuels for cooking and space heating in rural households (Lu et al. 2003). In this study, traditional use of non-commercial biomass resources for cooking and heating were not included, while the commercial use of biomass energy resources and the conversion of biomass to modern energy carriers are one important component of the CIMS model.

Wind Energy

The estimated exploitable wind resource in China is 253GW. By the end of 1995, the installed capacity of wind power was 35.3MW (Li and Zhu 1999; Yan et al. 2001). Wind power is expected to grow rapidly in the modelling period.

Solar Energy

China has abundant solar energy resources, and the constraint on this resource is the growth rate for the solar industry. In 1995, the photovoltaics (PV) capacity was 6.63 MWp (Wang 1999).

Geothermal Energy

According to the preliminary estimates, the total capacity of geothermal energy reaches 3,200 GW, 3.5 GW of which can be used for electricity generation (Zhang 1998). In 1995, the total installed geothermal power generation capacity was 28.78MW (Huttrer 2001).

3.5 Conversion Technologies for Primary Energy to Final Energy

A reasonably representative set of conversion technologies that includes 69 distinct technology types is developed into the energy supply and conversion module of CIMS. Conversion technologies are categorized as either *Base* or *Advanced*. The *Base* set includes 36 technologies that have the common feature of being either commercially available today or at a very advanced stage of commercial demonstration. The *Advanced* set includes 33 technologies that share the common feature of not being commercially mature at present (table 3-3).

- 1) *Stand-alone electricity production*: The electricity production module includes both *Base* and *Advanced* technologies.
- 2) *Cogeneration*: Cogeneration refers to the combined generation of electricity and heat. All cogeneration technologies fall in the category of the *Base* set.

- 3) *Polygeneration*: The polygeneration systems produce electricity together with one or more co-products, which include heat, methanol, town gas, Dimethyl Ether (DME), and hydrogen (H₂). All cogeneration technologies in this study fall in the category of the *Advanced* set.
- 4) *Production of Non-electricity energy carriers*: Conversion systems producing energy carriers other than electricity include both *Base* and *Advanced* technologies. The output energy carriers include methanol, Fischer-Tropsch (F-T) fuels, DME and H₂.

Table 3-3: List of Conversion Technologies in the CIMS Model

Base technologies		Advanced technologies	
Stand-alone electricity production			
Steam-cycle coal power	(11)	Coal, IGCC	(1)
Oil (traditional, combined cycle)	(2)	Coal, IGCC with CO ₂ capture	(1)
NG (single, combined-cycle)	(2)	Coal, SOFC with CO ₂ capture	(1)
Nuclear	(1)	Coal, HMSR-IGCC	(1)
Hydropower (small, large)	(2)	Coal, HMSR-IGCC with CO ₂ capture	(1)
Biomass FCB power	(1)	Biomass, village SOFC-microturbine	(1)
Solar PV	(1)	Solar, Centralized PV	(1)
Wind, small-scale local	(1)	Wind, remote large-scale	(1)
Geothermal steam plant	(1)		
Cogeneration, electricity + heat		Polygeneration, electricity + co-products	
Coal, district heat and power	(2)	Coal, IGCC, el + industrial process heat	(1)
Coal, industrial cogeneration	(1)	Coal, IGCC, el + DME (w/o, w CO ₂ capture)	(2)
NG, industrial cogeneration	(1)	Coal, HMSR-IGCC, el + H ₂ (w/o, w CO ₂ capture)	(2)
Biomass, village gasifier/IE engine	(1)	Coal, IGCC, el + methanol + process heat	(1)
		NG, combined cycle with CO ₂ capture	(1)
		NG, comb. Cycle el + F-T liquids	(1)
		Distributed fuel cell, el + heat (NG, H ₂)	(2)
		Biomass, IGCC, el (w F-T liquids or DME)	(2)
		Biomass, village microturbine, el + heat + gas	(1)
Production of non-electric energy carriers			
Coal, district heating plant	(2)	Coal, methanol	(1)
Coal, coke production	(1)	Coal, F-T liquids (w/o, w CO ₂ capture)	(2)
Coal, town gas	(2)	Coal, DME	(1)
Oil refinery	(1)	Coal, H ₂ (w/o, w CO ₂ capture)	(2)
Biomass, village-scale biogas	(1)	NG, Methanol	(1)
Biomass, village producer gas	(1)	NG, F-T liquids (w/o, w CO ₂ capture)	(1)
Coal washing	(1)	NG, DME	(1)
		NG, H ₂ (w/o, w CO ₂ capture)	(2)

Source: Summarized from Wu et al. (2001) Appendix B

Note: Figures in the parentheses indicate the number of energy systems under each category.

4. SIMULATION RESULTS

When the simulation of each policy run was completed, the output data were reviewed for consistency to identify errors and to determine the need for the next model iteration. The difference between a policy run and the *reference* run reflects impacts of the simulated policy instrument on the reference forecast. In this chapter, following a brief description of the *reference* run calibration, the detailed results of the *reference*, *CO₂ cap*, *SO₂ cap*, and *integrated* runs were compared with each other, in order to demonstrate how China's energy sector would respond if national emission control or energy security targets were set. Then the *CO₂ tax* runs were analyzed to distinguish changes from the *reference* run and determine the impacts of the CO₂ tax on the reference forecast by reviewing the level of CO₂ emissions, costs and associated benefits. The marginal abatement curves of CO₂ emissions were presented at both national and sectoral levels. Finally, the *SO₂ tax* runs were compared to the *reference* run to assess the effectiveness of the SO₂ tax on SO₂ emissions abatement and the associated impact on CO₂ emissions.

4.1 Calibration of the Reference Run

Based on the reference scenario defined in the Appendix A of the MARKAL report to CCICED, the reference energy consumption of CIMS was calibrated for each energy demand sector in 1995 and 2030. Table 4-1 shows that the variance levels are within $\pm 1\%$ range, except for the transportation sector. The inconsistency of the transportation sector calibration reflects the uncertain nature regarding the true size of this sector and the different modelling methods to track transport energy consumption between MARKAL and CIMS. However, the overall variance levels in 1995 and 2030 are still within $\pm 3\%$, which indicates that the impacts on national end energy use from the transportation sector calibration are still within an acceptable range.

Table 4-1: Calibration of the *Reference* Run, 1995 and 2030

	1995			2030		
	MARKAL (Mtce)	CIMS (Mtce)	Difference (%)	MARKAL (Mtce)	CIMS (Mtce)	Difference (%)
Industry	688	682	-0.9%	1,304	1310	0.5%
Commercial	29	29	0.0%	180	180	0.1%
Residential	129	129	-0.1%	487	491	0.8%
Transport	90	98	8.9%	507	427	-15.7%
Agriculture	39	39	0.0%	82	82	0.0%
Total	975	977	0.2%	2,561	2491	-2.7%

4.2 Detailed Results for Reference and Three Policy Runs

In this section, the impacts of different emissions and energy security constraints on China's energy sector are clarified from the following perspectives.

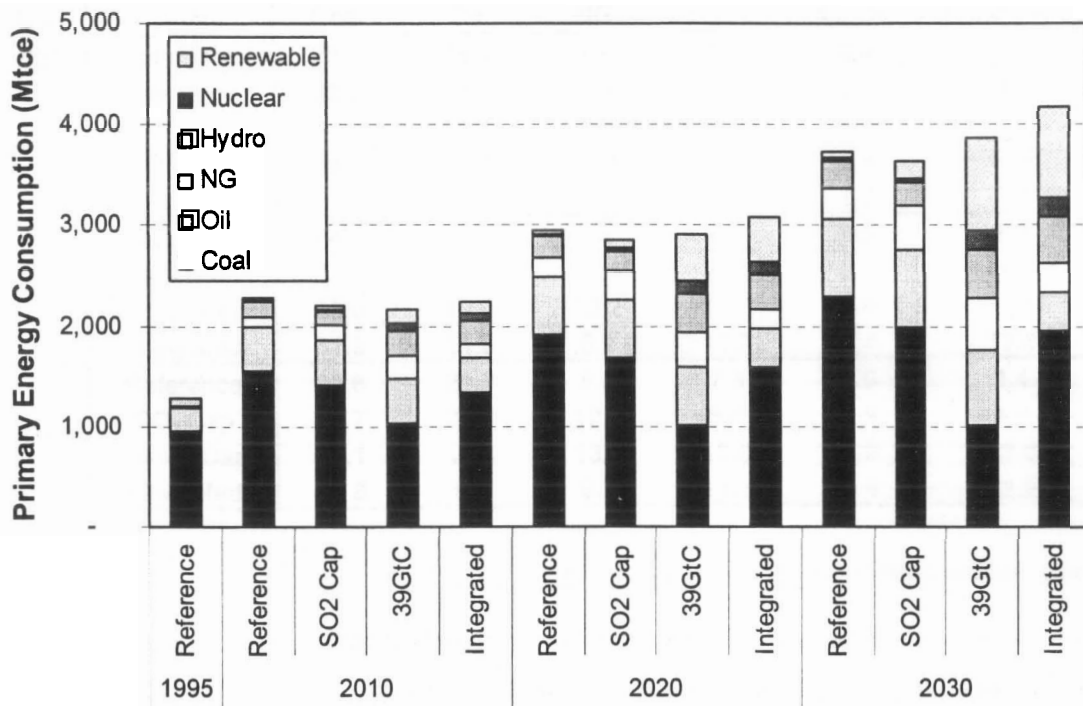
4.2.1 Total Primary Energy Consumption

Primary energy consumption¹¹ in the *reference* run grows rapidly from 1,288 Mtce in 1995 to 3,731 Mtce in 2030. Figure 4-1 shows that while the primary energy consumption of all three policy runs follow a similar trend, their relative fuel mixtures differ with each other.

In 2010, the primary energy consumption of the *reference* run is slightly higher than all the three policy runs. In 2030, this relationship only holds between the *reference* run and *SO₂ cap* run. Moreover, the primary energy consumption of both the *39GtC* run and *integrated run* are higher than the *reference run* in 2030. But the fossil fuel consumption of these two policy runs is much lower. Therefore, the higher primary energy consumption of these two policy runs in the late years is attributable to the increase in primary electricity consumption.

¹¹ The calculation of primary energy equivalent of this study is based on the partial substitution method, in which the primary energy equivalent of nuclear, hydro, wind, geothermal, PV electricity represents the amount of energy that would be necessary to generate an identical amount of electricity in conventional thermal power plants (IEA 2002).

Figure 4-1: Total Primary Energy Consumption



Coal is the dominant energy carrier in the *reference* run throughout the 35-year modelling period. Coal consumption increases from 952 Mtce in 1995 to 2,297 Mtce in 2030, falling only modestly in terms of the share of primary energy consumption from 74% in 1995 to 62% in 2030 (table 4-2). The fraction of coal used for electricity generation increases gradually from 32% in 1995 to 53% in 2030. To meet the emissions control, or energy security target, direct coal combustion in energy demand sectors is phased out and more coal is used to produce electricity or coal-derived oil and gas in all three policy runs.

Table 4-2 demonstrates that the share of coal in the *39GtC run* decreases significantly to 26.1% in 2030. Considering the abundant coal reserves in China, the energy mixture of this policy run is inappropriate for China's sustainable energy development. In contrast, the share of coal in the *SO₂ cap run* and *integrated run* decreases to 54.7% and 46.8% respectively in 2030.

Table 4-2: Share of Primary Energy Consumption by Fuels (%)

Year	Scenario	Coal	Oil	NG	Hydro	Nuclear	Renewable
1995	Reference	73.9	18.3	1.8	5.5	0.4	0.0
2010	Reference	68.2	19.1	4.5	6.6	0.8	0.8
	SO ₂ Cap	64.1	19.7	7.3	6.4	0.7	1.9
	39GtC Cap	48.1	19.8	10.4	11.8	3.8	6.0
	Integrated	59.7	15.9	5.4	10.7	3.5	4.8
2020	Reference	64.7	19.8	6.3	7.1	0.9	1.1
	SO ₂ Cap	59.1	20.3	10.1	6.7	0.8	3.0
	39GtC Cap	35.0	19.6	12.2	12.9	4.9	15.5
	Integrated	51.9	11.9	6.2	11.7	4.4	13.8
2030	Reference	61.6	20.7	8.0	7.3	1.0	1.4
	SO ₂ Cap	54.7	21.0	12.0	6.6	0.9	4.8
	39GtC Cap	26.1	19.3	13.3	12.6	4.9	23.8
	Integrated	46.8	9.3	6.7	11.3	4.4	21.5

In the *reference* run, the share of oil stays nearly constant over the modelling period, and the share of gas increases significantly from 1.8% in 1995 to 8% in 2030. For the *SO₂ cap* run and *39GtC cap* run, the share of oil is similar to the *reference* run, but the share of gas is significantly higher. Being the only run that could meet the energy security constraint, the *integrated* run relies the least on oil and gas consumption.

In the *reference* run, hydro and nuclear electricity together account for 310 Mtce, or 8.3% of primary energy consumption in 2030. Installed nuclear power increases from 2 GW in 1995 to 9 GW in 2030, and Hydro power grows from 52 GW in 1995 to 160 GW in 2030. The capacity of hydro and nuclear power peaks in the *39GtC* run. During the 35-year modelling period, hydro power grows to its maximum allowed level, 330 GW in 2030, and nuclear power reaches 54 GW in 2030.

4.2.2 Technology Selection

The different emissions and energy security constraints have fundamental impacts on the technology selection during the 35-year modelling period. Figure 4-2 shows that the natural gas consumption level of the *39GtC* run is the highest among all the runs. Natural gas and CBM together increase from 24 Mtce in 1995 to 516 Mtce in 2030. To allow

more natural gas consumption, the cumulative CO₂ emissions of this policy run are the lowest, while the imported natural gas is the highest among the 4 runs, peaking at 240 billion m³ in 2030.

To meet the SO₂ emission abatement target, coal gas in the *SO₂ cap* run increases rapidly after 2005, while the natural gas consumption maintains a high growth rate. In the *integrated* run, DME and Methanol from coal liquefaction and polygeneration grows quickly after 2005, and the proportion of imported oil and gas could be limited below the 30% energy security constraint. Demand for hydrogen also grows significantly after 2015, and the least costly source of hydrogen is from coal polygeneration technologies in the electricity sector.

Figure 4-2: Comparison of Gas and Synthetic Liquid Fuels

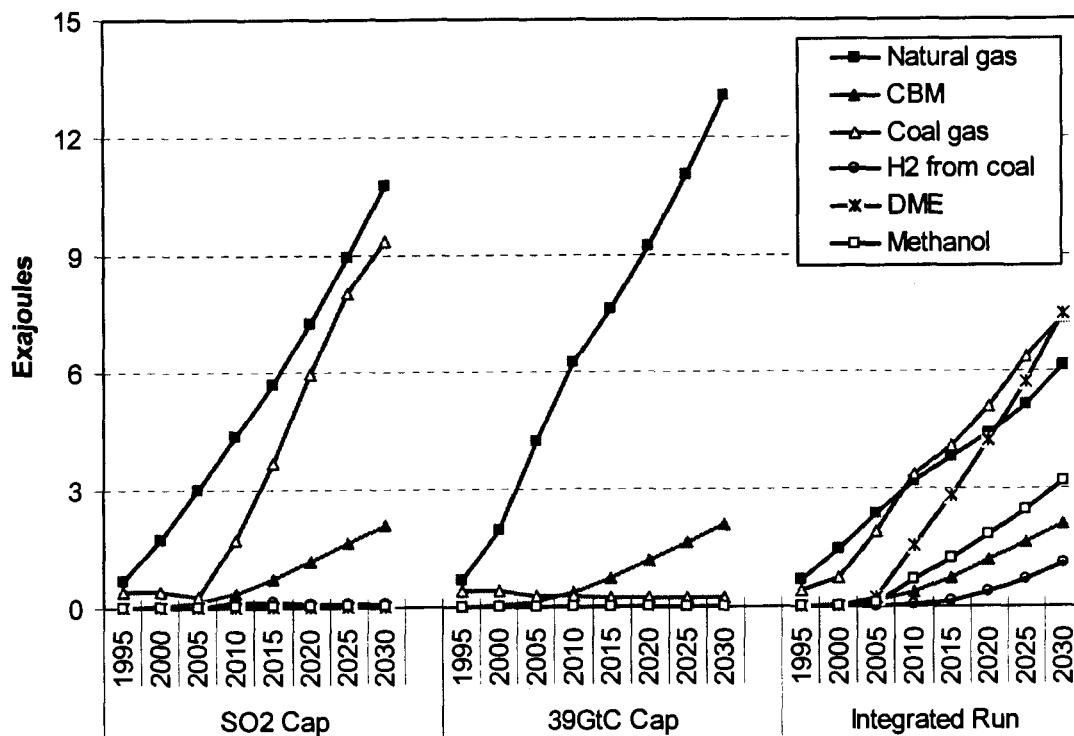


Figure 4-3 presents the full picture of electricity generation by fuel and technology class for the SO_2 cap run and 39GtC cap run. In the SO_2 cap run, coal-fired power plants dominate the electricity sector, providing 59.4% of electricity in 2030. The investment on coal-fired power plants without FGD units is phased out during the modelling period to achieve SO_2 emission reductions. Table 4-3 shows that electricity from NG-fired power plants increases from 0.3% in 1995 to 16.3% in 2030, while both hydro and nuclear power maintain the same generation mixture levels over time. In the 39GtC run, hydro power grows to its maximum allowed level (330 GW) in 2030, and nuclear power reaches 54 GW in 2030. Because the modelling period of this study is only 35 years, coal-fired power plants with carbon sequestration can only capture 3.3% market share in terms of electricity generation in 2030.

Figure 4-3: Fuel/Technology Selection Comparison of Electricity Generation

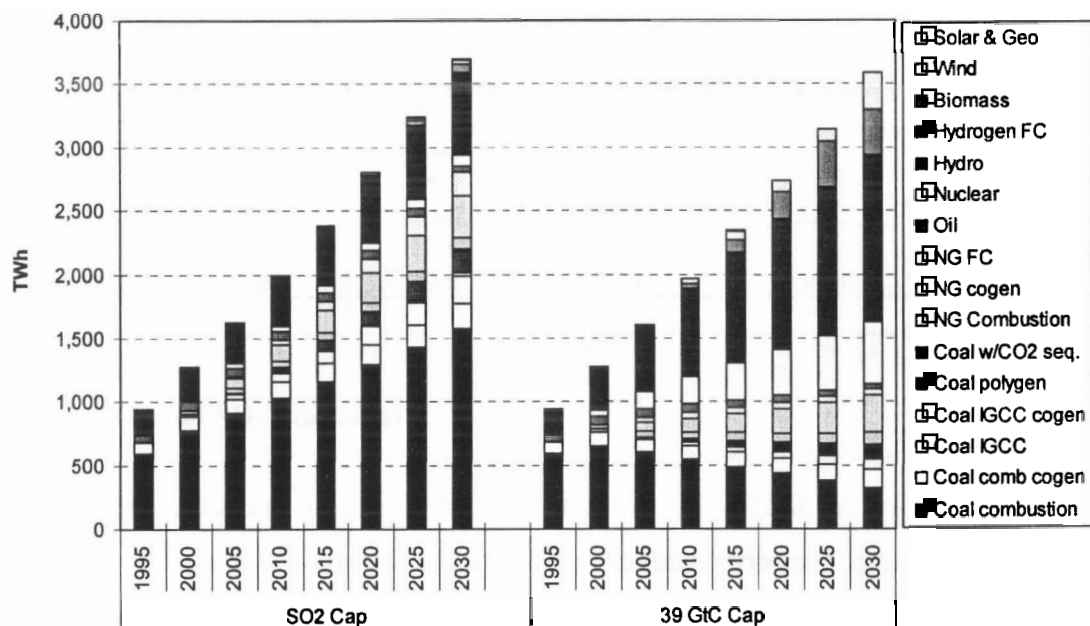


Table 4-3 shows that the market share of oil-fired power plants continues to decline in all runs. The explanations are as follows:

- 1) High fuel costs place oil-fired power plants in an unfavourable position to compete with electricity from coal or hydro sources to provide base load electricity;
- 2) NG turbine plants are more flexible than oil-fired plants to provide peak load electricity; and
- 3) CO₂ and SO₂ emission constraints, and the energy security target are all negative policy signals for oil-fired power plants.

In both the *39GtC* run and *integrated* run, electricity generated from renewable sources, notably large remote wind farm and biomass, grows very quickly. In 2030, renewable sources can provide about 18% of electricity in both runs.

Table 4-3: Share of Electricity Generation Mixture by Fuels (%)

	1995	2030			
	Reference	Reference	SO ₂ Cap	39GtC Cap	Integrated
Coal	72.3	73.2	59.4	18.4	22.1
Oil	5.8	0.8	1.5	1.0	0.8
NG	0.3	4.0	16.3	12.2	13.1
Hydro	20.2	18.7	17.5	36.3	33.9
Nuclear	1.3	2.5	2.2	13.6	12.9
Renewable	0.0	0.8	3.0	18.5	17.3
Total	100	100	100	100	100

4.2.3 CO₂ and SO₂ Emissions

CO₂ and SO₂ emissions hit as high as 2,256 MtC and 42 MtSO₂ in the *reference* run. The cumulative CO₂ and SO₂ emissions during the modelling period are 55 GtC and 1,193 MtSO₂ respectively.

In the *SO₂ cap* run, the cumulative SO₂ emissions decrease 43% but the cumulative CO₂ emissions only decline marginally by 7% (table 4-4). In the *39GtC* run, CO₂ emissions are 1,247 MtC in 2030, and SO₂ emissions follows a trend which is even lower than those

of the *SO₂ cap* run. The *integrated* run is able to meet both *SO₂* emission and energy security constraints, but the cumulative *CO₂* emissions are 12% higher than the *39GtC cap* run. This is because when coal gasification and liquefaction is accelerated in the *integrated* run to meet the energy security target, it is more difficult to achieve the same level of *CO₂* emissions abatement as the *39GtC* run.

Table 4-4: Comparison of *CO₂* and *SO₂* Emissions

	CO ₂ Emissions (MtC)				SO ₂ Emissions (MtSO ₂)			
	1995	2010	2020	2030	1995	2010	2020	2030
Reference	842	1,436	1,814	2,256	23.7	32.3	36.9	42.0
SO ₂ Cap	842	1,348	1,650	1,982	23.7	20.6	16.3	13.0
39GtC Cap	842	1,087	1,154	1,247	23.7	18.3	15.3	12.6
Integrated	842	1,181	1,341	1,555	23.7	19.0	16.0	13.0

4.2.4 *SO₂* Damage Costs Estimation for the *Reference* Run

Once *SO₂* emissions are calculated there are two alternative ways to estimate the *SO₂* damage costs. The simplest approach involves multiplying *SO₂* emissions by aggregate unit values that describe costs per tonne of *SO₂* emitted (\$/tonne) (Ayres and Walter 1991; Williams 2001). Alternatively, a more disaggregated, damage-function approach may be followed, as outlined in Rabl and Spadaro (2000). In this latter approach, *SO₂* emission changes are converted as changes in the ambient air concentration, followed by estimation of the effect on human and natural systems. Finally, the impact on human health and the environment is monetized to generate the final costs. Because the previous approach is less time consuming and involves more simplified assumptions than the latter, the aggregate unit values approach was used to calculate *SO₂* damage costs of the *reference* run in this study.

Based on the principle of Willingness-to-pay (WTP), Rabl and Spadaro (2000) reported that the median estimate of *SO₂* damage costs from power plant sitting in Europe was

10.44 US\$/kg. In this study, the following equation was used to adjust the income difference between China and Europe.

$$WTP_{\text{China}} = WTP_{\text{Europe}} (\text{Income}_{\text{China}}/\text{Income}_{\text{Europe}})^e \quad (5)$$

Where e represents the income elasticity of WTP, and GNI per capita was used as the proxy for Income in this study.

There is considerable uncertainty regarding estimates of the income elasticity of WTP. Assuming an income elasticity of WTP that is well below 1.0 often leads to implausibly high estimates of WTP. A conservative approach to benefits transfer is to use an income elasticity of 1.0¹².

Considering all the uncertainties and the controversial nature of the WTP method, the SO₂ unit damage costs of China are reported in a possible range instead of a single fixed value. In this study, the SO₂ unit damage cost from power plants was used as the proxy of SO₂ damage costs for all SO₂ emissions in China. Because the SO₂ emissions from non-electricity sources mainly come from the energy demand sectors, which are closer to the densely inhabited areas than power plants, the aforementioned approximation is a conservative estimate of the damage costs for national SO₂ emissions. This inference is supported by the findings from Lao (1998).

Table 4-5 displays that the SO₂ unit damage costs on the basis of WTP grows rapidly along with the expected economic boom in China, and the SO₂ damage costs increases more quickly than the unit costs. Measured as percentage of GDP, the SO₂ damage costs are at the range of 0.48% to 1.92% in 2030. If China's energy sector evolves according to the historical trend, the impacts on public health and the environment from SO₂ emissions are likely to be increasingly serious in the future.

¹² <http://www.cleanairnet.org/infopool/1411/article-35665.html>, accessed on January 22, 2004

Table 4-5: Illustration of SO₂ Damage Costs in the *Reference* Run

	1995	2010	2020	2030
	SO ₂ Unit Damage Costs (\$/kgSO ₂) ^a			
High	0.42	1.12	1.77	2.90
Low	0.10	0.28	0.44	0.72
Lao (1998) ^b	0.595			
	SO ₂ Damage Costs (Billion \$)			
High	9.9	36.1	65.3	121.7
Low	2.5	9.0	16.3	30.4
Lao (1998)	14			
	SO ₂ Damage Costs as Percentage of the GDP			
High	1.39	1.66	1.76	1.92
Low	0.35	0.42	0.44	0.48
Lao (1998)	1.99			

a: The rising trend of unit damage costs reflects the increasing income effect from 1995 to 2030.

b: The SO₂ unit damage cost used in this table actually comes from table 6 of Michaelowa et al. (2000).

The SO₂ damage costs estimation of this study is based on many simplified assumptions, and does not incorporate the cumulative effect of SO₂ emissions from previous years. Thus the figures presented in table 4-5 are only for illustrative purposes. In the future, if moderate geographic disaggregation is realized for CIMS China, the damage function approach could be used for more accurate estimation of SO₂ damage costs.

4.2.5 Evaluation of Different Runs

When different policy runs are formulated, it would be optimal to find an energy development path that performs better than all other runs in terms of emissions control, energy security and financial cost minimization. However, table 4-6 suggests that the aforementioned path might not exist. Any run in this study has its own advantage(s) and disadvantage(s) compared with other runs. For instance, although the *reference* run ranks poorly with respect to CO₂, SO₂ emissions control and energy security insurance, it can still be a desirable option for minimizing financial costs. Therefore, when energy policy makers try to design policy instruments to shape the future energy development path, it is very important to understand the necessary tradeoffs among different policy goals.

Table 4-6: Evaluation of Different Runs under a Multiple Account Framework

	Period: 1995 – 2030				
	CO ₂ Emissions	SO ₂ Emissions	Oil Consumption	Gas Consumption	Discounted TEC
<i>Reference</i>	100%	100%	100%	100%	100%
<i>SO₂ Cap</i>	92.7%	57.2%	99.4%	151.1%	103.3%
<i>39GtC Cap</i>	71.3%	54.1%	98.1%	188.9%	107.9%
<i>Integrated</i>	79.5%	55.9%	71.9%	104.6%	108.6%

Note: The percentages were derived by dividing the original numerical value of each run by that of the corresponding reference run.

4.3 CO₂ Tax Runs

4.3.1 The Effect of the CO₂ tax on Fossil Fuel Prices

The CO₂ tax has a great impact on the price of carbon intensive fuels. Table 4-7 presents the effect of the CO₂ tax on the various fossil fuels (expressed as a dollar addition per GJ to the reference scenario price). More specifically, a higher CO₂ tax rate always means greater price impact on carbon intensive fuels. For instance, when the CO₂ tax increases from 10\$/tCO₂ to 100\$/tCO₂, the associated price increase of coal grows from 0.9 \$/GJ to 9.3 \$/GJ. Similarly, the more carbon intensive a fuel is, the greater the price impact.

Table 4-7: Impact of a CO₂ Tax on Price of Fuels - Expressed as \$ Additions per GJ

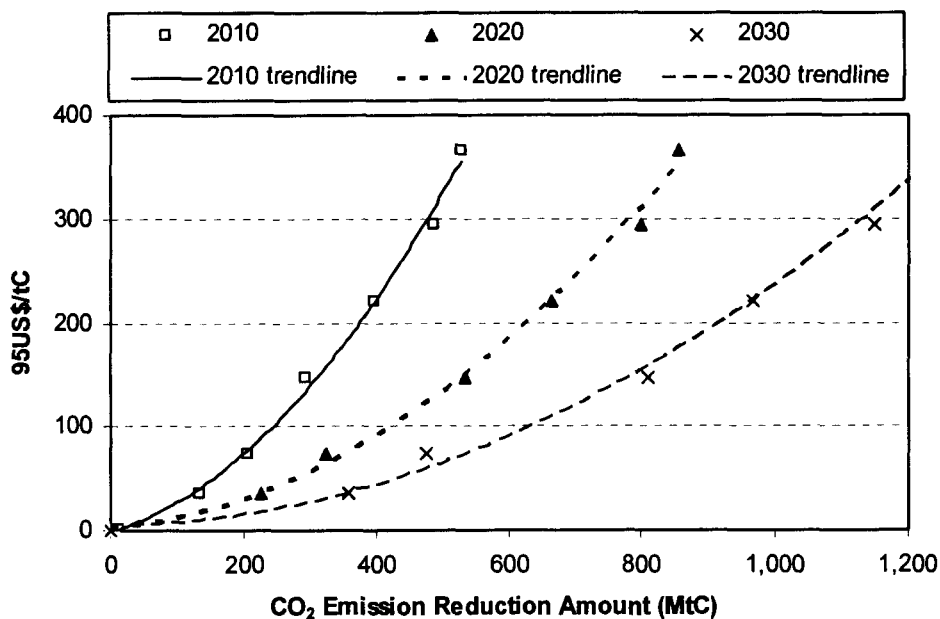
	CO ₂ tax					
	10 \$/tCO ₂	20 \$/tCO ₂	40 \$/tCO ₂	60 \$/tCO ₂	80 \$/tCO ₂	100 \$/tCO ₂
Coal	0.9	1.9	3.7	5.6	7.4	9.3
Oil	0.7	1.5	2.9	4.4	5.8	7.3
Gas	0.6	1.1	2.2	3.3	4.5	5.6

4.3.2 The Marginal Abatement Cost (MAC) for CO₂ Emissions

The marginal abatement cost (MAC) for CO₂ emissions represents the cost of the latest action to be undertaken in order to achieve a reduction target. Plotting MAC curves is a useful way to characterize the response of a model to emission controls. In this study, MAC curves are derived on the basis of the introduction of a shadow CO₂ tax in all areas

of fossil fuel energy use. This shadow CO₂ tax leads to adjustments in the final energy demand and supply within the CIMS model. Working from the *reference* run in which the shadow CO₂ tax is zero, it is then possible to calculate, by successive simulations, the emission levels associated with each shadow tax that varies from level to level. Then, for a given level of carbon shadow tax, the corresponding CO₂ emission abatement amount at every abatement year could be derived (Criqui et al. 1999). Figure 4-4 provides three MAC curves in terms of reduction amount for 2010, 2020 and 2030, where, at any particular shadow price associated with CO₂ emissions (y-axis), the quantity of emissions reduced can be determined (x axis). It is followed by Figure 4-5 that shows the three MAC cost curves in terms of emission reduction rate for 2010, 2020 and 2030.

Figure 4-4: CO₂ MACs in Terms of Emission Reduction Amounts

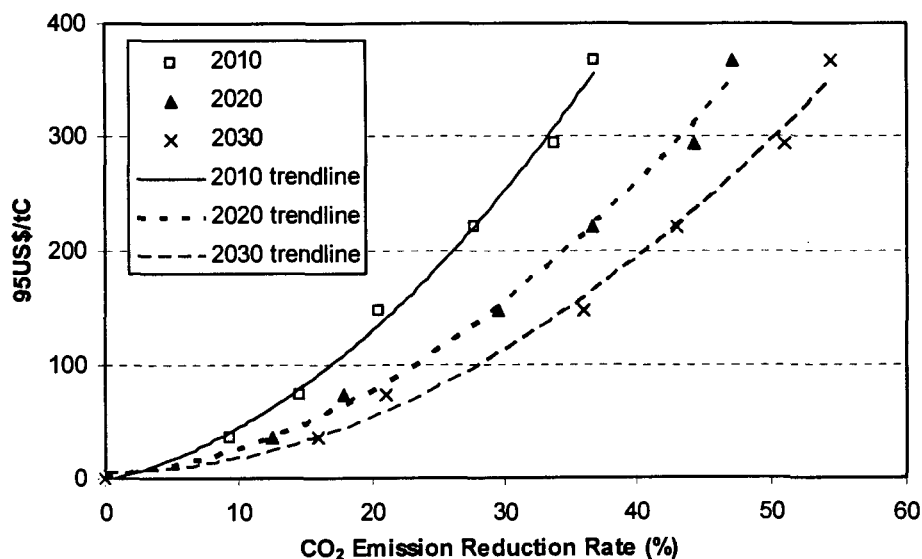


The MAC curves are upward-sloping curves: the marginal abatement cost rises as an increasing function of the emission reduction rate (or emission reduction amount). Both figure 4-4 and figure 4-5 show that the MAC curves for 2010, 2020 and 2030 become

more and more divergent when the carbon shadow tax rate increases, and the MAC for 2010 is the steepest while the MAC of 2030 becomes the flattest.

Figures 4-5 shows that the marginal abatement costs would be in the range of 10-100 $\$/tCO_2$ if the emission abatement rate was changed from 9% to 37%. For a same level of emission reduction rate (but different emission reduction amounts due to various reference emissions), the MAC for 2030 is lower than that of 2020, and the MAC for 2020 is lower than that of 2010. The gaps enlarge while the emission reduction rate rises.

Figure 4-5: CO₂ MACs in Terms of Emission Reduction Rate



Compared with OECD countries, China's MAC curve is at a relative low level (Ellerman and Decaux 1998; Criqui et al. 1999). The explanations are as follows:

- 1) In the *reference* run, carbon intensive coal is the dominant energy carrier throughout the 35-year modelling period. Therefore, fuel substitution could reduce emissions at little cost, simply by more natural gas, hydropower, nuclear and renewables. Moreover, the current coal price is extremely low in China. In 2002, the average price of commercial coal in China reached the highest level in

history, but it was only 167.81 RMB/t (20.2 \$/t). The average level of commercial thermal coal for power generation was even lower, only 137.25 RMB/t (16.5 \$/t) (Pan and Zhang 2003). A relatively low carbon tax rate can significantly increase the price of commercial coal, and accelerate the fuel substitution process in China.

- 2) There is a significant energy efficiency gap between China and developed countries in the energy demand sectors, and China can easily reduce GHG emissions by improving the energy efficiency of industrial processes.

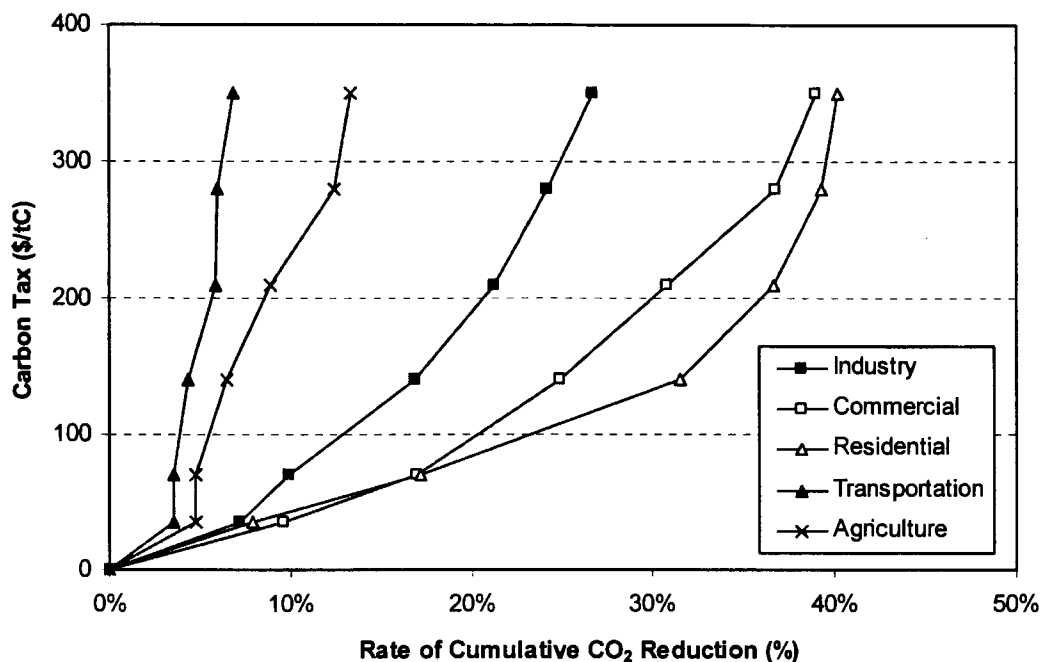
4.3.3 Sectoral CO₂ Emission Abatement Potential

Table 4-8 presents the sectoral share of cumulative CO₂ emission abatement in China's energy demand sectors. Following table 4-8, figure 4-6 depicts the CO₂ emissions abatement potential for China's energy demand sectors, where, at any particular CO₂ shadow price associated with CO₂ emissions (y-axis), the cumulative CO₂ emissions abatement rate from 1995 to 2030 can be determined (x axis).

Table 4-8: Share of Cumulative CO₂ Emissions Abatement in Energy Demand Sectors

	CO ₂ Shadow Price					
	10 \$/tCO ₂	20 \$/tCO ₂	40 \$/tCO ₂	60 \$/tCO ₂	80 \$/tCO ₂	100 \$/tCO ₂
Industry	64.3	58.0	59.6	61.7	58.4	62.1
Commercial	7.5	8.7	7.6	7.4	8.8	7.9
Residential	17.6	25.0	27.6	26.2	26.7	23.1
Transportation	8.1	6.7	3.8	3.2	4.1	5.2
Agriculture	2.4	1.6	1.3	1.5	2.1	1.7

Figure 4-6: Cumulative Sectoral CO₂ Emissions Abatement Potential under Different CO₂ Shadow Prices



Industry Sector

The marginal cost of CO₂ emissions abatement of the industrial sector is at the mid-range of the various energy demand sectors. However, table 4-8 indicates that the contribution for the cumulative national CO₂ emissions abatement from the industrial sector is the largest among all the energy demand sectors due to its sizeable reference CO₂ emissions level.

Commercial and Residential Sector

In the commercial and residential sector, the marginal cost for CO₂ emissions abatement is relatively low. The explanations are as follows:

- 1) More efficient energy systems, such as high efficiency air conditioning and space heating technologies, are mature and can be provided at competitive prices.

- 2) There are substantial fuel substitution opportunities in these two sectors. For example, both natural gas and coal gas can substitute for direct coal consumption.

Transportation Sector

To reach the same cumulative emissions abatement rate, figure 4-6 shows that the marginal abatement cost of the transportation sector is the highest among all the energy demand sectors. On one hand, this reflects the fact that the transportation sector has the lowest ability to respond to policy signals of CO₂ emissions abatement. On the other, this is also because the representation of policy options for CO₂ emissions abatement is limited in the current version of CIMS-China. In the future, when the following actions are incorporated, the potential of CO₂ emissions abatement from the transportation sector could be increased:

- 1) More fuel switching within the passenger vehicle market;
- 2) Shifts between passenger vehicles and public transit modes;
- 3) Mode switching between single occupancy and high occupancy vehicles, and
- 4) Changes in activity levels¹³.

Agriculture Sector

Figure 4-6 indicates that the cumulative CO₂ emissions abatement rate of agriculture is higher than that of transportation. However, considering the small size of this sector, agriculture's contribution to cumulative CO₂ emissions abatement under different CO₂ tax runs is the lowest among all the energy demand sectors.

¹³ Changes in activity levels can be enabled if the CIMS macroeconomic module is activated, in which higher costs of energy mobility would cause some reduction of mobility.

4.3.4 CO₂ Emissions Abatement and Associated Costs

Table 4-9 defines CO₂ emissions reduced in 2010, 2020, 2030, the techno-economic costs (TEC), expected resource costs (ERC) and perceived private costs (PPC) associated with cumulative CO₂ emission reductions throughout the 35-year modelling period. In this table all the TEC values include the electricity sector's techno-economic costs but exclude the cost of changing electricity prices.

Table 4-9: Emissions and Costs Associated With Emission Reduction in China

Carbon Tax	2010 Emission Reduced	2020 Emission Reduced	2030 Emission Reduced	TEC 1995-2030	ERC 1995-2030	PPC 1995-2030
(\$/tCO ₂)	(MtC)	(MtC)	(MtC)	(95 billion \$)	(95 billion \$)	(95 billion \$)
10	134	228	358	(55.9)	(7.8)	8.2
20	208	325	475	(60.1)	5.3	27.1
40	293	535	811	(65.9)	51.8	91.1
60	398	665	969	(69.2)	95.8	150.8
80	486	801	1,150	(73.7)	177.7	261.5
100	528	855	1,225	(78.4)	219.5	318.7

4.3.5 Co-benefits of the CO₂ Tax

Because of the local impact of CACs, such as SO₂, the planning of CO₂ emissions abatement policy becomes more complicated than if CO₂ emissions are considered alone. First, if densely populated areas in China such as Beijing and Shanghai are targeted with more CO₂ emission reductions, the potential co-benefits of SO₂ emissions abatement could be much greater. Second, co-benefits can alter the level of 'no regrets' GHG abatement. 'No regrets' refers to the level of abatement that could be achieved if all GHG measures with no net cost to society were implemented (Dessus and O'Connor 1999). When monetized co-benefits are included in the calculation of net costs or benefits, they could increase the no regrets level of abatement in China, and thus change the number of measures that could be taken with no net loss to social welfare.

Figure 4-7 displays that China's CO₂ emissions in 2010, 2020 and 2030 decline quickly as the rate of CO₂ tax increases. And the SO₂ emissions levels in 2010, 2020 and 2030 generally follow a similar trend.

Figure 4-7: CO₂ Emissions vs. SO₂ Emissions, 2010, 2020 and 2030

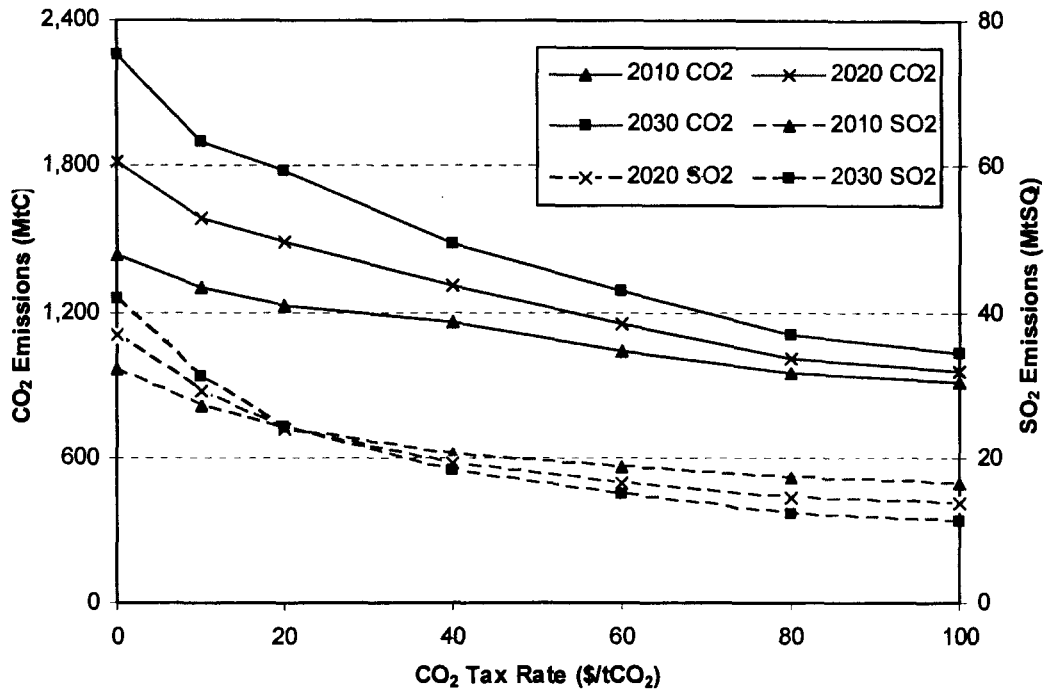


Table 4-10 illustrates that the CO₂ tax can more effectively reduce SO₂ emissions in terms of cumulative emission reduction rate. For instance, when the carbon shadow price is 20 \$/tCO₂, the cumulative SO₂ abatement rate through the modelling period is 27.8%, which is significantly higher than the cumulative CO₂ emissions abatement rate under the same carbon tax. A major reason for a higher SO₂ emissions abatement rate is that the CO₂ tax accelerates fuel substitution such as natural gas for coal that reduces SO₂ emissions even more effectively.

Table 4-10: Percentage of Cumulative Emissions Abatement (%)

	CO ₂ Tax (\$/tCO ₂)					
	10	20	40	60	80	100
CO ₂	10.3	15.3	23.5	30.5	36.8	39.4
SO ₂	16.6	27.8	38.4	44.2	49.0	50.8

Table 4-11 presents the avoided SO₂ damage costs of various CO₂ tax runs as percentage of the GDP in 2010, 2020 and 2030. In the most optimistic case (high SO₂ unit damage costs), a 100 \$/tCO₂ tax could cut the SO₂ damage costs at a level of 1.41% of the GDP in 2030. However, there is high uncertainty regarding this co-benefit. When the low SO₂ unit damage costs are applied, the avoided damage costs become 0.35% of the GDP in 2030. Similarly, when the tax rate is lowered to 10 \$/tCO₂, the 2030 avoided SO₂ damage costs range from 0.12% to 0.50% of GDP. Therefore, when the monetized co-benefits are included in the calculation of net costs or benefits, they could increase the no regrets level of abatement in China, and thus change the number of measures that could be taken with no net loss to social welfare.

Table 4-11: Avoided SO₂ Damage Costs as Percentage of the GDP (%)

	CO ₂ Tax Run (\$/tCO ₂)					
	10	20	40	60	80	100
High SO ₂ Unit Damage Costs						
2010	0.26	0.43	0.61	0.70	0.78	0.81
2020	0.37	0.62	0.85	0.97	1.07	1.11
2030	0.50	0.82	1.09	1.24	1.36	1.41
Low SO ₂ Unit Damage Costs						
2010	0.06	0.11	0.15	0.18	0.20	0.20
2020	0.09	0.16	0.21	0.24	0.27	0.28
2030	0.12	0.20	0.27	0.31	0.34	0.35

4.4 SO₂ Tax

China first applied SO₂ emission charges as a fee of 0.04 RMB/kgSO₂ (4.82 \$/tSO₂) on excess emissions from industrial processes only (excluding electric utilities) in 1982.

With the increased emphasis on SO₂ emission control in the following decades, the rate has grown significantly, resulting in a nation-wide 0.63 RMB/kgSO₂ (76 \$/tSO₂) tax applied to all SO₂ emissions from both industrial process and electric utilities in 2003 (Zhang and Wang 2003).

4.4.1 Comparison of the Effect of Different Taxes on the Price of Raw Coal

Table 4-12 presents the maximum price increase of raw coal associated with different levels of SO₂ taxes ranging from 300 \$/tSO₂ to 1,500 \$/tSO₂. When raw coal is directly burnt for fuel, the SO₂ tax has the strongest impact on its price. However, compared with a 10\$/tCO₂ carbon tax, a SO₂ tax with much higher magnitude (1080 \$/tSO₂) is needed to induce a similar price shock on raw coal.

Table 4-12: Impact of Different Emission Taxes on the Price of Raw Coal - Expressed as \$ additions per GJ

	Emission Tax					
	300\$/tSO ₂	600\$/tSO ₂	900\$/tSO ₂	1200\$/tSO ₂	1500\$/tSO ₂	10\$/tCO ₂
Coal	0.258	0.516	0.774	1.032	1.290	0.927

4.4.2 SO₂ Emissions vs. Sulphur Emission Ratios of Different Runs

As defined in section 2.5, SER represents the percentage of sulphur emitted as SO₂ versus the total sulphur content in fossil fuels. A lower SER reveals that more sulphur content is removed by desulphurization processes such as coal washing¹⁴, FGD unit¹⁵ or refinery¹⁶. While fuel substitution can significantly reduce SO₂ emissions, its impact on SER is insignificant.

¹⁴ Coal washing can remove 10-40% of inorganic sulphur from raw coal.

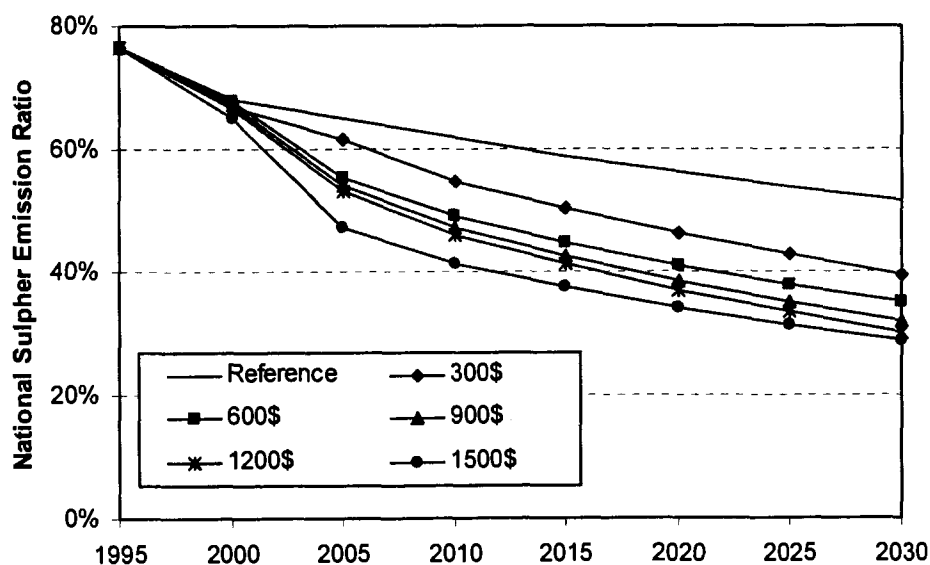
¹⁵ Recent FGD units can reduce 80% - 90% SO₂ content from the exhaust of coal-fired power plants.

¹⁶ The Sulphur content of most refined petroleum products such as gasoline and diesel is significantly lower than that of crude oil.

Figure 4-8 depicts the SER trends of different SO₂ tax runs from 1995 to 2030. In the *reference* run, SER decreases from 72% in 1995 to 52% in 2030, while the SO₂ emissions increase rapidly from 23.7 Mt in 1995 to 42 Mt in 2030 (table 4-13). The downward trend of SER in the *reference* run is closely related to the fact that coal-fired power plants with FGD units penetrate moderately over the 35-year modelling period, and the rate of coal washing increases from 18% in 1995 to 50% in 2030. The SER curves of the policy runs generally follow a similar trend as the *reference* run, but a higher SO₂ tax rate can always bring down the SER curve further. In another words, the higher the SO₂ tax rate, the lower the SER curve. For instance, the 1500 \$/tSO₂ tax could bring down SER from 52% in the *reference* run to 29% in 2030. The explanations for the significant change are:

- 1) The 1500 \$/tSO₂ tax could accelerate the market penetration rate of coal-fired power plants with FGD units, and
- 2) Sulphur removal by coal washing process is the equivalent of a 430 \$/tSO₂ tax in this study, therefore the proportion of washed coal quickly reaches the maximum allowed ratio in the 1500 \$/tSO₂ tax run.

Figure 4-8: Sulphur Emission Ratios of Different Runs



However, table 4-13 shows that even a 1500\$/tSO₂ tax rate is not enough to decrease the future SO₂ emissions to attain the SO₂ cap specified in this study. Therefore, the current SO₂ tax rate of 76 \$/tSO₂ in China is too low.

Considering the fact that a high SO₂ tax rate might be politically undesirable, SO₂ emission control in China could be achieved by a package of policy instruments instead of the SO₂ tax alone. Currently, the SO₂ emission control target set for the Two Control Zones (Hao et al. 2001) and stringent fuel standards (Yamaguchi et al. 2002) serves well for this purpose.

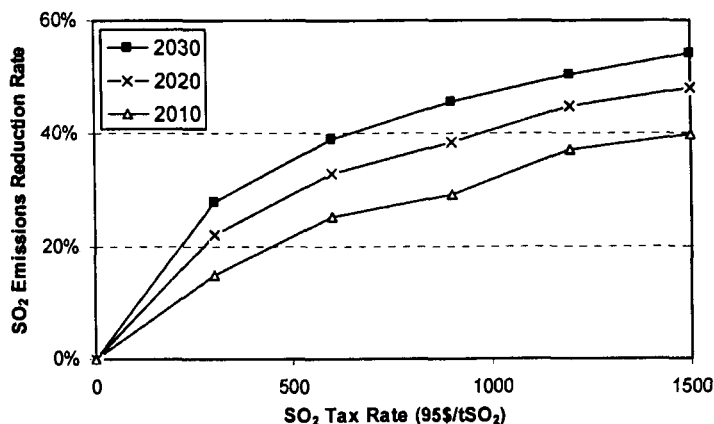
Table 4-13: SO₂ Emissions vs. Sulphur Emission Ratio of Different Runs

	SO ₂ Emissions (Mt)				Super Emission Ratio (%)			
	1995	2010	2020	2030	1995	2010	2020	2030
Reference	23.6	32.3	36.9	42.0	76	62	56	52
300\$	23.6	27.5	28.8	30.3	76	55	46	40
600\$	23.6	24.2	24.8	25.6	76	49	41	35
900\$	23.6	22.8	22.7	22.8	76	47	39	32
1200\$	23.6	20.3	20.3	20.8	76	46	37	30
1500\$	23.6	19.5	19.2	19.3	76	41	34	29

4.4.3 Effects of SO₂ Tax on SO₂ and CO₂ Emissions

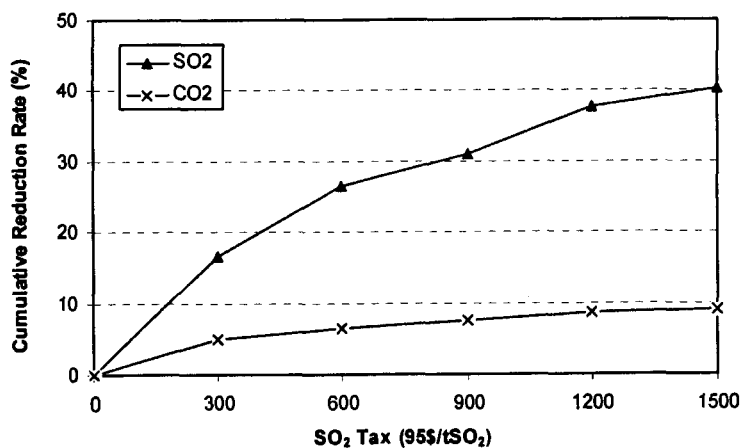
Figure 4-9 provides three MAC curves for SO₂ emission in terms of emission reduction rate for 2010, 2020 and 2030. The 2010, 2020 and 2030 MAC curves generally follow a similar trend. A higher SO₂ tax rate can always further bring down the SO₂ emissions. For instance, the SO₂ emission reduction rate in 2010 is only 15% under a 300 \$/tSO₂ tax rate, and becomes 29% under a 900 \$/tSO₂ tax rate, and further grows to 40% under the 1500 \$/tSO₂ tax rate. Moreover, the emission reduction rate in later years is always higher. For instance, the SO₂ emission reduction rate under a 1500 \$/tSO₂ tax rate is 40% in 2010, and increases to 48% and 54% in 2020 and 2030 respectively.

Figure 4-9: SO₂ Shadow Price vs. SO₂ Emission Reduction Rate in 2010, 2020 and 2030



While the co-benefits of the CO₂ tax are substantial, figure 4-10 conveys a different picture about the impact on CO₂ emissions from the SO₂ tax. In the 1500 \$/tSO₂ tax run, the cumulative SO₂ emission abatement rate is 40%, but the associated cumulative CO₂ reduction is only about 9%. The wide divergence between the two curves can be attributed to the desulphurization opportunities that exist for coal-fired energy systems, such as coal washing, FGD units, coal gasification and liquefaction. Thus a high SO₂ emission reduction rate could be achieved without heavy reliance on relatively more expensive fuel substitution.

Figure 4-10: Impacts on Cumulative CO₂, SO₂ Emissions by SO₂ Tax



4.5 Sensitivity Analysis

Sensitivity analyses were completed on one input and two parameters in CIMS: fuel prices, discount rates and the variance parameter applied in the inverse power algorithm (see equation 1, chapter 2). Each of these variables was analysed in terms of the impact of changes in their value on levels of energy consumption in order to test the model's response to these changes and to understand the degree of the uncertainty surrounding the input and parameters. The analysis is focused on the industrial sub-sector¹⁷, commercial and residential sectors.

4.5.1 Analysis of Fuel Prices

To test the model's responsiveness of energy consumption to changes in fuel prices, a number of analyses were completed on price changes in natural gas and coal. The analyses attempted to assess the model's response to a change in the price of one fuel while others remain constant. The values reflect both efficiency improvements and fuel switching in the industrial sub-sector in table 4-14.

Table 4-14: The Effect of Change in Price of Coal and Natural Gas on Energy Consumption in China's Industrial Sub-sector

Fuel Price Change from Reference Run	Change in Fuel Use, % in 2000, 2010, 2020, 2030							
	Coal				Natural Gas			
	2000	2010	2020	2030	2000	2010	2020	2030
-10%	0.13	0.33	0.45	0.47	0.03	0.02	-0.03	-0.13
-5%	0.10	0.23	0.29	0.27	0.05	0.08	0.05	-0.03
Reference run	-	-	-	-	-	-	-	-
+5%	0.04	0.03	-0.02	-0.13	0.09	0.19	0.22	0.16
+10%	0.01	-0.06	-0.17	-0.32	0.11	0.24	0.30	0.26

¹⁷ China's industry sector is divided to "industrial sub-sector" and "other industries" in this study. Please refer to section 3.2.1 for details.

The industrial sub-sector in this analysis includes China's energy-intensive steel, cement, paper, ammonia, and aluminium industries. In 1995, these five industries alone accounted for about 32% of China's final energy consumption.

The price of China's domestic coal is very competitive. In 1995, coal accounted for 62% of energy demand of the five energy-intensive industries. The changes of the coal price within the range of $\pm 10\%$ are not enough to induce significant fuel switching or energy efficiency. Similarly, the five energy-intensive industries are not sensitive to the change of natural gas price within the range of $\pm 10\%$. However, the reason is different in this case. In the industrial sub-sector, natural gas systems are often capital intensive, and fuel costs only account for a small fraction of their life cycle costs. In 1995, only 2% of energy-intensive industrial sub-sector's energy demand came from natural gas. Changes of the natural gas price within the range of $\pm 10\%$ have no significant impacts on the market penetration rate of natural gas.

4.5.2 Analysis of Discount Rates

Discount rates were varied incrementally $\pm 5\%$ within a range of $\pm 15\%$ over those initially applied to the sectors tested (i.e., if the *reference* run rate was 30%, sensitivity analysis tested rates at 15%, 20%, 25%, 35%, 40% and 45%).

For the residential sector, table 4-15 shows that the variance of energy demands under these discount rates are within $\pm 2\%$ range, and a higher discount rate increases the energy consumption level. The reason is that a higher discount rate places greater weighting on capital costs and leads to a high LCC, while a lower discount rate will produce a lower LCC, given equal operating and energy costs. Hence, a high discount rate will hinder the ability of technologies with high capital costs and lower operating and energy costs to gain market share. Because new, energy efficient technologies in the residential sector that have a high capital to operating cost ratio, a high discount rate will impede the market penetration of these technologies (Nyboer 1997).

Table 4-15: The Effect of Uncertainty in Discount Rate on Energy Consumption

Discount Rate Change from Reference Run	Change in Fuel Use, % in 2000, 2010, 2020, 2030							
	Commercial				Residential			
	2000	2010	2020	2030	2000	2010	2020	2030
-15%	0.70	2.02	1.98	1.59	-0.47	-1.11	-1.35	-1.52
-10%	0.56	1.81	1.80	1.45	-0.30	-0.66	-0.80	-0.97
-5%	0.32	1.29	1.35	1.11	-0.15	-0.33	-0.39	-0.46
Reference run	-	-	-	-	-	-	-	-
+5%	-0.48	-1.93	-2.12	-1.93	0.16	0.31	0.34	0.39
+10%	-0.68	-2.85	-3.67	-3.77	0.33	0.61	0.64	0.70
+15%	-1.63	-3.35	-4.03	-4.45	0.49	0.89	0.90	0.93

For the commercial sector, when the changes to the discount rates fall in the negative range, energy demand under these discount rates shows, at maximum, a 2% change. However, when the discount rate approaches +15%, the deviation of energy demand can be as high as -4.5%. The reason is that oil or gas energy systems in this sector generally have higher fuel costs and lower capital costs than coal-fired technologies. A high discount rate will encourage the market penetration of more efficient oil and gas energy systems in the commercial sector.

4.5.3 Analysis of the Variance Parameter

Values of 6, 8, 20, and 30 were tested in a sensitivity analysis of the variance parameter (value in the *reference* run was 10). A variance parameter value of “6” would suggest that, if the life-cycle costs of competing technology prices were 15% different, 72% of decision makers would purchase the cheaper technology, about 80% would buy the cheaper technology at a variance of 8, 93% at 20 and 95% at 30 (Jaccard and Nyboer 1997). Over the 35-year simulation period, this behavioural variation causes less than $\pm 3\%$ change in energy consumption.

As the variance parameter approaches maximum economic sensitivity (high value) or complete indifference to life-cycle cost minimization (low value), the changes become

more dramatic, but, within this range, the impact is relatively small, and CIMS can obtain credible results.

Table 4-16: The Effect of Uncertainty in the Variance Parameter on Energy Consumption

Variance Parameters Tested	Change in Fuel Use, % in 2000, 2010, 2020, 2030							
	Commercial				Residential			
	2000	2010	2020	2030	2000	2010	2020	2030
6	-0.57	-1.52	-1.80	-1.88	0.63	1.06	0.83	0.42
8	-0.19	-0.68	-0.81	-0.83	-0.32	-0.54	-0.41	-0.19
Reference 10	-	-	-	-	-	-	-	-
20	0.47	1.77	1.81	1.48	-1.02	-1.82	-1.57	-1.10
30	0.68	2.05	2.03	1.64	-1.47	-2.68	-2.37	-1.76

4.5.4 Analysis of the Fuel Emission Coefficients

The study team working for the Asian Development Bank's ALGAS project (1998), reported that the conversion factor of primary energy, fraction of carbon oxidized and other default data recommended by IPCC Guidelines are not suitable for China; they could make the estimated emissions larger than actual ones. However, because the China-specific fuel emission coefficients are unavailable, the default carbon emission factors and oxidization rates recommended by the IPCC¹⁸ were nonetheless used in this study.

The possible range of CO₂ emissions in the *reference* run was derived by changing the oxidation rates of coal and oil from the lower values caused by inefficient combustion to the theoretically optimal value of 1.0. Table 4-17 indicates that the impacts on the CO₂ emissions from uncertain fuel emission coefficients are substantial. In the future, China-specific fuel emission coefficients need to be developed to allow more accurate CO₂ emission projection. However, given the 35-year modelling period and the emphasis on the relative emission changes instead of absolute values, the overall impacts from the uncertain emission coefficients are still at an acceptable level for this study.

¹⁸ Please refer to appendix A for details.

Table 4-17: Sensitivity Analysis on Emission Coefficients of Coal and Oil for the *Reference* Run

	1995	2010	2020	2030	1995-2030
Min CO ₂ Emissions	94%	94%	94%	94%	94%
Reference Emissions	100%	100%	100%	100%	100%
Max CO ₂ Emissions	103%	103%	103%	103%	103%

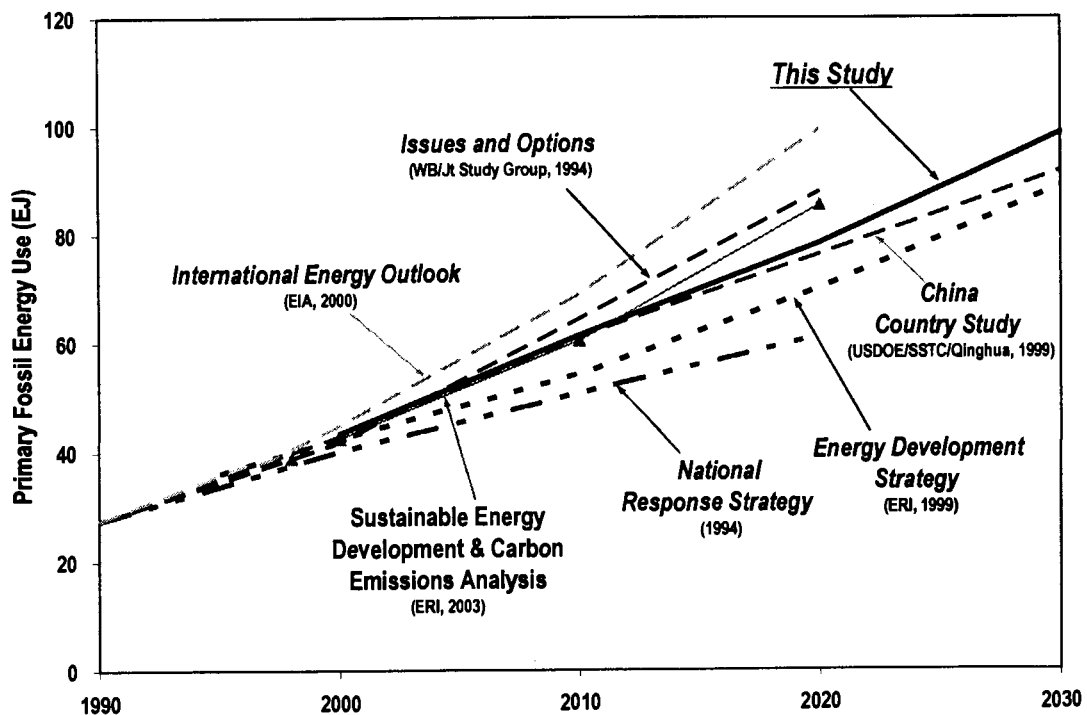
Note: Oxidation rate of Coal: 0.9 – 1.0; oxidation rate of oil: 0.92-1.0.

5. COMPARISON WITH OTHER STUDIES

5.1 Baseline Fossil Energy Use

Establishment of a baseline forecast is a crucial step. Unrealistic baselines can undermine an energy economy model's credibility and usefulness and result in an extremely high or low marginal abatement cost curve. The reference assumptions of the CIMS model result in about a 178% increase of fossil energy consumption between 1995 and 2030, which falls in the mid-range of baseline fossil fuel energy estimates made by a number of other analysts (figure 5-1).

Figure 5-1: Comparison of Baseline Fossil Energy Use in China



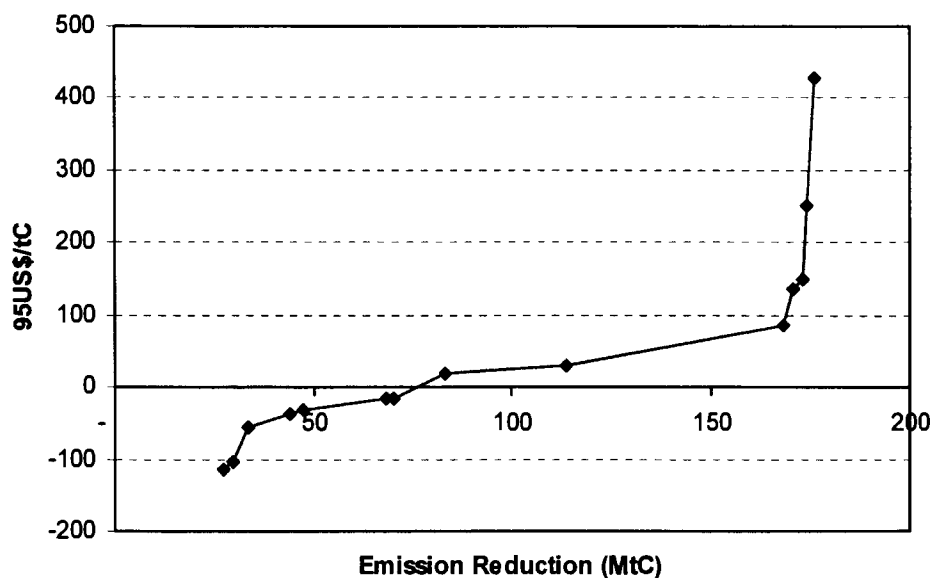
Source: Sinton and Fridley (2000), ERI (2003) scenario 1.

5.2 Comparison of MAC Curves from Different Sources

As mentioned in section 4.3.2, the MAC curve for CO₂ emissions represents the cost of the most expensive action undertaken in order to achieve a reduction target. Normally, there are three methods to evaluate the MAC curve for a country. First, in a process optimization model, emission constraints could be introduced to backcast the associated marginal abatement cost. Second, top-down models (e.g., CGE) and some hybrid models (e.g., CIMS) assess the MAC curves on the basis of the introduction of a shadow carbon tax in all areas of fossil fuel energy use. Working from a reference scenario in which the shadow carbon tax is zero, it is then possible to calculate, by successive simulations, the emission levels associated with a shadow tax that varies from level to level. Third, the *ad hoc* approach usually involves a comparison of a limited number of CO₂ abatement options, and can be used to identify cost-efficient technologies to achieve the specific abatement goal (Zhang 1998).

The Asian Development Bank (1998) identified China's various emission reduction potentials with associated marginal cost levels on the basis of the *ad hoc* approach. Figure 5-2 was obtained through analyzing the incremental cost and mitigation potential of key technical measures adopted in China's energy sector by the year 2010. The key advantage of the *ad hoc* approach is that it is able to not only identify the reduction potentials of "no-regret" options, but also allows for ranking the options examined in term of their cost-effectiveness and hence prioritizes investment. However, the *ad hoc* approach ignores the transaction costs, and unlike the energy-economy models, is not suited for inferring the most cost-efficient mix and scale of abatement technologies.

Figure 5-2: MAC Curve for China' Energy Sector in 2010 from ALGAS study.



Note: The unit marginal costs were converted from 1990 constant dollars per ton carbon.

Source: Asian Development Bank (1998), Appendix 4.

The MAC curves for China could also be observed from several other sources, like the Emission Prediction and Policy Assessment (EPPA) model, the Global Trade and Environment Model (GTEM), the Prospective Outlook on Long-term Energy Systems (POLES) model, and the Tsinghua MARKAL model (table 5-1).

Table 5-1: Sources of Different CO₂ Marginal Abatement Cost Curves

Model	Model Developer	Type	Source
EPPA	MIT's Joint Program on the Science and Policy of Global Change	CGE	Yang et al. (1996) Ellerman and Decaux (1998) Ellerman et al. (1998) http://web.mit.edu/globalchange
GTEM	Australian Bureau of Agricultural and Resource Economics	CGE	Tulpule et al. (1998) Grutter (2000) http://www.abare.gov.au
POLES	The European Commission (EC)	Hybrid	EC (1995; 1996) Criqui, Mima et al. (1999)
Tsinghua MARKAL	Energy Technology Systems Analysis Programme	Optimization	Chen (2002) http://www.ecn.nl/unit_bs/etsap/markal

EPPA provided the MAC curves in the form of the following quadratic function (Ellerman et al. 1998).

$$MAC = aQ^2 + bQ \quad (6)$$

where:

MAC	=	marginal abatement cost in 1985 US\$/tC,
Q	=	emission reduction in MtC,
a	=	time and region dependent constant, 0.00007 in 2010 for China,
b	=	time and region dependent constant, 0.0239 in 2010 for China.

The form of MAC curves derived from GTEM is represented as the following exponential function (Gruetter 2000).

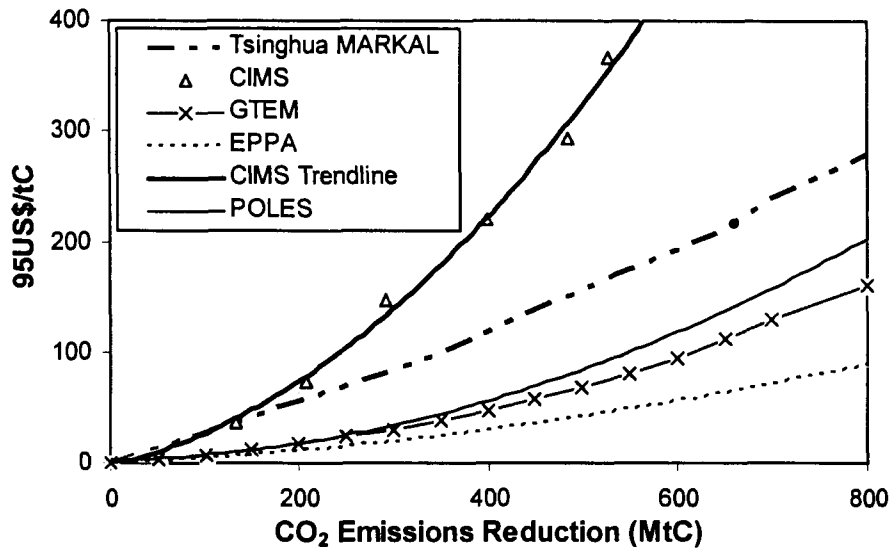
$$MAC = a(\exp(bQ) - 1) \quad (7)$$

where the units of marginal abatement cost MAC and emission reduction Q are 1995 US\$/tC and MtC respectively, and a is 27.25, b is 0.0024889 for China's 2010 MAC curve.

The MAC curve from POLES for China in 2010 is expressed in 1990 constant dollars and illustrated in figure 7 of Criqui et al. (1999). The MAC curve from Tsinghua MARKAL model for China in 2010 is expressed in 2000 constant dollars (Chen 2002).

Figure 5-3 compares the MAC curves for China from different models and shows that the lowest marginal cost curves come from the two CGE models (EPPA and GTEM) and the highest MAC is from this study. The disparity on MAC curves from different models could be explained as follows:

Figure 5-3: Comparison of China's MAC Curves in 2010 from Different Sources



Note: all costs are converted to and expressed in 1995 constant dollars by using the deflators of 1 for 1985, 1.214 for 1990, and 1.416 for 1995 and 1.600 for 2000.

- 1) *Different modelling Methodologies.* The modelling approach contrast between MARKAL and CIMS and the associated impacts on cost estimation were discussed in section 5.3.
- 2) *Different macroeconomic assumptions.* Different macroeconomic assumptions lead to the divergence among reference emission trajectories. A higher reference emission projection tends to produce a lower MAC curve.
- 3) *Different abatement opportunities and the associated incremental cost assumptions in the models.* The more abatement opportunities exist, the lower the MAC would be. Similarly, a lower incremental cost assumption regarding a key abatement opportunity could bring down the MAC curve. Moreover, the MAC curve is sensitive to whether and how the capital costs of energy systems are set to change over the modelling period. For instance, EMRG has improved the learning curve function for individual technologies in the CIMS model. If this function was incorporated into the CIMS-China model, the MAC curve of this study could be lower.

- 4) *Different assumptions regarding the market potential (upper bound constraint) of abatement opportunities*¹⁹. For example, hydro power is considered a proven method with an enormous potential for a large-scale generation of electricity without the parallel production of CO₂ emissions. However, different models are unlikely to agree with each other about the upper bound constraint for this technology, and the model with a smaller upper bound constraint inclines to produce a higher MAC curve.
- 5) *Different energy substitution options and associated incremental cost assumptions in the models*. The more possibility for energy substitution, the lower MAC would be. For example, one of the two "backstop" sectors that produce perfect substitutes for refined oil and electricity in EPPA models is liquid fuel derived from shale (Yang et al. 1996), which is not explicitly represented in most of other models. Similarly, a lower incremental cost assumption regarding fuel substitution options could bring down the MAC curve.
- 6) *The package of mitigation measures considered in the reference scenario*. The more mitigation measures considered in the reference scenario, the lower the reference emissions while the higher the MAC curve. For instance, most of the "non-regret" options in figure 5-2 have already been included in the reference scenario of the CIMS model; otherwise, the MAC curve of this study would be lower.

5.3 Methodological Contrasts between CIMS and MARKAL

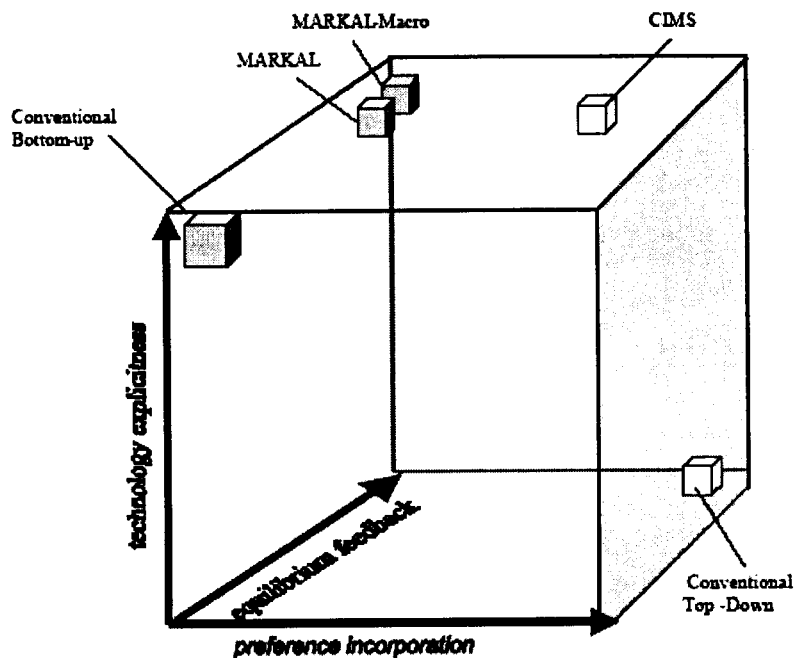
Among the many sources of uncertainty regarding GHG abatement cost estimation, the methodological difference in modelling technological change is a key one. In this section, the importance of methodological contrasts between MARKAL and CIMS in cost estimates of CO₂ emissions abatement is discussed.

¹⁹ Only applies to bottom-up and hybrid models.

5.3.1 Situating MARKAL and CIMS among Energy Models

Figure 5-4 situates CIMS and MARKAL among the different types of energy economy models. The graph has three dimensions: technological explicitness, preference incorporation and equilibrium feedback²⁰.

Figure 5-4: Depiction of Energy Economy Models



Source: Jaccard et al. (2002)

Both MARKAL and CIMS differ from the top-down models in that they feature detailed representation of technology stocks and thus do well on the axis of technology explicitness. In contrast, conventional top-down models lack the representation of detailed technologies, and only focus on aggregate relationships between inputs and outputs of the economy estimated from historical market data. Ideally, these relationships provide revealed consumer and firm preferences regarding technology acquisition. Considering that these models can link the aggregate relationship in an equilibrium portrayal of the economy's feedback loops, a conventional top-down model does well on

²⁰ The feedback between the economy and energy supply and demand.

two of the three axes: preference incorporation and equilibrium feedback. However, the poor performance on technology explicitness makes it an inappropriate tool to assess policy instruments focusing on individual technologies. Technology-explicit models have been developed to deal with this problem. A technology-explicit optimization model, especially one with extensive macroeconomic feedbacks such as MARKAL-Macro does well on two of the axes but poorly on preference incorporation. In comparison, CIMS, a bottom-up hybrid model, is designed to perform well on all of the three attributes.

5.3.2 Key similarities of MARKAL and CIMS

Both MARKAL and CIMS do well on technology explicitness. Currently, they share the same technological database, and both models have about 10 characteristics for each technology in the database as follows:

- Capital cost;
- Operation and maintenance costs;
- Fuel coefficient (efficiency);
- Emission coefficients;
- Size, in terms of annual output of service or product;
- Lifespan;
- Year of market availability;
- Base year market share;
- Linkage to other services and products, technologies and processes;
- Special market constraints;
- Other information, such as an annual availability factor, etc.

Moreover, in both models, the technologies are allocated to the energy demand sectors – industrial, residential, commercial, transportation and agricultural sectors and the energy supply sectors – electricity, resource mining, oil refining, natural gas extraction.

Both MARKAL and CIMS attempt to capture system equilibrium feedbacks. However, neither model is as general equilibrium as a top-down model. In the former case, MARKAL currently does not include the broader, macroeconomic relationships that are common to general equilibrium models. In the case of this CIMS application to China, the macro-economic feedback loop was disabled to permit the isolation of the direct emission reductions associated with policy alternatives.

Finally, both MARKAL and CIMS are based on a similar stock accounting process, and they also use similar financial and technical information to determine technology stock shares, although their cost algorithms for technology competition is very different.

5.3.3 Major Differences between MARKAL and CIMS

The objectives of MARKAL and CIMS are very different despite the aforementioned similarities. MARKAL seeks to achieve policy goals represented by various constraints at least financial cost. In contrast, CIMS seeks to predict how firms and households will respond to various policies to induce changes in their technology choices. Therefore, CIMS must focus not just on technology-specific financial information but also on the behavioural side of technology acquisition, such as risk premiums and intangible consumer preferences. These different objectives lead to different cost algorithm for technology competition as follows: (Nyboer 1997)

1) Pure financial costs versus intangible cost incorporation

MARKAL's cost algorithm is based on several simplified assumptions:

- Fully competitive markets (prices equal marginal costs),
- Perfect information available to all producers and consumers,
- Long-term optimisation perspectives for producers and consumers, and
- Producers and consumers all have the same time preference (D'Abate 2001).

In contrast, CIMS recognizes market heterogeneity, and allows for a technology-specific discount rate. Moreover, the intangible cost factor described in section 2.2.3 enables CIMS to incorporate the intangible values attached to certain technologies, such as consumers' surplus loss. Otherwise, the failure to include the above-mentioned intangible costs will overestimate the willingness of consumers to switch to emerging technologies.

2) *Winner-take-all versus probabilistic technological acquisition*

Like any optimization model, MARKAL's cost algorithm of technology competition is based on the principle of winner-take-all. Small changes in life cycle costs can lead to dramatic changes in outcomes, referred to as penny-switching or absolute shift. MARKAL modellers are able, however, to alleviate the impact from winner-take-all by the careful application of exogenously specified lower and upper constraints on the market share of each technology. In contrast, the intention of CIMS is to simulate the probabilistic results of technological acquisition decisions. As discussed in section 2.2.3, the relationship between life cycle costs and market share for different technologies is determined by the magnitude of *variance parameter* v . The advantage of incorporating *variance parameters* is that the potential of using behaviour evidence to approximate the "real" market share tradeoff between different technologies.

3) *System optimization versus bounded rationality*

As an optimization model, MARKAL is based on long-term optimization perspectives for producers and consumers. MARKAL always makes normative, optimal allocations of technologies to simultaneously satisfy all the constraints and minimize financial costs for all time periods and all sectors. In other words, every technological choice is informed by all other technology choices in all time periods. In contrast, as a simulation model, CIMS recognizes that technology competition mostly occurs in differentiated sub-segments. The technology allocation of one sub-segment is usually independent of the results in any other

sub-segment. That is, the technology choices are rational given sub-segment boundaries. Such bounded rationality suggests that decision makers typically make decisions only within the context of the portion of the technology represented by that sub-segment, and see the price of fuels and other temporal factors for only that time period. Therefore, the simulation of CIMS needs to be completed sequentially from one time period to the next one. The solution in the next period has no bearing on the previous one.

4) *Marginal cost versus average cost pricing*

Consistent with its optimization logic, all prices in MARKAL are based on marginal costs, the cost of the last unit of product or service provided in every sector. For example, both an economy-wide constraint on CO₂ emissions in MARKAL and a shadow CO₂ tax in CIMS can affect new investment in the electricity sector, whose marginal cost is likely higher than the average electricity price of the reference scenario. However, unlike MARKAL, CIMS sets electricity prices based on an assessment of average production cost, the higher costs associated with new investments to reduce CO₂ emissions in this sector lead to higher electricity price, but only to the extent that average costs are driven up by incremental investments.

In addition to these fundamental differences between an optimization and a simulation model, the models also have other differences in this particular application. These relate more to how the terms of reference were interpreted and the current state of each model's development.

5) *Different treatment of coal exports*

The Chinese version of MARKAL has the capability to model coal exports, but CIMS does not currently have the capability to trace this part of the coal industry, and simply excludes the carbon content of exported coal from domestic emission accounting.

6) *Different treatment of domestic oil extraction*

Another difference arose because the two teams interpreted differently one of the terms of reference. While domestic output of crude oil is assumed to remain constant in CIMS, MARKAL allows the domestic oil output to fluctuate over time. Because of the high uncertainties associated with domestic oil extraction, it is very hard to tell which approach is better.

7) *Different treatment of advanced technologies*

CIMS and MARKAL consider a lot of advanced technologies, both in the energy supply and demand sides. Most of the advanced technologies are much more competitive than the base technologies in terms of life cycle cost, especially when their capital costs are exogenously set to decline in the future. Thus, the availability of the advanced technologies has great impacts on energy end use, emission reduction potential, as well as the associated incremental costs. In the CIMS model, the advanced technologies exist both in the *reference* and policy runs. Based on an intensive literature review, the maximum future market shares of the advanced technologies were estimated for the *reference* run. According to these estimations, the intangible cost factor i discussed in section 2.2.3 was utilized in the calibration process to incorporate risk premiums and intangible consumer preferences into the perceived private costs faced by decision makers. Because these intangible cost factors remain the same in the policy run, the advanced technologies capture less market share than had it been the case that no intangible costs were considered. However, because intangible costs such as risk premiums are not real financial costs, CIMS could exclude the intangible cost factor when it generates the output for TEC. In contrast, MARKAL uses a different approach to deal with advanced technologies. The market performance of these technologies is determined both by the availability and the constraints on the market share of each technology. Therefore, if all other assumptions were the

same, the difference in treating the advanced technologies between the two models would make CIMS' MAC curve higher than that estimated by MARKAL.

8) *Global constraints versus emission taxes*

MARKAL and CIMS can assess command and control instruments such as the CO₂ emission cap, but they solve this in different ways. As an optimization model, MARKAL can simply include a global constraint that matches the CO₂ emission control target, then find a solution at the least financial cost. As a simulation model, CIMS differs in that a global constraint is not possible with this type of model. Instead, a package of policy instruments including perhaps constraints on individual technologies has to be activated in the model to meet the same CO₂ emission cap.

In summary, the difference between the model methodologies and applications has significant impacts on cost estimations of MARKAL and CIMS as follows:

- 1) Except for the basic financial costs considered by MARKAL, CIMS also includes monetary estimates of intangible financial costs. This would make CIMS' cost estimates higher.
- 2) The winner-take-all characteristic of MARKAL means that the lowest cost choice is always taken to the full extent, specified by the upper bound constraint. With its probabilistic approach, CIMS allows higher cost technologies to capture parts of the market. This would make CIMS' cost estimates higher.
- 3) The bounded rationality of CIMS, in time and space, leads to higher costs.
- 4) The marginal cost pricing in MARKAL versus average cost pricing in CIMS will lead to higher costs in CIMS.
- 5) The uniform treatment of the advanced technologies and the application of the intangible cost factor i during the reference scenario calibration make CIMS' cost estimates higher.

- 6) Finally, one difference discussed in section 5.2 works in the opposite direction in terms of cost estimates. More recent findings regarding the fuel mixture projection from ERI (2003) have been incorporated in the reference scenario of CIMS, which make the reference emissions of CIMS higher than those of the Tsinghua MARKAL.

5.4 Summary

The disparity of different MACs in this chapter illustrates that it is essential for the decision makers to understand the modelling methodology, reference assumptions and other relevant information before using the MAC curves from a study.

In the case of CIMS and Tsinghua MARKAL's application in China, both models share the same technological database and similar reference assumptions. The difference of MACs is primarily attributable to the way in which technology choices are modelled, that is process optimization versus behavioural simulation. Other factors that lead to the cost deviation are their different treatment of advanced technologies and the different reference CO₂ emissions.

In the future, it is possible to bring these models closer together through the following exercises: Tsinghua MARKAL model could incorporate intangible costs such as risk premiums. Also, the CIMS model could apply a form of marginal cost pricing as well as changing its treatment of the coal and oil mining industries. Another issue for CIMS is to assess how not just capital costs, but also intangible costs, might decrease as new technologies gain market shares. Some of these modifications are currently available in the newer version of the CIMS model.

6. CONCLUSION

6.1 Summary of Research Findings

An important conclusion from this study is that if China's energy development path follows the reference scenario, China's ambitious economic growth over the next three decades will come with the price of greater CO₂ and SO₂ emissions, and greater energy security vulnerability. While the energy development path of the reference scenario is undesirable for China's sustainable development, this study suggests that it is plausible to design appropriate policy instruments to induce an alternative energy development path which would enable China to continue social and economic development while ensuring security of energy supply, and acceptable local and global environmental quality. The modelling outputs of this study also indicate that advanced technologies are the key drivers to achieve ambitious emission control and energy security targets in various policy runs. Thus the demonstration and commercialization of advanced technologies should be accelerated in the near future to ensure long-term sustainable development in China's energy sector.

However, to resolve the challenges of local air pollution, climate change and energy security, energy policy makers in China need to understand the tradeoff among these policy issues and the associated incremental costs. For example, to meet the 39GtC cumulative CO₂ emission control target, the policy makers might be able to discover abatement options with very low or even negative incremental costs, such as enhanced oil and CBM recovery. However, if the assumptions regarding the reference scenario are reasonable, such "no-regrets", or low-cost options, alone are not enough to meet the other ambitious policy target(s).

Furthermore, during the 35-year modelling period, this study shows that when CO₂ emission control and energy security targets are both rigorously pursued, the tradeoff

between these different policy targets is inevitable. While a stringent CO₂ emission cap would significantly lower coal consumption and increase oil and gas imports, a stringent energy security constraint would accelerate coal gasification and liquefaction in China. This study also reveals that there could be great potential to sequester CO₂ through enhanced resource recovery and through electricity generation with carbon sequestration at acceptable incremental costs by 2030. This provides great potential for further research and commercial demonstration in future.

As illustrated in section 3.4.5, this study shows that the side benefits of CO₂ emission abatement are substantial. In comparison, the impact of the SO₂ tax on cumulative CO₂ emissions is far less significant, because there are abundant desulphurization opportunities for coal-fired energy systems such as coal washing, coal gasification and FGD units.

It is further worth noting that the CO₂ MAC curve of this study is the highest among similar research. Since the disparity of CO₂ MAC curves comes from many sources, it is essential for energy policy makers to understand the reference scenario assumptions, modelling methodology and other relevant information used in a research before they can rely on the MAC curves to set policy targets.

Finally, the modelling exercises presented in this report should be viewed as the starting point for further detailed analysis. The conclusions are based on many simplified assumptions. In the future, more detailed analyses should be pursued.

6.2 Policy Recommendations

1) *Encouraging energy conservation*

Compared with developed countries, the energy end use efficiency in China is extremely low. There is great potential to reduce the future energy demand growth in China by energy conservation measures with low incremental costs.

2) *More incentives for renewable energy*

Currently, most of the renewable energy sources cannot compete with conventional fuels such as coal. However, the findings from this study indicate that renewable energy sources can play a very important role to meet energy demand increases in the future. Therefore, more incentives need to be provided to accelerate the development of renewable energy resources, especially small hydro power in rural areas, large wind farms in remote wind-rich regions connected by long-distance high-voltage DC transmission lines to major load centers, and biomass gasification.

3) *Application of a national renewable portfolio standard*

Electricity sector can play a very important role in emissions control. Currently, a compulsory renewable portfolio standard across the country is a sound policy instrument with which to accelerate the development of wind, solar, biomass and small hydro power.

4) *Encouraging CDM development*

CDM could reduce domestic CO₂ emissions and attract foreign investment simultaneously. To become a key player in the international CDM market, the learning-by-doing effects from the implementation of the past projects in China should be disseminated to the local level. Moreover, it is essential for the Chinese policy-makers to overcome the scepticism that participation in the CDM market is the precursor for agreeing to quantitative GHG emission reduction commitments in the near future.

5) *Transferring Canadian experience to China*

If more than one model were chosen for energy policy planning, policy makers would benefit greatly by learning the importance of model choice in determining the differences in cost estimates. In 1998, the Canadian government initiated the National Climate Change Implementation Process, and selected both MARKAL

and CIMS to integrate the specified policy actions and test the effect of different implementation policies and different assumptions about external developments (Jaccard et al. 2003a). So far, the research findings and policy recommendations from the above-mentioned modelling exercise have substantially narrowed down the uncertainties facing Canada's policy makers and helped them better deal with the climate change issues. In the future, a similar modelling exercise is highly recommended for China.

6.3 Data Constraints

The structure and databases of CIMS allows energy policy modellers to analyze any technology related issue, many of which are crucial to global, national and regional policy development. However, in the case of CIMS' first application to China, progress is hampered by primary data constraints in the following two areas:

- 1) *The data for baseline year calibration is poor.*

Energy supply and consumption data are often improperly aggregated. Sometimes, the disaggregated data are unavailable or confidential. In an effort to properly quantify the historical energy consumption data, adjustments have to be made to the official energy statistics to better represent the true size of sectoral consumption.

- 2) *The recent reported energy consumption trend in China is not consistent with the reported GDP growth rate.*

From 1995 to 2000, the primary energy consumption of China decreased slightly while the reported annual GDP growth rate was as high as 8.4% (National Bureau of Statistics 2003). The strange relationship between energy and macroeconomic statistics makes it very hard to improve the reference scenario projection of this study using recent statistics. Given the 35-year length of the modelling period and the emphasis on the relative change instead of absolute values, the overall impacts

on the analysis seem to be acceptable. However, it is worth noting that the aforementioned inconsistency makes it difficult to gain insights from the modelling output near the year 2000.

6.4 *Future Research Recommendations*

This study represents the first attempt to apply CIMS, a technology specific, behaviorally realistic, energy-economy simulation model to China. As such, there are a number of opportunities for future research that would improve the quality of the analysis and expand the types of policy questions that can be addressed.

- 1) *Improving reference scenario projection* - Better quality data would help improve the reference scenario projection. If it is necessary, adjustment could be made to the reported energy statistics based on the following hypotheses.
 - China's recent GDP growth rate might be overestimated (Maddison 1997; Rouen 1997; Rawski 2001).
 - The recent energy statistics regarding China's coal supply and consumption are inaccurate, and are likely to be underreported (ERI 2003).
 - Before December 1998, there were incentives in some regions to overreport the coal supply (Pan 2002).
- 2) *Improvement of the technological database* - In the future, more GHGs such as CH₄ and N₂O and more CACs such as NO_x and particular matters should be included into CIMS-China's technological database. When the model development is finished, the future researcher could cover the GHG emissions and local air policy issues in a more comprehensive framework.
- 3) *Moderate geographic disaggregation* - In this study, China is treated as a single geographic region with six major economic sectors. One disadvantage of not using geographic disaggregation in the model is that locally significant energy development opportunities cannot be highlighted. Another disadvantage is that the regional cost

and resource availability disparity could not be explicitly represented in the model. Therefore, in the future, moderate geographic disaggregation may be desirable.

- 4) *Application at the provincial (municipal) level* - CIMS could be applied to provincial or municipal levels. For example, similar research could be conducted for a province like Guangdong, or at a city level such as Beijing or Shanghai.
- 5) *Sectoral level modelling exercise* - The detailed technological database of the electricity sector makes CIMS a suitable tool to assess policy instruments targeting the sustainable development of this sector. For instance, CIMS could be used to evaluate the impacts of a nation-wide renewable portfolio standard on China's electricity sector.
- 6) *Cogeneration analysis* - CIMS has a detailed database of cogeneration technologies in both Canada and China. An analysis of the cogeneration potential in industry and other demand sectors with regard to both electricity and heat generation and their transportation and distribution could be conducted for China.
- 7) *Moving from partial equilibrium to full equilibrium* - Future research can develop a link between CIMS' macroeconomic module and the energy demand and conversion modules, and assess the methodological contrast between the bottom-up approach in this study and future hybrid exercises in China.

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8. APPENDICES

Appendix A: Detailed Results of the Reference Run

A.1: Calibration to Appendix A of MARKAL Report to CCICED

	1995			2030		
	MARKAL (Mtce)	CIMS (Mtce)	Difference (%)	MARKAL (Mtce)	CIMS (Mtce)	Difference (%)
Industry	688	682	-0.9%	1,304	1310	0.5%
Commercial	29	29	0.0%	180	180	0.1%
Residential	129	129	-0.1%	487	491	0.8%
Transport	90	98	8.9%	507	427	-15.7%
Agriculture	39	39	0.0%	82	82	0.0%
Total	975	977	0.2%	2,561	2491	-2.7%

A.2: Primary Energy Consumption by Fuel

	Primary Energy Consumption (Mtce)				Fuel Share (%)			
	1,995	2,010	2,020	2,030	1,995	2,010	2,020	2,030
Coal	952	1,557	1,907	2,297	74%	68%	65%	62%
Oil	236	436	584	772	18%	19%	20%	21%
NG	24	103	186	298	2%	4%	6%	8%
Hydro	71	151	210	272	6%	7%	7%	7%
Nuclear	5	18	27	37	0%	1%	1%	1%
Renewable	0	19	34	53	0%	1%	1%	1%
Total	1,288	2,284	2,948	3,731	100%	100%	100%	100%

A.3: Final Energy Consumption by Sector

	Final Energy Consumption (Mtce)				Sectoral Share (%)			
	1,995	2,010	2,020	2,030	1,995	2,010	2,020	2,030
Industry	682	1,037	1,168	1,310	70%	64%	58%	53%
Commercial	29	79	119	180	3%	5%	6%	7%
Residential	129	238	355	491	13%	15%	18%	20%
Transport	98	206	301	427	10%	13%	15%	17%
Agriculture	39	59	70	82	4%	4%	3%	3%
Total	977	1,620	2,013	2,491	100%	100%	100%	100%

A.4: Final Energy Consumption by Fuel

	Final Energy Consumption (Mtce)				Fuel Share (%)			
	1,995	2,010	2,020	2,030	1,995	2,010	2,020	2,030
Coal	608	820	880	946	62%	51%	44%	38%
Oil	197	388	528	705	20%	24%	26%	28%
Gas	22	82	149	243	2%	5%	7%	10%
Electricity	114	251	352	463	12%	16%	18%	19%
Heat	36	70	92	120	4%	4%	5%	5%
Renewable	0	9	12	14	0%	1%	1%	1%
Total	977	1,620	2,013	2,491	100%	100%	100%	100%

A.5: CO₂ Emissions by Sector

	CO ₂ Emissions (MtCO ₂)				Sectoral Share (%)			
	1,995	2,010	2,020	2,030	1,995	2,010	2,020	2,030
Industry	1,449	2,038	2,163	2,318	47%	39%	33%	28%
Commercial	61	151	224	336	2%	3%	3%	4%
Residential	290	445	597	751	9%	8%	9%	9%
Transport	214	433	628	889	7%	8%	9%	11%
Agriculture	76	110	128	145	2%	2%	2%	2%
Electricity	865	1,847	2,578	3,391	28%	35%	39%	41%
Total	3,089	5,266	6,652	8,271	100%	100%	100%	100%

A.6: SO₂ Emissions by Sector

	SO ₂ Emissions (kt)				Sectoral Share (%)			
	1,995	2,010	2,020	2,030	1,995	2,010	2,020	2,030
Industry	11,119	13,548	13,447	13,601	47%	42%	36%	32%
Commercial	552	1,036	1,454	2,109	2%	3%	4%	5%
Residential	2,640	2,890	3,115	2,937	11%	9%	8%	7%
Transport	626	758	1,011	1,310	3%	2%	3%	3%
Agriculture	409	609	678	737	2%	2%	2%	2%
Electricity	7,721	13,327	17,091	21,174	33%	41%	46%	50%
Total	23,644	32,272	36,902	41,985	100%	100%	100%	100%

Appendix B: Conversion Factor, Carbon Emission Factor and Carbon Oxidization Ratio for China's Main Fossil Fuels

In this appendix, inventories of CO₂ emissions for China's main fossil fuels are compiled according to the IPCC method, format, and default data except for the conversion factor of coal. All conversion factors, potential carbon emissions factors, and fraction of carbon oxidized are derived according to IPCC Guidelines.

Table: B.1 Conversion Factor and Carbon Emissions Factors of Main Fossil Fuel

	Conversion factor GJ/t	Carbon Emission Factor tC/TJ
Coal	20.93 ^a	25.8
Coke	28.47	29.5
Crude Oil	42.62	20
NGL	42.62	17.2
Gasoline	44.8	18.9
Jet Kerosene	44.59	19.5
Other Kerosene	44.75	19.6
Diesel Oil	43.33	20.2
Residual Fuel Oil	40.19	21.1
LPG	47.31	17.2
Other Oil	40.19	20
Natural Gas (Dry)	39 TJ/mm ³	15.3
CBM	39 TJ/mm ³	16.3
Hydropower		0
Nuclear Power		0
Renewable		0

a: This value is slightly different with IPCC default value

Table B.2: Fraction of Carbon Oxidized during Combustion (IPCC Default Assumptions)

	Percent
Solid Fuels	98
Liquid Fuels	99
Gaseous Fuels	99.5