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The costs of mitigating carbon emissions in China: findings from China MARKAL-MACRO modeling

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Abstract

In this paper MARKAL-MACRO, an integrated energy-environment-economy model, is used to generate China's reference scenario for future energy development and carbon emission through the year 2050. The results show that with great efforts on structure adjustment, energy efficiency improvement and energy substitution, China's primary energy consumption is expected to be 4818 Mtce and carbon emission 2394 MtC by 2050 with annual decrease rate of 3% for the carbon intensity per GDP during the period 2000–2050. On the basis of this reference scenario, China's marginal abatement cost curves of carbon for the year 2010, 2020 and 2030 are derived from the model, and the impacts of carbon emission abatement on GDP are also simulated. The results are compared with those from other sources. The research shows that the marginal abatement costs vary from 12US$/tC to 216US$/tC and the rates of GDP losses relative to reference range from 0.1% to 2.54% for the reduction rates between 5% and 45%. Both the marginal abatement costs and the rates of GDP losses further enlarge on condition that the maximum capacity of nuclear power is constrained to 240 GW or 160 GW by 2050. The paper concludes that China's costs of carbon abatement is rather high in case of carbon emissions are further cut beyond the reference scenario, and China's carbon abatement room is limited due to her coal-dominant energy resource characteristic. As economic development still remains the priority and per capita income as well as per capita carbon emission are far below the world average, it will be more realistic for China to make continuous contributions to combating global climate change by implementing sustainable development strategy domestically and playing an active role in the international carbon mitigation cooperation mechanisms rather than accepting a carbon emission ceiling.
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1. Introduction

In 2000, China emitted around 800 million tons of carbon from fuel combustion, accounting for about 13% of the world total and being the second largest CO_2 emitter in the world. China is facing mounting pressure such as "voluntary commitment of GHG reduction" from the developed countries in international negotiation on global climate change issue although China has done and will continue to do considerable efforts to cut carbon emission. Is China really a nation with quite low carbon abatement costs as widely regarded by the developed countries? Can China afford to commit itself a carbon emission cap? This paper attempts to analyze China's marginal abatement cost of carbon and potential impacts of carbon mitigation on GDP with application of China MARKAL-MACRO model, an integrated energy, environment and economy non-linear dynamic programming model.

2. Modeling methodology

2.1. MARKAL-MACRO

MARKAL is a well-known dynamic linear programming model built on the concept of a Reference Energy System, RES. It incorporates full range of energy processes, e.g. exploitation, conversion, transmission, distribution and end-use. The model can consider existing as well as advanced technology that may be deployed in future. The objective function includes the capital costs of energy conversion technologies, capital costs of end-use technologies, fuel costs, infrastructure costs, and operating and maintenance costs. The model searches for a least-cost combination of technologies

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and fuels dynamically over the planning period to meet user-specified energy service demands.

MARKAL has been used in a standalone model in China (Chen and Wu, 2001; Wu and Chen, 2001; Wu et al., 2001). However there is no feedback between energy service demand and energy prices. MACRO bridges the gap (Hamilton et al., 1992). MACRO is a macroeconomic model with an aggregated view of long-term economic growth. The basic input factors of production are capital, labor and energy service demands. The economy's outputs are used for investment, consumption and inter-industry payments for the cost of energy. Investment is used to build up the stock of capital. There are four restrictions for MACRO: *PRD* (production function), *USE* (usage of production), *CAP* (capital accumulation) and *TC* (terminal condition) (Hamilton et al., 1992).

$$PRD: \quad \begin{aligned} &Y_t = \left[akl(K_t)^{\rho\alpha}(L_t)^{\rho(1-\alpha)} + \sum b_{dm}(D_{dm,t})^{\rho}\right]^{1/\rho},\\ &L_0 = 1, \quad L_t = (1 + grow_{t-1})^{ny} L_{t-1},\\ &\alpha = kpvs,\\ &\rho = 1 - 1/ESUB, \end{aligned}$$

where akl, b_{dm} are coefficients determined by a base year benchmarking procedure, K_t is the capital stock accumulated up to period t, L_t is the labor in period t, $D_{dm,t}$ is the demand for energy services of type dm in period t, $grow_t$ is the potential growth rate of the economy, ny is number of years per period, $ESUB$ is the elasticity of substitution between the energy and the capital-labor aggregates, and $kpvs$ is the optimal value share of capital in the value added aggregate.

The production function is an aggregate, nested, CES (constant elasticity of substitution) form. At the top level, there is a capital-labor aggregate that may be substituted for an energy aggregate. At the bottom level, there is a unitary elasticity of substitution between capital and labor, and the energy aggregate in separable.

$$USE: \quad Y_t = C_t + I_t + EC_t,$$

where Y_t, C_t, I_t and EC_t are the production, consumption, investment and energy costs in period t, respectively.

$$CAP: \quad \begin{aligned} &K_{t+1} = tsrvK_t + (ny/2)(tsrvI_t + I_{t+1}),\\ &tsrv = (1 - depr)^{ny},\\ &I_0 = (grow_0 + depr)K_0, \end{aligned}$$

where $tsrv$ is the capital survival fraction, and $depr$ is the annual depreciation rate.

$$TC: \quad K_T(grow_T + depr) \leqslant I_T.$$

The objective function of MARKAL-MACRO is the maximization of the discounted log of consumer utility, summed over all periods:

$$\begin{aligned} UTILITY = &\sum_{t=1}^{T-1}(udf_t)(\log C_t)\\ &+ (udf_T)(\log C_T)/[1 - (1 - udr_T)^{ny}],\\ udf_t = &\prod_{\tau=0}^{t-1}(1 - udr_\tau)^{ny},\\ udr_t = &(kpvs)/(kgdp) - depr - grow_t, \end{aligned}$$

where $kgdp$ is the initial capital-to-GDP ratio, udr_t is utility discount rate for period t, and udf_t is utility discount factor for period t.

The link between MACRO and MARKAL has to generate the energy service demands from the state of MACRO. Let X_j be an activity of MARKAL supplying energy service demand of the form dm proportional to $supply_{j,dm}$. With the 'autonomous energy efficiency improvements factor' $aeeifac_{dm}$, MARKAL supply activities are linked to MACRO demand variables through:

$$\sum_j supply_{j,dm,t} X_{j,t} = aeeifac_{dm,t} D_{dm,t}.$$

To transfer the costs from MARKAL to MACRO the link computes for each activity and period the cost $cost_{j,t}$ per unit of activity $X_{j,t}$, and quadratic penalty terms are introduced to smooth the rate of market penetration of new technologies:

$$\sum_j \mathrm{cost}_{j,t} X_{j,t} + c\sum_{tch} c_{tch} XCAP^2_{tch,t} = EC_t,$$

$$CAP_{tch,t+1} = expfCAP_{tch,t} + XCAP_{tch,t+1},$$

where $CAP_{tch,t}$ is the capacity for technology tch during period t, and $XCAP_{tch,t}$ is the amount of capacity installed beyond the capacity expansion factor $expf$ for technology tch in period t.

MARKAL-MACRO, merging the bottom-up engineering to top-down macroeconomic approaches, adds price elasticity on energy service demands and links changes in the energy system to the level of economic activity while maintaining the technological richness and flexibility of MARKAL.

2.2. China MARKAL-MACRO

With the MARKAL-MACRO modeling framework and windows-based software ANSWER 3.5.9, we developed China MARKAL-MACRO model in 5-year intervals extending from 1995 through 2050. The model provides detailed description for China energy system, covering from energy resource mining, energy import/export, conversion, transmission and distribution to end-use. The primary energy considers not only conventional fossil fuel such as coal, oil, natural gas and coal bed methane, but also new and renewable energy like hydro, nuclear, wind, solar, geothermal and biomass. About 50 conversion technologies (Table 1), including both existing and advanced, are defined in the model to convert primary energy into final energy.

Demand sector are divided into agriculture, industry, commercial, urban residential, rural residential, and transportation, and further disaggregation of these sectors are shown in Table 2. For each sub-sectors, the choice of technologies includes those that are commercially available today, as well as technologies that might be commercially introduced in the future. Totally around 90 end-use technologies are presented in the model.

The detail description and assumption for resource availability, technical and economic parameters for each technology, and etc. could be found in other literatures (Chen and Wu, 2001; Wu and Chen, 2001; Wu et al., 2001). The basic assumptions for future social and economic development to generate energy service demand are displayed in Table 3, and the energy service demand projection approaches as well as results could also be found in above-mentioned literatures.

With the projected energy service demands, China MARKAL can be run in a standalone mode with application of GAMS, and it was calibrated in the base year. To link China MARKAL with MACRO, the steps described in Appendix A. While completing all the steps, China MARKAL-MACRO was run to generate reference scenario for future energy development and carbon emission, and to estimate the cost of carbon emission abatement.

Table 1
Main conversion technologies defined in China MARKAL-MACRO

Stand-alone electricity production	*Co-production of electricity, heat, etc.*
Coal-steam $\leqslant$ 100 MW	Coal, traditional cogeneration
Coal-steam, 100–200 MW	Coal, advanced cogeneration
Coal-fired, 200–300 MW, ESP	Coal, IGCC, electricity + industrial process heat
Coal-fired, $\geqslant$ 300 MW, ESP	Coal, IGCC, electricity + DME
Coal-fired, $\geqslant$ 300 MW, ESP & dry FGD	Coal, IGCC, electricity + methanol + process heat
Coal-fired, $\geqslant$ 300 MW, ESP & wet FGD	Coal, IGCC, electricity + methanol + heat + town gas
Coal-fired, $\geqslant$ 300 MW, ESP & SO_2/NO_x	Coal, electricity + H_2
Coal, atmosphere pressure fluid bed combustion	NG, combined cycle cogeneration
Coal, pressurized fluid bed combustion	Biomass, gasification, electricity and heat
Coal, ultra-supercritical steam	*Production of non-electric energy carriers*
Coal, integrated gasification combined cycle (IGCC)	Coal washing
Oil, traditional steam	Coal, central station district heating plant
Oil, combined cycle	Coal, central station district heat, advanced boiler
NG, simple cycle gas turbine, peaking	Coal, coke making
NG, combined cycle	Coal, gasification, existing
Biomass, fluid bed combustion	Coal, gasification, advanced
Solar, residential PV system	Coal, direct liquefaction
Solar, Central PV power plant	Coal, indirect liquefaction
Wind, small-scale local turbines	Coal, hydrogen production
Wind, remote large-scale	Oil refinery
Hydropower (> 25 MW)	Biomass digester
Small Hydropower (< 25 MW)	
Geothermal power generation	
Nuclear power generation	

Table 2
Demand sector disaggregation in China MARKAL-MACRO

Agriculture	*Commercial*	*Transportation*
Electric motors	Space heating and water heating	*Freight*
Irrigation	Cooling	Air
Agro-process	Lighting and electric appliances	Railway
Farming machines	*Urban residential*	Highway
Industry	Space heating	Waterway
Aluminum	Cooking and water heating	Pipeline
Ammonia	Air conditioning	*Passenger*
Cement	Lighting and electric appliances	Air
Paper	*Rural residential*	Railway
Steel	Space heating	Bus
Other industry electricity	Cooking and water heating	Car
Other industry heat	Air conditioning	Waterway
Non-energy use	Lighting and electric appliances	

3. Results

3.1. Reference scenario

The modeling results for the reference scenario from China MARKAL-MACRO are summarized in Table 4. During the period 1995 to 2050, the final energy consumption in China is expected to increase from 981 to 3638 MtC with share of industry in the total energy consumption falling from 72.2% to 42.8%, while shares of transportation, commercial and residential rising 17.3%, 3.4% and 9.8%, respectively. The great fall of industry sector's final energy consumption will be attributed to energy efficiency improvement, and in particular to reduced value-added share of industry in GDP as well as structural adjustments of both industrial branches and products. By 2050, the primary energy consumption is expected to hit as high as 4818 MtC with coal share dropping sharply to 50.2% and percentage of hydro, nuclear and other new and renewable energy reaching 17.3%. By 2050 almost all available hydro resources are expected to be exploited and utilized leading to a capacity of 250 GW, occupying 18.6% in the total installed capacity, i.e. 1347 GW, with annual output sharing 14.3% in the total electricity output of 6411 TWh. Apart from hydropower, currently nuclear is the sole energy that might substitute fossil fuels in large scale. In the short term, nuclear power expansion in China is mainly restricted by investment funds. The Chinese government has adopted a policy to design and manufacture nuclear power plants domestically in order to lower investment costs. In the next few decades, nuclear energy will play quite an important role, especially in the southeast coastal region. Nuclear power

Table 3
Basic assumption for future social and economic development to generate energy service demands

	1995	2000	2010	2020	2030	2040	2050
Population (billion)	1.211	1.267	1.386	1.495	1.560	1.590	1.575
GDP (billion US$, 1995 price)	700	1042	2172	3710	6338	9382	13887
Urbanization (%)	29.0	36.2	42.4	51.4	58.4	65.0	70.0
Industrial structure							
Primary (%)	20.5	16.4	15	12.5	10	8	6
Secondary (%)	48.8	50.2	45	43.5	42	40.5	39
Tertiary (%)	30.7	33.4	40	44	48	51.5	55

Table 4
Modeling results for reference scenario from China MARKAL-MACRO

	1995	2000	2010	2030	2050
Final energy consumption (Mtce)	981	950	1442	2398	3638
Agriculture (%)	4.0	4.4	4.5	3.7	2.9
Industry (%)	72.2	69.2	59.7	48.6	42.8
Transportation (%)	5.3	8.8	14.9	21.1	22.6
Commercial (%)	5.4	6.3	6.5	8.5	8.8
Residential (%)	13.1	11.3	14.5	18.1	22.9
Primary energy consumption (Mtce)	1311	1280	1867	3102	4818
Coal (%)	74.6	67	68.3	57.8	50.2
Oil (%)	17.5	23.6	15.8	19.0	21.3
Gas (%)	1.8	2.5	5.0	8.2	11.1
Hydro (%)	5.27	6.85	8.0	8.3	7.0
Nuclear (%)	0.36	0.47	2.6	5.8	8.1
Other new and renewable (%)	0.01	0.03	0.3	0.8	2.2
Power capacity (GW)	217	319	409	771	1347
Hydro (%)	24	24.9	26.9	24.7	18.6
Nuclear (%)	1.0	0.7	4.9	9.6	11.9
Other new and renewable (%)	0.05	0.05	1.2	2.9	7.6
Electricity output (TWh)	1007	1368	1942	3693	6411
Hydro (%)	18.6	17.8	20.8	18.9	14.3
Nuclear (%)	1.27	1.22	6.8	13.1	16.4
Other new and renewable (%)	0.04	0.1	0.7	1.6	4.2
Carbon emission (MtC)	819	792	1077	1655	2394
Per capita carbon emission (tC/capita)	0.676	0.625	0.777	1.061	1.520
Energy intensity per GDP (Kgce/US$, 1995 price)	1.819	1.229	0.859	0.489	0.347
Carbon intensity per energy consumption (Kg-C/Kgce)	0.635	0.618	0.577	0.533	0.497
Carbon intensity per GDP (Kg-C/US$, 1995 price)	1.156	0.76	0.496	0.261	0.172

is expected to grow to 160 GW by 2050 accounting for 11.9% in the total capacity, with annual output of 1051 TWh, occupying 16.4% in the total electricity output, close to world average level (18%) in 1995. In addition, more and more new energy including solar, geothermal and especially wind, will be developed for power generation. By 2050 the capacity of other new and renewable energy power generation (mainly wind power) is expected to increase to 100 GW with annual electricity output of 270 TWh. In contrast, percentage of thermal power capacity is expected to decline gradually. By 2050 the percentage of thermal power plants in total electricity output will drop to 65%, close to world average level (62%) in 1995. Moreover, for the thermal power plants, owing to application and popularization of large generation units and advanced technologies, thermal power efficiency will further improve, reaching 42% by 2050.

With the steady economic growth, CO_2 emission is expected to keep on increasing in future, reaching 2394 MtC by 2050. CO_2 emissions can be subdivided as follows:

$$C = \left(\frac{C}{FEC}\right) \times \left(\frac{FEC}{TEC}\right) \times \left(\frac{TEC}{GDP}\right) \times \left(\frac{GDP}{POP}\right) \times POP,$$

where C is the amount of CO_2 emissions, FEC is the total carbon-based fossil fuel consumption, TEC is the total commercial energy consumption, GDP is the Gross Domestic Products, and POP is the population.

The change of CO_2 emissions would result from the change in fossil fuel carbon intensity (C/FEC), the penetration of carbon-free fuel ($1 - FEC/TEC$), energy intensity (TEC/GDP), per capita GDP (GDP/POP), and population (POP). Table 5 shows the contribution of these factors to China's CO_2 emission growth during 1980–2050.

The expected sustaining growth of economy is the root of carbon emission increase in future. Owing to the continuous considerable efforts on industrial and product structure adjustment, energy efficiency improvement (both of these two cause drop of energy intensity in Table 5), as well as energy substitution, the increase of carbon emission is expected to greatly slow down with annual decrease rate of carbon intensity per GDP maintaining as high as 3% in the course of 2000–2050.

3.2. Marginal abatement cost curves

3.2.1. Marginal abatement cost curves from China MARKAL-MACRO

To plot marginal abatement cost (MAC) curves is a useful way to characterize the response of a model to emission controls. MAC curves are derived by imposing progressively stricter constraints on allowed carbon emissions within the models and recording the resulting carbon shadow prices (implicit values of the carbon emission constraints) or by introducing progressively higher carbon taxes and recording the quantity of abated emissions. We designed three carbon abatement scenarios, that is, M2010, M2020 and M2030 in this study. For M2010, M2020 and M2030, a same percentage of carbon reduction wrt reference is set from the year 2010, 2020 and 2030, respectively, and lasting to 2050. For a given level of carbon limit, the corresponding carbon shadow prices at every abatement year (the year with carbon constraints, e.g., 2030, 2035, 2040, 2045 and 2050 for M2030 in the 5-year intervals model) could be derived from China MARKAL-MACRO for each reduction scenario. We take the progressively more stringent carbon limits and the resulting carbon shadow prices in the year 2010, 2020 and 2030 from M2010, M2020 and M2030 to plot the MAC curves for these years, respectively, shown in Fig. 1.

The MAC curves are upward-sloping curves: the marginal abatement cost rises as an increasing function of emission reduction rate (or emission reduction amount). Varying the emission reduction rate from 5% to 45%, the marginal abatement costs would be in the range of 12–216US$95/tC. For a same level of emission reduction rate (but different emission reduction amounts due to various reference emissions), the MAC for 2030 is higher than that of 2020, and the MAC for 2020 is higher than that of 2010. The gaps enlarge while the emission reduction rate rises. Below around 200 MtC of reduction, the MAC curves for 2010, 2020 and 2030 almost converge; above this total, the curves diverge with that for 2010 becoming the steepest while that for 2030 the flattest.

Table 5
Breakdown of the contribution to CO_2 growth, MtC

	Due to change in fossil fuel carbon intensity	Due to penetration of carbon free fuel	Due to change in energy intensity	Due to per capita GDP growth	Due to population growth	Total change in CO_2 emissions
1980–2000	−8	−19	−782	1042	147	380
2000–2050	−151	−161	−1850	3512	251	1601

Source: Own calculation.

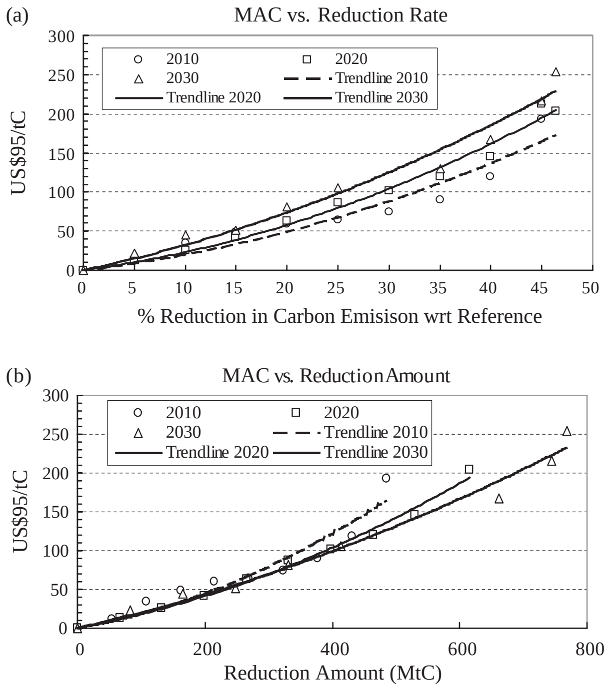

Fig. 1. MAC curves for the year 2010, 2020 and 2030.

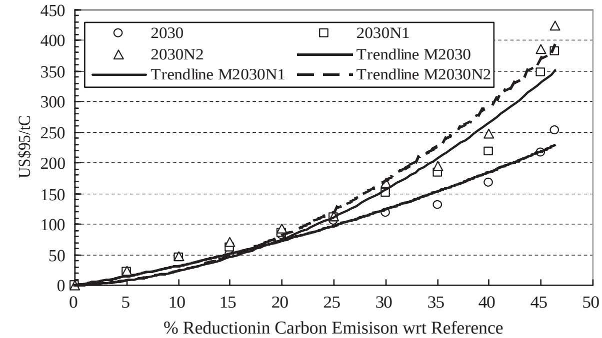

Fig. 2. Comparison of MAC curves for 2030 with constrains on nuclear power development or not.

The modeling results of the mitigation technology mixes for the abatement scenarios imply heavy dependence on the development of nuclear power especially under high carbon reduction rates, e.g., about 480 GW of nuclear power by 2050 is required for the abatement rate of 30%. However, concerning the appropriate scale for nuclear power development by 2050, some experts provided the value lying between 160 and 250 GW. In consideration of the factors like site selection, public acceptance, investment, safety, waste disposal and etc., two scenarios with constrains on nuclear power development were introduced in the model, namely, N1 and N2. It was assumed that the maximum capacity for nuclear power is 150% and 100% of that in the reference scenario, viz. 240 and 160 GW by 2050 for N1 and N2, respectively. To get the marginal abatement cost curves with nuclear power development constrains, two additional abatement scenarios, M2030N1 and M2030N2, were designed with restricted carbon emission starting from 2030 and lasting to 2050. Fig. 2 compares the MAC curves for 2030 with nuclear power development constrains or not. The MAC curves for M2030, M2030N1 and M2030N2 almost converge as long as emission reductions are below 20% of the reference emissions. When the abatement rate is above 20%, the three MAC curves begin to diverge, and the tighter constrain on nuclear power development, the steeper the MAC curve would be. The gap of MAC between the scenarios with nuclear power development constrains or not enlarges sharply as the reduction rate rises.

3.2.2. *Comparison of MAC curves from different sources*

The MAC curves for China could also be observed from several other sources, like EPPA (Emission Prediction and Policy Assessment) model developed by MIT's Joint Program on the Science and Policy of Global Change, Global Trade and Environment model (GTEM) developed by Australian Bureau of Agricultural and Resource Economics (ABARE), POLES model developed at Institut d'Economie et de Polotique de l'Ebergie-CNRS (IEPE), Integrated Policy Analysis model for China (IPAC) developed by Energy Research Institute of National Development and Reform Commission, China (ERI), Asia Least-cost Greenhouse Gas Abatement Strategy (ALAGS), etc.

EPPA is a recursive dynamic multi-region, multi-sector, computable general equilibrium (CGE) model of the world economy (Yang et al., 1996). In the basic version of EPPA model, there are 8 sectors (agriculture, coal, crude oil, natural gas, refined oil, electricity, energy intensive products, and other industrial products). Each of the eight sectors has a multi-layer CES nesting structure that combines the output of other sectors as material or energy inputs, and uses labor and capital as primary factors. It solves for a sequence of new equilibrium for future periods, based on assumptions about exogenous trends in the rate of population and labor productivity growth and technology change, as well as endogenous changes in capital stocks and fixed factor supplies. EPPA covers 12 regions with China as one of them.

GTEM is a recursive dynamic general equilibrium model of the world economy built on the Global Trade Analysis Project (GTAP) database version 4.0e (Tulpule and Brown, 1998). It includes 50 industries in 45 countries and regions. The greenhouse gas coverage in GTEM includes combustion and non-combustion carbon dioxide and methane and nitrous oxide, which account for around 99 percent of global anthropogenic GHG emissions.

POLES is a model of the world energy system with 26 regions. Like MARKAL-MACRO, POLES combines some features of "top-down" models in that prices play a key role in the adjustment of most variables in the model but retains detail in the treatment of technologies characteristic of "bottom-up" models. The dynamics of the model is given by a recursive simulation process that simulates energy demand, supply and price adjustment (Criquil et al., 1999).

Similar to China MARKAL-MACRO and POLES, IPAC model is also a hybrid model integrating the advantages of both "top-down" and "bottom-up" models. The Macro economy module in IPAC was developed based on the Edmonds-Reilly Barns (ERB) model which is a macroeconomic partial-equilibrium model dealing with energy activities and forecasting energy demand over the long term. ERB uses GDP and population as future development drivers, combined with other energy-related parameters to forecast energy demand based on the supply and demand balance. IPAC also has detail description on technologies (Jiang and Hu, 2002).

EPPA provided the MAC curves in the form of

$$MC = aQ^2 + bQ,$$

where MC is marginal abatement cost in US\$85/tC; Q is emission reduction in MtC; a and b are coefficients. For China's MAC curve in 2010, a is 7.00E-5, and b 0.024 (Ellerman et al., 1998).

The form of MAC curves derived from GTEM is represented as

$$MC = a(\exp(bQ) - 1),$$

where marginal abatement cost MC in US\$95/tC, emission reduction Q in MtC. For China's MAC curve (for combustion CO_2 only) in 2010, a is 27.25 and b 0.0024889 (Gruetter, 2000).

The MAC curve from POLES for China in 2010 is expressed in 1990 constant dollars and illustrated in a figure in one of Criqui's papers (Criquil et al., 1999).

Based on the estimation of Jiang from ERI, the MAC curve for China in 2010 from IPAC could also be represented in the same form as EPPA's. But the value for a and b are 0.0008 and 0.1596, respectively, and the cost is in 1990 constant dollars.

Fig. 3 compares the MAC curves for China from different models with all costs are converted to and expressed in 1995 constant dollars by using the deflators of 1 for the year 1985, 1.196 for the year 1990, and 1.36 for 1995.

From Fig. 3, we can see that, IPAC provides the steepest MAC curve and China MARKAL-MACRO next, while EPPA gives the flattest MAC curve and the MAC from GTEM is higher than EPPA's but lower than POLES's. General speaking, MAC are lower in the general equilibrium models (like EPPA and GTEM) than in partial equilibrium models of the energy system

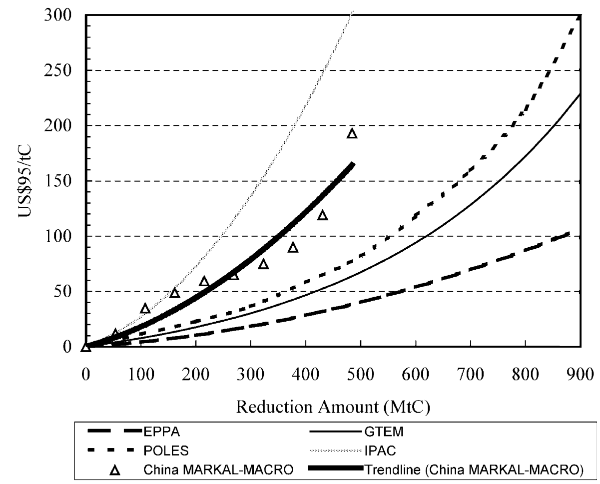

Fig. 3. Comparison of MAC curves for China in 2010 from different models.

(such as POLES, IPAC and China MARKAL-MACRO). One source of difference is that general equilibrium models take into account trade and income effects while POLES, IPAC and China MARKAL-MACRO, as sectoral models, consider only the adjustments achieved in the energy system. Normally in general equilibrium models, revenue from carbon taxation is recycled and thus the overall economic cost of emission control is reduced.

Apart from diverse modeling approach and model structure, the disparity on MAC curves from different models could also be traced to:

(1) Distinct abatement opportunities as represented by the estimated MAC curves in various models.
(2) Different energy substitution possibility assumed in the models. The higher possibility for energy substitution, the lower MAC would be.
(3) Dissimilar cost assumptions for technologies etc. in various models. Higher cost assumptions would result in higher MAC.
(4) Different basic assumptions for GDP growth, population growth, GDP structure etc. in various models leading to distinct reference emissions and thus disparate MAC curves.
(5) Diverse "no-regret", low cost and even some high cost mitigation measures considered in the reference scenario in different models. The more mitigation measures considered in the reference scenario, the lower reference emission while the higher MAC would be. For example, the reference emission in 2010 for China was estimated to be 1792 MtC in EPPA, as opposed to only 1077 MtC according to China MARKAL-MACRO with a lot of mitigation countermeasures consistent to China's energy development strategy considered in its reference scenario.

MAC curves could either be evaluated by introducing an emission constraint or a carbon tax in the models, or based on ''bottom-up'' studies in which the potentials for emission reduction are plotted for various kinds of abatement options with different marginal cost levels, like ALGAS study did (Asian Development Bank, 1998). Fig. 4 was obtained on the basis of analyzing incremental cost and mitigation potential of main technical measures adopted in China's energy sector for the year 2010 (the original cost was presented in 1990 constant dollars and was converted to 1995 constant dollars in this figure). The distinct advantage of this ''bottom-up'' engineering approach is that it is able to identify the reduction potentials of ''no-regret'' options. The ''no-regret'' options shown in Fig. 4 are mainly energy conservation technologies in the end-use sectors such as electric motors renovation, industrial boilers renovation and so on. Most of these ''no-regret'' options have already been included in the reference scenario in China MARKAL-MACRO.

Comparing Figs. 3 and 4, we can see that, models provide lower marginal abatement costs while higher reduction potentials than ''bottom-up'' studies. For example, for abatement cost of not higher than 150US$95/tC, the ALGAS displays only around 175 MtC of reduction potentials, while IPAC, China MARKAL-MACRO, POLES, GTEM and EPPA show approximately 300, 450, 680, 750, 1100 MtC of reduction potentials, respectively.

Therefore, it is essential for us to understand the modeling approach, assumptions, reference scenario emission and etc. before using the MAC curve from a model. For the study of Clean Development Mechanism (CDM) potentials, we had better apply the MAC curves from the ''bottom-up'' studies. There are two main reasons for that. Firstly, models usually ignore some of the constraints on energy substitution thus to over-estimate reduction potentials than the ''bottom-up'' studies. Secondly, all abatement opportunities in models have an associated cost, even opportunities that may be identified as ''no-regret'' opportunities by ''bottom-up'' studies (Tulpule, 2000).

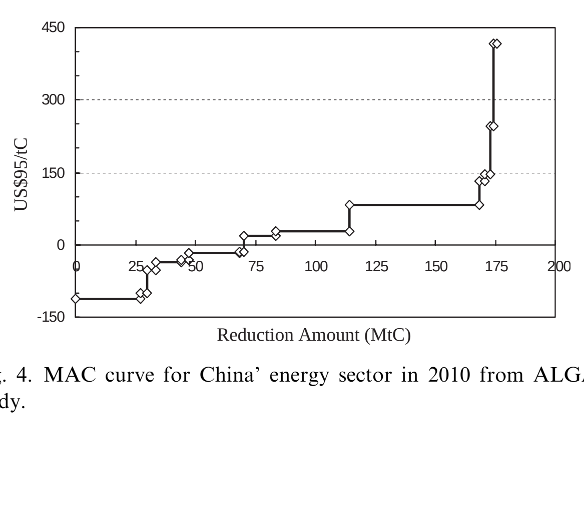

Fig. 4. MAC curve for China' energy sector in 2010 from ALGAS study.

3.3. Impact of carbon emission abatement on GDP

3.3.1. Modeling results from China MARKAL-MACRO

Within a closed economy, a constraint on carbon emission will reduce available choices of energy. As a result, prices of fuels will rise, costs of energy to the economy will increase, and both consumption and investment will be reduced. Fig. 5 illustrates the modeling results of percentage of GDP loss wrt reference for the three emission reduction scenarios, viz. M2010, M2020 and M2030. GDP starts to decline from 2000 for M2010 and from 2005 for both M2020 and M2030, which indicates that it is impossible for emission reduction to be achieved overnight and it needs several decades for the energy system and economy to

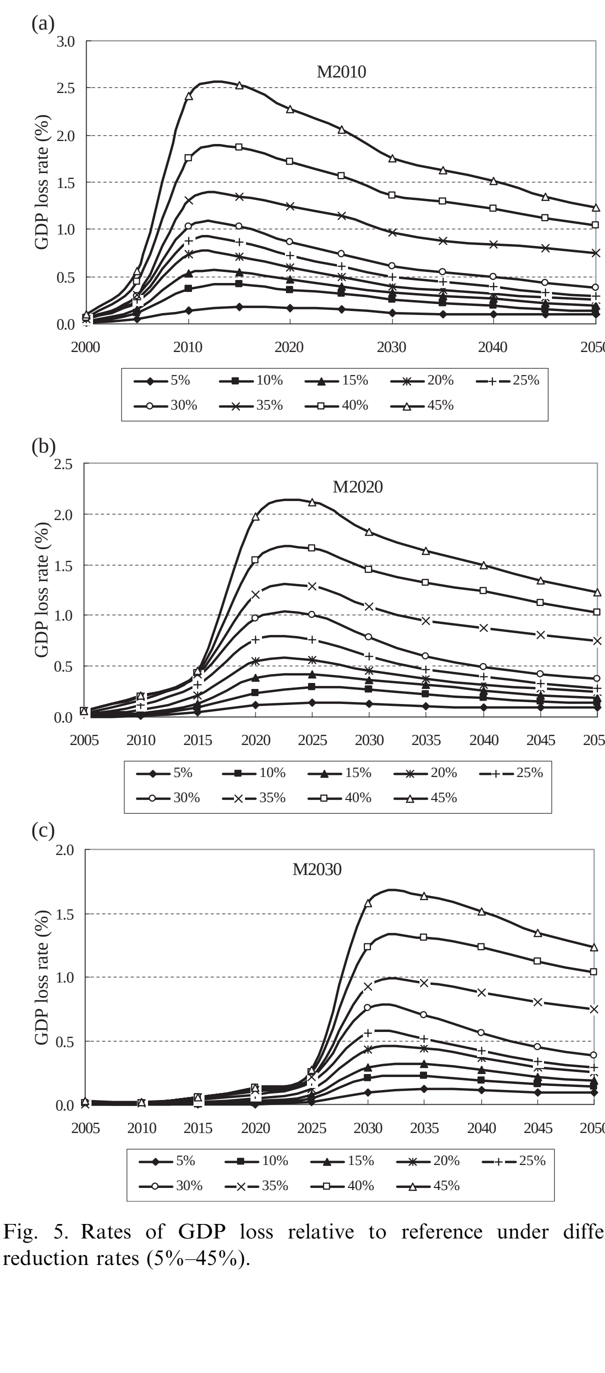

Fig. 5. Rates of GDP loss relative to reference under different reduction rates (5%–45%).

make the adjustment accordingly. The rate of GDP loss relative to reference climbs up steadily and reaches the highest within the planning period (5 years per period) from whose starting year the emission constraints are initially introduced (namely, 2010–2015 for M2010, 2020–2025 for M2020, and 2030–2035 for M2030), and then tends to fall gradually. Giving an example of M2020, when the emission reduction rate is 40%, the rate of GDP loss relative to reference ascends from 0.06% in 2005, reaches the highest during 2020–2025 (1.54% in 2020 and 1.66% in 2025), and then drops gradually to 1.03% in 2050.

Fig. 6 displays the change of the highest GDP loss rate (relative to reference) with the reduction rate for the three emission reduction scenarios. The highest GDP loss rate goes up as the reduction rate increases. For a same reduction rate, the highest GDP loss rate is the biggest for M2010 and the smallest for M2030, which indicates that the earlier to start to bind an emission limit, the larger GDP loss rate would be.

Fig. 7 presents the percentage of GDP loss wrt base year (1995) instead of reference GDP. When the emission reduction rate is below 30% for M2020 and M2030, or below 15% for M2010, the absolute value of GDP loss mounts up continually till some 10 years later than the year in which emission constrains are initially introduced (viz. 2020 for M2010, 2030 for M2020, and 2040 for M2030), and then maintains nearly constant in the remaining planning periods. Taking an example of M2020, when the reduction rate is 30%, the rate of GDP loss relative to base year GDP climbs up fast from 0.49% in 2010 to 5.05% in 2020, 7% in 2030, and then retains nearly unchanged in the course of 2030–2050 with the highest value of 7.37% by 2050. Whereas in case that the emission reduction rate is above 30% for M2020 and M2030, or above 15% for M2010, the absolute value of GDP loss moves up ceaselessly in the whole planning horizon. For instance, when the emission reduction rate is 45%, the rates of GDP loss relative to the base year GDP goes up endlessly from 7.4% in 2010 to 24.2% by 2050 for the case of M2010.

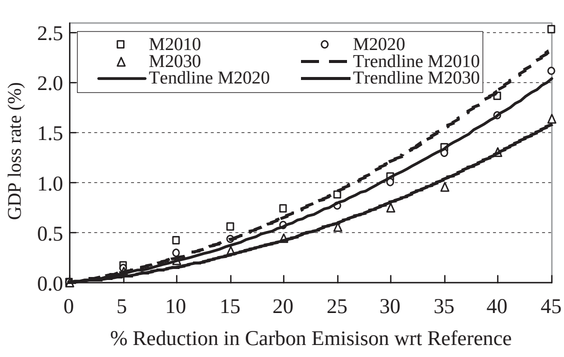

Fig. 6. Highest GDP loss rates (relative to reference GDP) for different emission reduction scenarios.

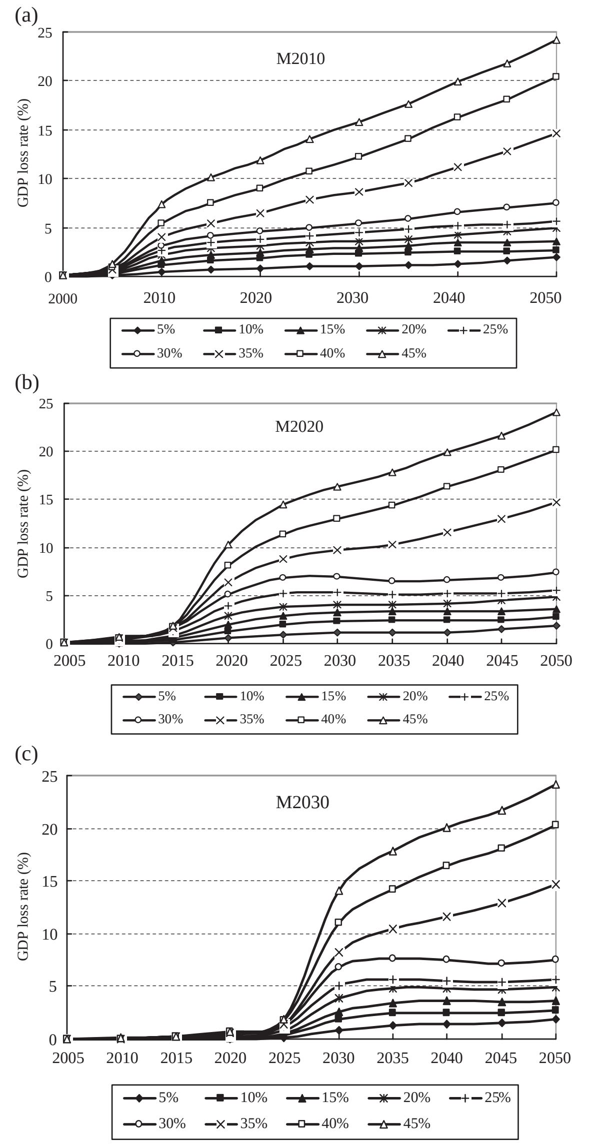

Fig. 7. Rates of GDP loss relative to base year GDP under different reduction rates (5%–45%).

The rates of GDP loss relative to base year GDP rise to be the highest in the year 2050 and these highest values are close to each other for the three different emission reduction scenarios under a given reduction rate, e.g., they are all around 2.7%, 4.9%, 14.6% and 20.3% under the reduction rates of 10%, 20%, 30% and 40%, respectively, for the three scenarios. However, the accumulative GDP losses in the planning periods for M2010 are approximately 1.03–1.22 times of M2020s or 1.32–1.36 times of M2030s for the reduction rates varying from 5% to 45%, as shown in Fig. 8. It implies that to reach a same emission level in a target year, various emission reduction pathways would cause diverse accumulative GDP losses due to disparate accumulative emission reductions, and the earlier to start to abate carbon emission the higher accumulative GDP losses would be.

Setting constrains on nuclear power development would not only rise marginal abatement costs but also heighten GDP losses. Fig. 9 compares the GDP loss rates (relative to reference) for the scenarios M2030, M2030N1 and M2030N2. It could be seen that when the reduction rate is below 15% the three GDP loss rate curves almost converge but diverge as long as the reduction rate is above 15%, and the curves for those with nuclear power development constrains tends to rise more sharply as the emission reduction rates increase. Moreover, the more stringent constrains on nuclear power development, the higher associated GDP losses would be. Fig. 8 illustrates that the accumulative GDP losses in the whole planning horizon for M2030N1 and M2030N2 are approximately 1.0–1.67 or 1.0–1.8 times of M2030s for the reduction rates lying between 5% and 45%.

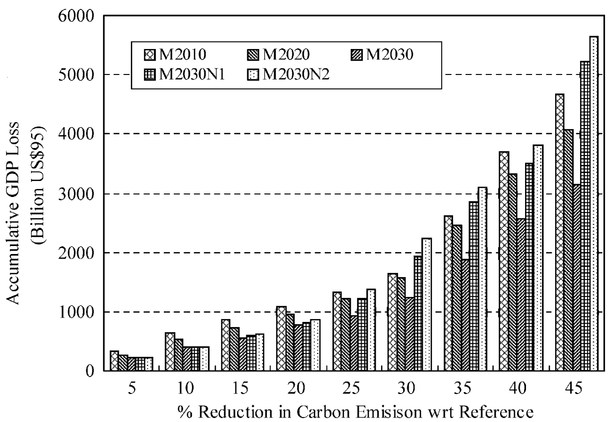

Fig. 8. Accumulative GDP losses under different emission abatement scenarios.

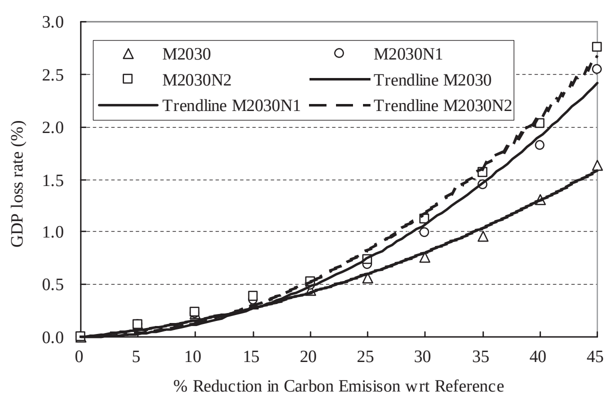

Fig. 9. Comparison of highest GDP loss rates (relative to reference GDP) for the scenarios with nuclear power development constrains or not.

3.3.2. *Comparisons of GDP loss rate estimations from different models*

Table 6 provides a comparison of GDP loss rates for China across models in 2010. Zhang explained that the disparity of GDP loss rate estimations from different models mainly roots in diverse model types, various disaggregation degrees of models, different projections of reference carbon emissions (Zhang, 1996). We would like to stress the impact of different projections of the reference carbon emission here. The reference carbon emission from Zhang's CGE model is 34% higher than that from China MARKAL-MACRO. In Zhang's model, the corresponding emission reductions are 290 and 434 MtC for the reduction rates of 20.1% and 30.1%, respectively. If considering the same level emission reductions of 290 and 434 MtC in China MARKAL-MACRO, 27% and 40% reduction rates are required, and the associated GDP loss rates would climb up to 0.938% and 1.749%, respectively. Apart from these wherefore given by Zhang, different level of GDP (GNP) projection is also an important cause for

Table 6
A comparison of GDP loss rates for China across models in 2010

Model	Abatement rate (%)	Marginal carbon abatement cost[a] (US$/tC)	Rate of GDP (GNP) loss relative to reference (%)
GLOBAL 2100	20.1	84	0.976
	30.1	167	1.893
GREEN	20.1	14	0.253
	30.1	25	0.458
Zhang's CGE model	20.1	23	1.521
	30.1	45	2.763
China MARKAL-MACRO[b]	20(27)	59(69)	0.732(0.938)
	30(40)	75(119)	1.026(1.749)

Sources: Zhang (1996); Author's calculations.

[a] Marginal carbon abatement costs were originally measured at 1990 prices in GLOBAL 2100, at 1985 prices in GREEN, and at 1987 prices in Zhang's CGE model, but were converted to 1995 prices in order to be compared with that from China MARKAL-MACRO.

[b] The figures in parentheses indicate the percentage of reductions required, the associated marginal abatement costs and the GDP loss rates in order to achieve the same amount of carbon reductions as those in Zhang's model.

the disparity of GDP loss rate estimations. For instance, our projection of GDP for China in 2010 is over 16% higher than Zhang's projected GNP (he calculated GNP instead of GDP loss rate). If measured in the same level of GDP as in China MARKAL-MACRO, the loss rate in Zhang's would drop to 1.28% and 2.33% for emission reduction rates of 20.1% and 30.1%, respectively.

The US MARKAL-MACRO modeling analysis provided the results of marginal abatement cost of 145US$95/tC and GDP loss rate of 0.59% (relative to reference) for the case of stabilization USA's carbon emission in 2010 at its 1990 levels (24% reduction wrt reference in 2010). Considering same reduction rate of 24% in 2010, China MARKAL-MACRO gives the GDP loss rate of 0.85%, higher than USA's.

The Stanford Energy Modeling Forum (EMF) study evaluated costs of the Kyoto Protocol using multi-models. The Asian-Pacific Integrated Model (AIM) is the only model in the EMF study that considered rich set of energy technologies (existing and new technologies) in both supply and demand side, like China MARKAL-MACRO did (the availability of new technologies can significantly reduce the costs of carbon abatement). AIM provided the GDP loss rate (relative to reference) of 0.45% and 0.31% for the USA and EU, respectively, to meet the Kyoto target (25% and 17% reduction wrt reference for USA and EU, respectively) (Weyant, 1999). While China MARKAL-MACRO presented 0.88% and 0.61% of GDP loss rates (relative to reference) for the reduction rate of 25% and 17%, respectively, in 2010, higher than AIM's estimations for both USA and EU.

4. Concluding remarks

Currently, China's economic development is inadequate. In 2000, China's per capita GDP was about 800US$ and there were still 30 million people whose annual incomes were lower than 72US$. Thus, to develop economy and to eliminate poverty is the priority task for China. Projected continuous rapid economic growth will considerably augment carbon emission if no emission reduction relevant actions are taken. In the past two decades (1980–2000), China's annual growth rates of energy consumption and carbon emission were only 3.83% and 3.64%, respectively, while keeping annual economic growth rate of as high as 9.63%. Owing to continuous great efforts on structure adjustment, energy efficiency improvement and energy substitution, the increase of carbon emission is expected to drop significantly from 3763 MtC (attributed to population expansion and mainly economic growth) to as low as 1601 MtC in the course of 2000–2050. The carbon emission is expected to be 2394 MtC and the carbon intensity per GDP 0.172 Kg-C/US$ by 2050 with annual decrease rate of 3% during 2000–2050.

To further cut carbon emission on the basis of this reference scenario will cause rather high marginal abatement costs and GDP losses. Varying carbon reduction rates from 5% to 45%, the marginal abatement costs are in the range of 12–216US$95/tC, and the rates of GDP loss relative to reference 0.1–2.54%. Future carbon emission reduction, in particular high percentage reduction, will heavily depend on the development of nuclear power. Setting constrains on the maximum capacity of nuclear power to 150% or 100% of the reference scenario, viz. 240 GW or 160 GW by 2050, will further heighten both the marginal abatement costs and the GDP losses. China's coal-dominant energy resource characteristic determines her limit carbon abatement room. Other strategies, such as carbon capture and underground storage, might release China's carbon abatement from the heavy dependence on nuclear power. However, these technologies have not been proven on the large commercial scales and the cost of these technologies will be a crucial issue to their successful application and popularization.

The earlier to start to set limits on carbon emission, the higher GDP loss rates (relative to reference) and the more accumulative GDP losses in the whole planning horizon would be. The accumulative GDP losses in the planning periods of 1995–2050 for M2010 are approximately 1.03–1.22 times of M2020s or 1.32–1.36 times of M2030s for the reduction rates varying from 5% to 45%.

China MARKAL-MACRO considers a lot of advanced technologies both in the energy supply and demand sides. The availability of these technologies greatly reduces the reference carbon emission as well as the carbon emission abatement costs. Along with emphasis on technology transfer from developed countries, policies and programs that encourage the development, demonstration and commercialization of the advance energy technologies are needed.

China's per capita CO_2 emission was only 0.676 tC in 2000, much lower than those of world average (1.06 tC/capita) and OECD (3.02 tC/capita) at the same year. Although China's per capita CO_2 emission is expected to grow to 1.535 tC/capita by 2050, it is still only half of that of OECD in 2000. China has made unique achievement to significantly debase the increases of energy consumption as well as carbon emission while keeping high economic growth rate in the past two decades. In accordance with the principle of "common but differentiated responsibilities", it will be more realistic for China to make continuous contributions to combating global climate change by implementing sustainable development strategy domestically and energetically participating in international cooperation to abate GHGs emission like CDM rather than accepting a carbon emission ceiling. To take the road of sustainable development, China is still faced with considerable restrains and difficulties. It is highly necessary for the developed countries to achieve their commitments defined in the United Nations Framework Convention on Climate Change to provide new and additional financial as well as technical transfers to developing countries including China to help them to protect global environment and to realize sustainable development throughout the world.

Appendix A. Steps taken to link China MARKAL with MACRO

(1) Run standalone China MARKAL and modify the database to ensure shadow prices of all demand categories in the 1st time period are non-zero.
(2) Set basic parameters for MACRO, including GDP in the first year (700 billion US$), depreciation rate on capital (5%), ESUB (0.2), capital-GDP ratio in the 1st period (*kgdp* 1.8), and optimal share of capital in the value added aggregate (*kpvs* 0.24). Edit file GR.DD to set projected GDP annual growth rates for all periods (from Table 3), and ESUB (0.2).
(3) Run 'DDFNEW MARKAL'' to generate DDF.DD containing GROWV (potential GDP annual growth rates), DDAT (shadow prices of demand categories in the first period), DDF (demand decoupling factor for each category in each period), and EC0 (energy system cost in the 1st period).
(4) Run MARKAL-MACRO with DDF.DD included to generate DDFNEW.DD.
(5) Compare calculated GDP growth rates (in DDFEW.DD) with projected GDP growth rates (in GR.DD) and resultant energy system cost (in DDFEW.DD) with EC0 (in DDF.DD). Run DDENEW MARKAL-MACRO to generate an updated DDF.DD and MARKAL-MACRO to generate an updated DDFNEW.DD until calculated GDP growth rates are close to the projected GDP growth rates, and resultant energy system cost is close to EC0.
(6) Compare projected energy service demands with calculated energy service demands from MARKAL-MACRO run. Lower DMTOL and repeat steps 4 to 6 to ensure all demand categories' calculated demands do not differ too much from projected demands.
(7) Import EC0, GROWV, DDAT, DDF in file DDF.DD to China MARKAL-MACRO database.

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