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Carbon emission control strategies for China: A comparative study with partial and general equilibrium versions of the China MARKAL model

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Abstract

China's carbon dioxide emissions from fossil fuel combustion had increased with an annual growth rate of 4.36% since 1980, hitting 1 GtC in 2003. The global climate change issue is becoming more and more important and hence to be the fourth challenge for China's future energy development, following energy supply shortages, energy security, and local environmental protection. This paper used three MARKAL (MARKet ALlocation) family models, that is, MARKAL, MARKAL-ED (MARKAL with elastic demand), and MARKAL-MACRO, to study China energy system's carbon mitigation strategies and corresponding impacts on the economy. The models' structures and the economic feedback formulations used in MARKAL-MACRO and MARKAL-ED are briefly described. The endogenous demands in MARKAL-MACRO and MARKAL-ED enable them to partly satisfy carbon abatement constraints via energy service demand reductions, and the reduction levels for the 30 demand sectors from these two kinds of models for given carbon emission constraints are presented and compared. The impact of carbon mitigation on social welfare from MARKAL and MARKAL-ED, and on GDP, investment and consumption from MARKAL-MACRO are evaluated. The changes in both final and primary energy mix, changes in technology development, as well as marginal abatement costs for given carbon constraints from the three models, are analyzed.

Keywords: MARKAL; MARKAL-ED; MARKAL-MACRO; Energy system; Carbon emission mitigation; China

1. Introduction

China's primary energy consumption increased from 603 Mtce in 1980 to 1678 Mtce in 2003 with an annual growth rate of 4.55%, as illustrated in Fig. 1 [1]. The energy consumption elasticity during this period was 0.48. And the elasticity of 0.5 is projected to remain in order to achieve Chinese government's fourfold economy development goal with double energy consumption during 2000–2020. Coal still dominated in China's primary energy consumption, accounting for as high as 67% in 2003, compared to only 23.5% for the world average in 2000.

China's growing primary energy consumption and the little changed coal-dominated structure cause its carbon emissions to increase by 4.36% annually, from 387 MtC in 1980 to 1033 MtC in 2003. However, owing to the structure adjustments in economy, industrial branches and industrial products, as well as energy efficiency improvement and substitution to low- and non-carbon energy, carbon intensity decreased dramatically from 2.75 kgC/95 US$ in 1980 to 0.92 kgC/95 US$ in 2003 with an annual decrease rate of 4.63%, as displayed in Fig. 2. However, compared with the world average and OECD levels [2], China's carbon intensity is still much higher. China's carbon intensity in 2000 was 2.7 and 4.6 times higher than the world average and OECD, respectively. However, if Power Purchase Parity (PPP) applied, the gap reduces considerably, as illustrated in Fig. 3.

Although China's per capita carbon emissions is still low, it increased by 3.14% per year in the course of 1980–2003, reaching 0.8 tC per capita in 2003. The gap between China's per capita carbon emissions and the world average level is shrinking, as displayed in Fig. 4.

Driven mainly by population expansion, economy growth, urbanization level improvement, and booming transportation, China's future energy consumption as well as carbon emissions will unavoidably continue to increase.

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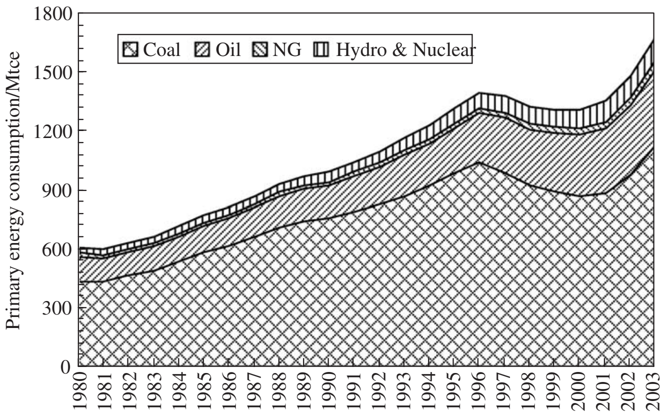

Fig. 1. China's primary energy consumption during 1980–2003.

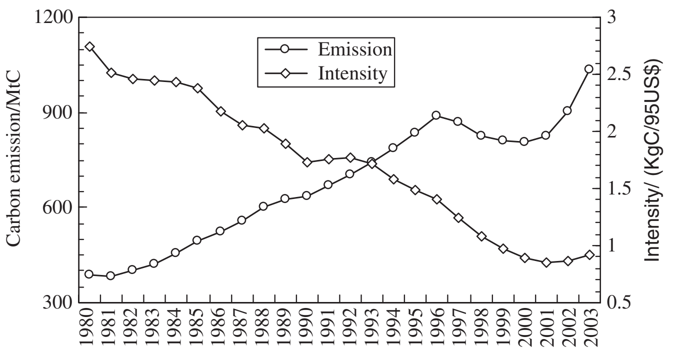

Fig. 2. China's carbon emission and carbon intensity during 1980–2003.

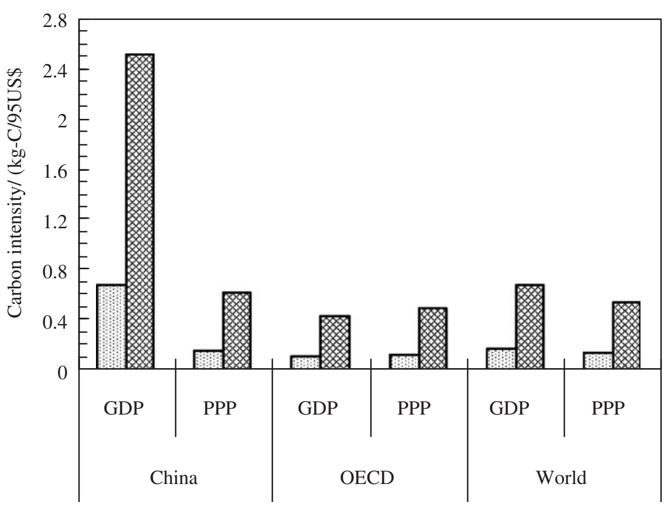

Fig. 3. Comparison of carbon intensity per GDP.

Future China's energy development faces the challenges of energy supply shortages, energy security, domestic environmental protection, and global climate change. How to ensure sustainable development and in the mean time to mitigate carbon emissions will become more and more important for China.

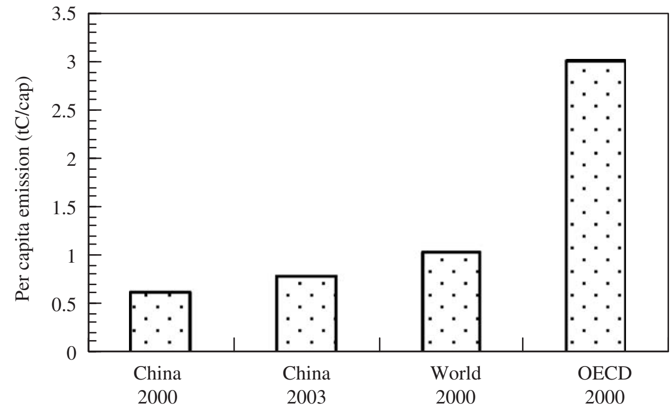

Fig. 4. Comparison of per capita carbon emission.

Different models covering bottom-up, top-down and hybrid have been used to study China's future sustainable energy development strategies and carbon mitigation strategies. Integrated energy system simulation models and dynamic energy optimization models are the most often used for the bottom-up approaches. Both of these two types of models are driven by exogenous demand projection, and they can have explicit, detailed description of the whole energy system. Top-down modeling approaches apply either Input–output models, macroeconomic models or CGE models. Bottom-up models do not include feedback from and to other sectors of an economy, and lack of demand–price interactions. Top-down models are not able to indicate detailed technology mix. In the hybrid approaches, top-down and bottom-up models are linked to complement each other [3].

In this paper, three MARKAL (MARKet ALlocation) family models, that is MARKAL, MARKAL-ED (MARKAL with elastic demand), and MARKAL-MACRO are used to study China energy system's carbon emission control strategies, and the results from the three models are compared with each other.

2. Methodologies and models

2.1. China MARKAL

MARKAL, an integrated energy, environmental and economic model, is a dynamic linear programming model based on reference energy system (RES) which minimizes the total discounted energy system cost, including the investment cost, the variable and fixed operational and maintenance costs on both the supply and the demand sides. The MARKAL model incorporates a full range of energy processes, exploitation, conversion, transmission, distribution and end-use. The model can optimizes over existing as well as advanced technologies that may be deployed in the future.

The China MARKAL model was firstly developed in the end of 1999 and has been updated constantly [4–10]. Three basic sets of input information for each time step over the entire planning period are required: (1) the maximum possible supply and the cost of primary energy resources, (2) the cost and performance characteristics of both energy conversion and end-use technologies, (3) energy service demands. These inputs could be found in the literatures [4–10]. The energy service demands for most sectors and sub-sectors are projected via regression analysis using historical data (1978–2000), which provides the relationships between the energy service demands and the key indicators such as GDP or per capita GDP, etc. For the sectors and sub-sectors without enough historical data for the regression analysis, the per capita energy service demands are projected via the comparisons with those of OECD countries in the year with the same level of per-capita GDP as China's future.

2.2. China MARKAL-MACRO

In MARKAL, there is no feedback between energy service demands and energy prices. MACRO bridges the gap. MACRO is a macroeconomic model with an aggregated view of long-term economic growth [11,12]. The production function is an aggregate, nested, constant elasticity of substitution (CES) form:

$$Y_t = \left[akl(K_t)^{\rho\alpha}(L_t)^{\rho(1-\alpha)} + \sum_{dm} b_{dm}(D_{dm,t})^{\rho} \right]^{1/\rho}, \tag{1}$$

$$L_0 = 1, \tag{2}$$

$$L_t = (1 + grow_{t-1})^{ny} L_{t-1}, \tag{3}$$

$$\alpha = kpvs, \tag{4}$$

$$\rho = 1 - 1/ESUB, \tag{5}$$

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

$$UTILITY = \sum_{t=1}^{T-1} (udf_t)(\log C_t) + (udf_T)(\log C_T)/[1 - (1 - udr_T)^{ny}], \tag{6}$$

$$udf_t = \prod_{\tau=0}^{t-1} (1 - udr_\tau)^{ny}, \tag{7}$$

$$udr_t = (kpvs)/(kgdp) - depr - grow_t, \tag{8}$$

where udr_t is the utility discount rate for period t, udf_t is utility discount factor for period t, $kgdp$ is the initial capital-to-GDP ratio, $depr$ is the annual depreciation rate, C_t is the consumption which is determined by aggregate output, aggregate investment, and energy costs:

$$C_t = Y_t - I_t - EC_t, \tag{9}$$

where I_t *is* investment for building up the stock of capital, and EC_t is interindustry payments for energy costs.

The MARKAL-MACRO model solution algorithm involves two separate decision processes: MARKAL solves for the least-cost choice of technologies and fuels, and MACRO solves for an optimal consumer utility level, which is determined by optimal aggregate investment level and demand for energy services. Over time, substitution between capital/labor and energy service demand can reduce *EC*. A decrease in *EC*, given investment, will increase consumption and consumer utility. In addition, an increase in the aggregate investment can also increase future capital stock and raise future aggregate output, consumption, and utility level. After each MACRO solution iteration, energy service demands are passed to MARKAL. Once MARKAL finds the least-cost way to meet the demand, the solution on energy costs (*EC*) is passed back to MACRO, where the cost is compared with what is happening in the rest of economy. If the model determines that an adjustment in the level of energy demand would increase consumer utility, it sets a new demand level to be met. MARKAL, in turn, repeats the cost analysis described above and finds a new least-cost way to supply the demand. The process continues until the highest possible level of consumer utility is found.

Application of MACRO in this study is appropriate since the main purpose/benefit for using MACRO is to get the demand response, and since it employs a single-sector production function based on maximizing consumption this is not that unreasonable simplification of where the China economy is headed. In addition, three important issues were addressed for China MARKAL-MACRO. Firstly, the key MARCO parameters were set based on Chinese situation, e.g., ESUB 0.2, *kgdp* 1.8, and *kpvs* 0.24. Secondly, GDP calibration was made to ensure future GDP growth rates generated from MACRO to be consistent with the projected GDP growth rates for all time periods. The projected GDP growth rates are one of the main drives for future energy service demands in the stand-alone MARKAL. Finally, energy service demand calibration was made to ensure energy service demands generated from MACRO to be consistent with those energy service demand inputs in the stand-alone MARAKL for all demand categories in all time periods. The calibrations are achieved by numerous iterations.

More detailed information regarding China MARKAL-MACRO can be found in the literature [13]. This hybrid model, 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.

2.3. China MARKAL-ED

Our modeling experiences on MARKAL-MACRO summarize that this model has three disadvantages: (1) a lot of time should be spent on linking MARKAL with MACRO; (2) computational time for MARKAL-MACRO is much longer compared with MARKAL; (3) the MACRO production function only has a uniform elasticity of substitution between the energy service demand and the capital–labor aggregates. To overcome the disadvantage of exogenous rigid energy service demand in MARKAL, another simpler way is to extend MARKAL to MARKAL-ED by introducing energy demand elasticity, thus the demands of energy services can vary according to the changes of price, revenue, and other factors. The advantages of MARKAL-ED are: (1) it contains both technological and behavioral responses to price increases induced by carbon emission constraint or carbon tax; (2) it is fully compatible with MARKAL and requires no additional programming of equations; (3) the price elasticity of one demand category can vary from another.

The approach of MARKAL-ED is based on the following Equivalence Theorem: a supply/demand equilibrium is reached when the sum of the producers' and the consumers' surpluses is maximized [14]. Fig. 5 illustrates this theorem. The intersection of the inverse supply and the inverse demand curves, Point E, which is the equilibrium point, is also the point at which the area between the two curves is maximized (this area is the sum of the producers' and the consumers' surpluses, sometimes called net social surplus).

The Equivalence Theorem states that such an equilibrium is reached as the solution of the following mathematical program:

$$\mathrm{Max} \sum_i \sum_t \int_{DM_i=0}^{DM_i(t)} p_i^0(t) \times (q/DM_i^0(t))^{1/E_i} \times (Y_0/Y)^{F/E_i}\,\mathrm{d}q - cX \tag{10}$$

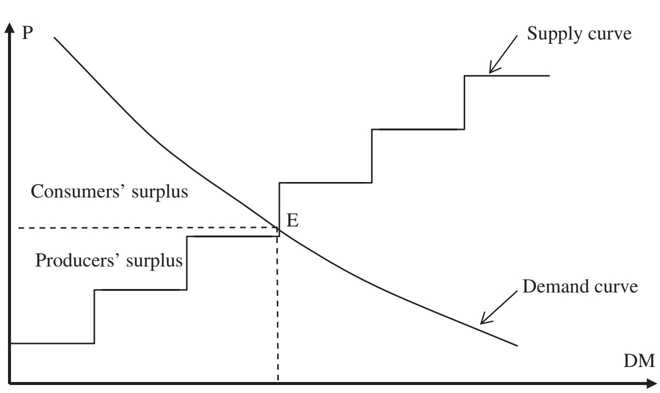

Fig. 5. Illustration of supply demand equilibrium.

$$\text{s.t.} \sum_k CAP_{k,i}(t) - DM_i(t) \geqslant 0; \quad i = 1, \dots I; \quad t = 1, \dots T, \tag{11}$$

$$BX \leqslant b, \tag{12}$$

where DM_i is the ith demand, p_i^0 is the marginal cost of demand category DM_i derived from MARKAL run, E_i is the price elasticity of demand DM_i, F is income elasticity, CAP is the capacities of end-use technologies, X is the vector of all MARKAL variables, B expresses the constraints for the variables, c is the discounted costs of the variables.

The above non-linear convex objective function is separable, and can be easily linearized by piece-wise linear functions which approximated the integrals in Eq. (10). This is the same as saying that the inverse demand curves are approximated by staircase functions, as illustrated in Fig. 6 [14].

For the China MARKAL-ED model, variation of demand is set as 0.5 (upper bound $UB_i = 1.5\mathrm{D}M_i^{\;0}$, lower bound $LB_i = 0.5DM_i^{\;0}$) and number of demand growth/reduction steps is 20. Price elasticity for each demand category (totally 30 demand categories) is set as −0.5, and the sensitivity analysis are done for price elasticity in the range of −0.1 to −0.5. Income elasticity of demand is 0 or 1. If it is 0, then the model is marked as MARKAL-ED; otherwise the alternate annual GDP growth rate is set as 5.225% instead of 5.5%, and 3.8% instead of 4% for the periods of 2020–2030 and 2030–2050, respectively, and the model is marked as MARKAL-EDI.

2.4. Sector disaggregation and technologies considered in the three models

The China MARKAL family models are developed in 5-year intervals extending from 1995 through 2050. The models consider not only conventional fossil fuels such as coal, oil, natural gas, coal gas, etc., but also new and renewable energy like hydro, nuclear, wind, solar, geothermal, and some synthetic fuels-like hydrogen, methanol,

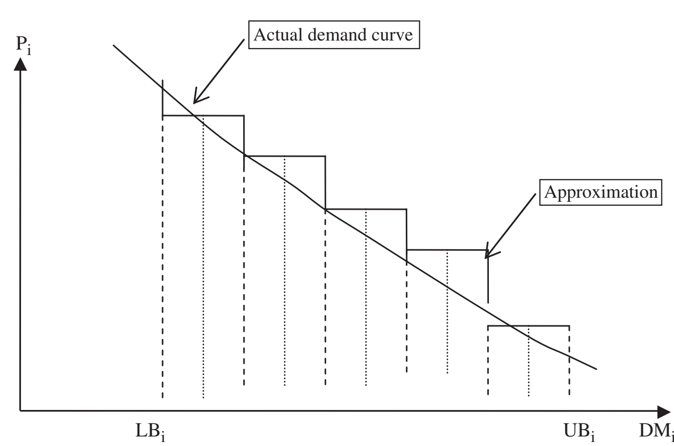

Fig. 6. Staircase approximation of demand function.

DME and so on. The models include around 50 power generation technologies covering current thermal power generation technologies, advanced thermal power generation technologies, poly generation technologies, new and renewable power generation technologies, etc. There are more than 20 process technologies including not only coal washing, coke production, oil refinery, and biomass digester, but also coal gasification, coal liquefaction, bio-liquid fuel production, and hydrogen production, etc. The models include five energy demand sectors, agriculture, industrial, commercial, residential (divided into urban and rural) and transportation, and these sectors are further divided into 30 sub-sectors (Table 1), with approximately 90 end use technologies considered. Fig. 7 illustrates the simplified RES of the China MARKAL family models [4–10].

3. Comparison of model results

3.1. Energy service demand

Figs. 8–10 show the percentage of energy service demand reductions from the China MARKAL-MACRO, China MARKAL-ED, and China MARKAL-EDI, respectively,

Table 1
Demand sector disaggregation in China MARKAL family models

Agriculture	Commercial	Transportation
AE Electric motors	CH Space heating and water heating	Freight
AH Heat process	CC Cooling	TFP Rail
AI Irrigation and machines	CL Lighting and electric appliances	TFT Truck
Industry	Urban residential	TFS Ship
IC Cement	US Space heating	TFP Pipeline
IA Aluminum	UC Cooking and water heating	Passenger
IM Ammonia	UA Air conditioning	TPB Bus
IP Paper	UO Lighting and electric appliances	TPC Car
IS Steel	Rural residential	TPR Rail
IOE Other industry electricity	RS Space heating	TPS Ship
IOH Other industry heat	RC Cooking and water heating	TA Air
ION Non-energy use	RO Lighting and electric appliances	

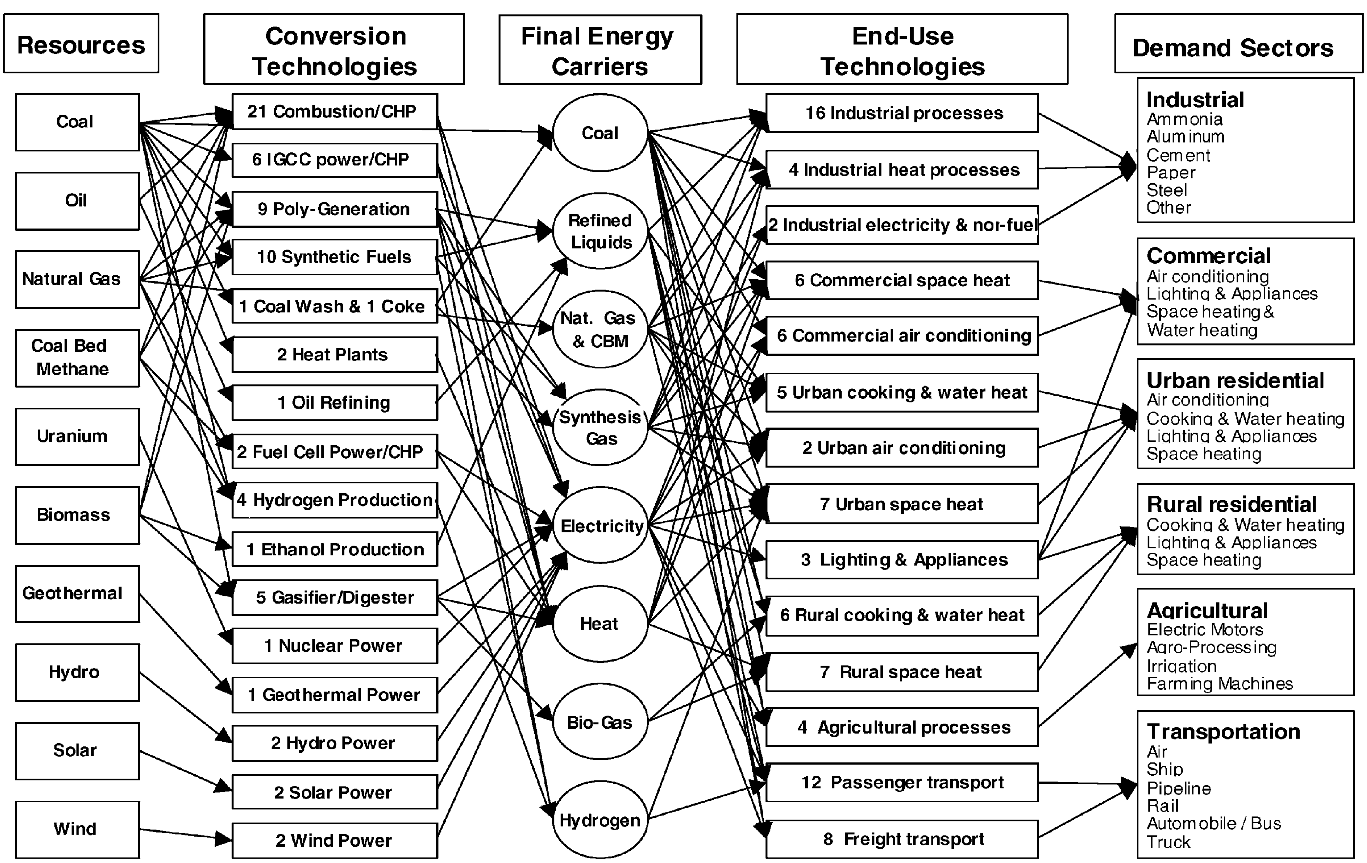

Fig. 7. Simplified reference energy system of China MARKAL family models.

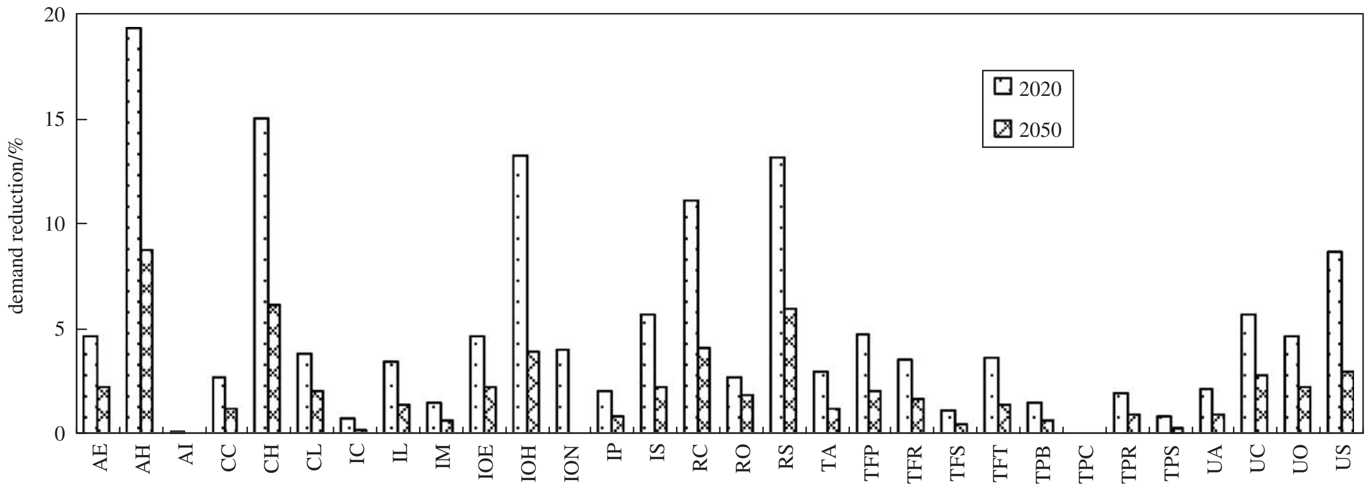

Fig. 8. Demand reductions from China MARKAL-MACRO for the reduction rate of 20% from 2020 onwards.

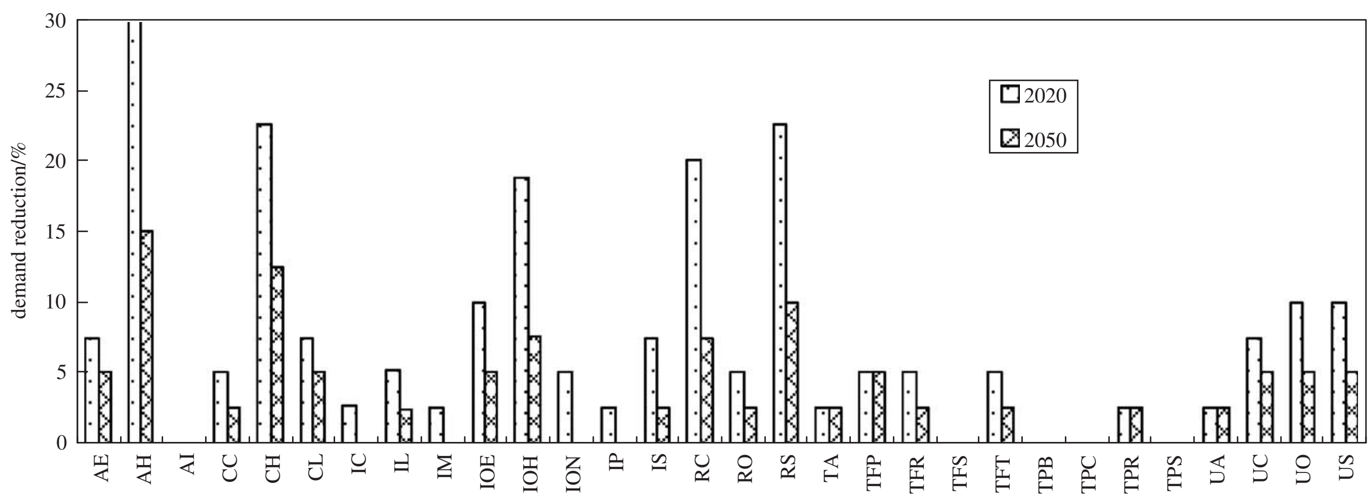

Fig. 9. Demand reductions from China MARKAL-ED for the reduction rate of 20% from 2020 onward.

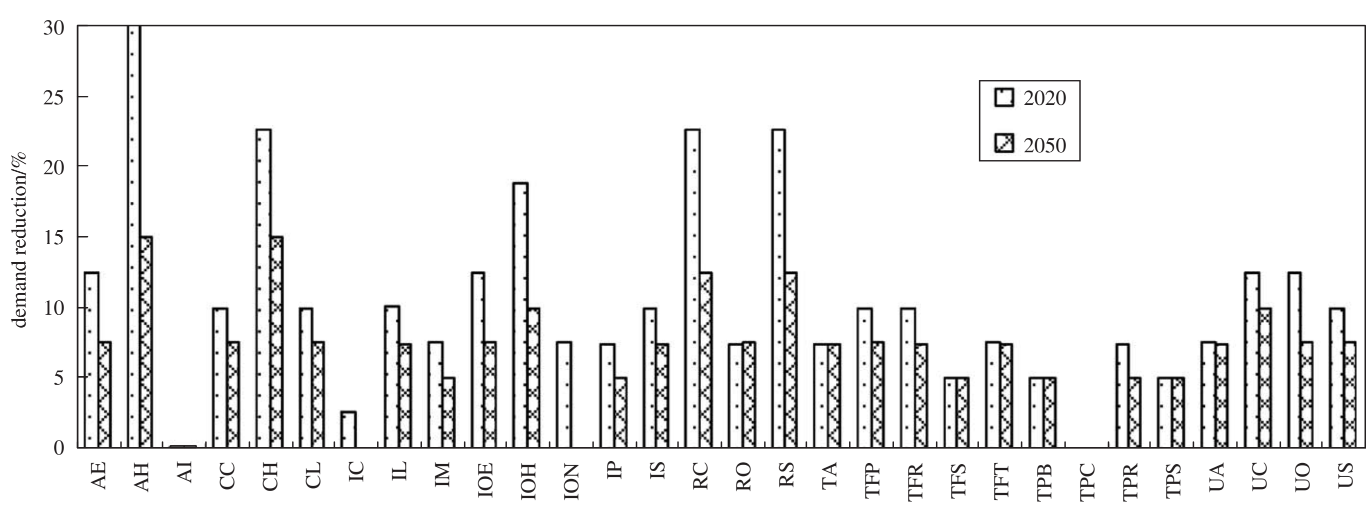

Fig. 10. Demand reductions from China MARKAL-EDI for the reduction rate of 20% from 2020 onwards.

for the constraint of 20% reduction relative to the reference scenario from 2020 onwards. The demand reductions for all demand categories in the year 2050 are lower than those in the year 2020, i.e. 50–70%, 30–60%, and 25–45% less for most sectors for China MARKAL-MACRO, MARKAL-ED, and MARKAL-EDI, respectively. The emission reductions in the first emission constraint year would more deeply tie to demand reductions while the later years can more rely on higher efficiency and cleaner technologies. This implies that it needs time for the energy system to make the adjustment to satisfy carbon reduction targets and the advanced clean energy technologies could play an increasingly important role in the future.

The demand reductions for most demand categories from MARKAL-MACRO are 20–50%, and 40–60% lower than those from MARKAL-ED, for 2020 and 2050, respectively. Similarly, most sectors' demand reductions from MARKAL-ED are lower than those from MARKAL-EDI for both the year 2020 and 2050 (30–70% less). The largest demand reductions are from the sectors such as agriculture heat process (AH), other industrial heat process (IOH), space heating, water heating and cooking (CH, RC, RS, UC, US), in the range of 10–30%, 7.5–30%, and 6–19% in 2020; 7.5–15%, 5–15%, and 3–9% in 2050, for MARKAL-EDI, MARKAL-ED and MARKAL-MACRO, respectively. All of these sectors provide heat mainly by coal. To reduce emissions in these sectors would more depend on demand reductions rather than technology and fuel shift partly due to limit natural gas resources and high costs for natural gas in China.

3.2. Social welfare loss and GDP loss

The objective function of MARKAL-ED represents the social surplus or social welfare consisting of both the cost of technologies and fuels, and the cost due to demand reductions (i.e. loss of consumer surplus), whereas that of MARKAL represents only the cost of technologies and fuels. Fig. 11 compares the two compositions and the total welfare loss in the whole planning period for the reduction rates of 0–45% from 2020 onwards from MARKAL, MARKAL-ED and MARKAL-EDI. Striking a compromise between additional technology/fuel costs and demand reductions induces a significantly smaller total welfare loss for MARKAL-ED/EDI compared to that of MARKAL, where carbon constraints are solely satisfied via technology/fuel costs. Taking an example of the emission reduction rate of 20%, the total welfare loss will drop from 62.1 BUS$ (US$ is in 1995 constant price in this paper) in MARKAL to 41.6 BUS$ in MARKAL-ED, and further to 17.2 BUS$ in MARKAL-EDI, with 33% and 72% reductions, respectively. Moreover, with more stringent emission constraints, the reductions of the total welfare loss from MARKAL to MARKAL-ED would enlarge, for instance, the total welfare loss will drop from 449 BUS$ in MARKAL to 192 BUS$ in MARKAL-ED (57% decrease) for the emission reduction rate of 45%.

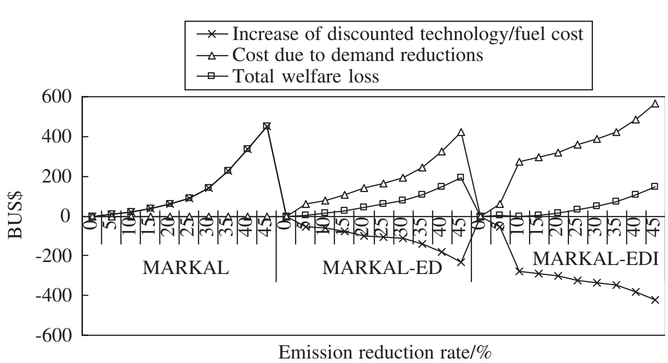

Fig. 11. Comparisons of total welfare loss from China MARKAL, MARKAL-ED and MARKAL-EDI.

While varying the price elasticity from −0.5 to −0.1 for each demand category, the discounted technology/fuel cost increases but the cost due to demand reductions decreases, which causes the total welfare loss to increase (Fig. 12). For 20% emission reductions from 2020 onwards, compared with MARKAL, MARKAL-ED shrinks the total welfare loss by 9.6%, 18.2%, 24.2%, 29%, and 33% for price elasticity of −0.1, −0.2, −0.3, −0.4, and −0.5, respectively.

Fig. 13 displays the GDP loss in the whole planning period for the emission constraints set from 2020 and onwards from MARKAL-MACRO. The absolute GDP loss increases gradually in the planning horizon and reaches the highest by 2050. Taking an example of the reduction rate of 20%, the GDP loss peaks at 34.7 BUS$ in 2050 and the accumulative GDP loss in the whole period is 1048 BUS$.

Fig. 14 shows the reduction rates of the key MACRO indicators, namely, GDP, investment, and consumption, relative to the references in 2020 and 2050 for the 20% emission reductions from 2020 onwards. As can be noticed, the reduction rate of investment is much higher than that of GDP and consumption. And the reduction rate of investment in 2020, the year to start to set the emission constraint, is much higher than that in 2050, and it peaks at 8.8% in 2020 for the emission reduction rate of 45%. Compared with investment, the GDP loss rate is much lower, in the ranges of 0.11–1.91% in 2020 and 0.10–1.20% in 2050 for the reduction rates varying from 5% to 45%. The reduction rate of consumption is the lowest among the three indicators.

3.3. Marginal abatement costs

Fig. 15 displays marginal abatement costs for the emission reduction rate of 20% from 2020 onwards from different models. As can be noticed, for every kind of model, the marginal abatement cost peaks in 2020, the year to start to introduce the emission constraint, and then it declines gradually till 2050. In the year 2020, the marginal abatement cost from MARKAL is the highest, reaching 111 US$/tC. When considering price elasticity, it drops sharply to 73 US$/tC for the MARKAL-ED(−0.1), and to

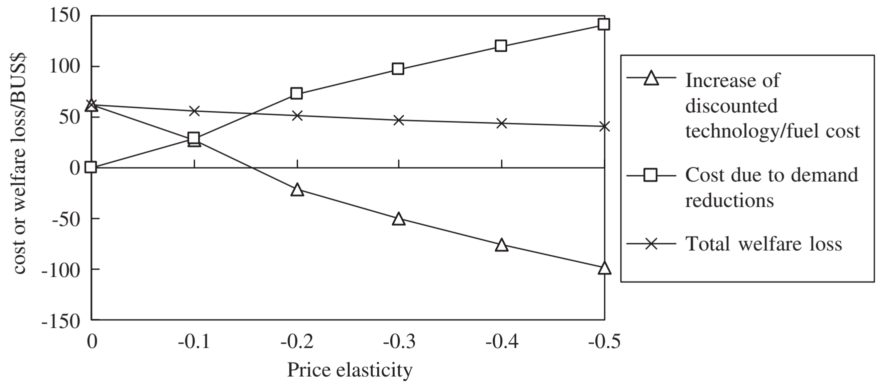

Fig. 12. Impact of price elasticity on social welfare loss for emission reduction rate of 20% from 2020 onward.

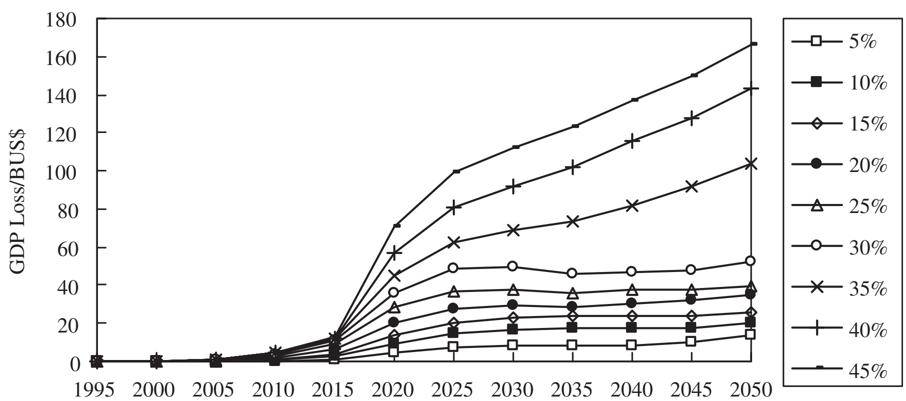

Fig. 13. GDP loss from China MARKAL-MACRO for different emission reduction rates from 2020 onwards.

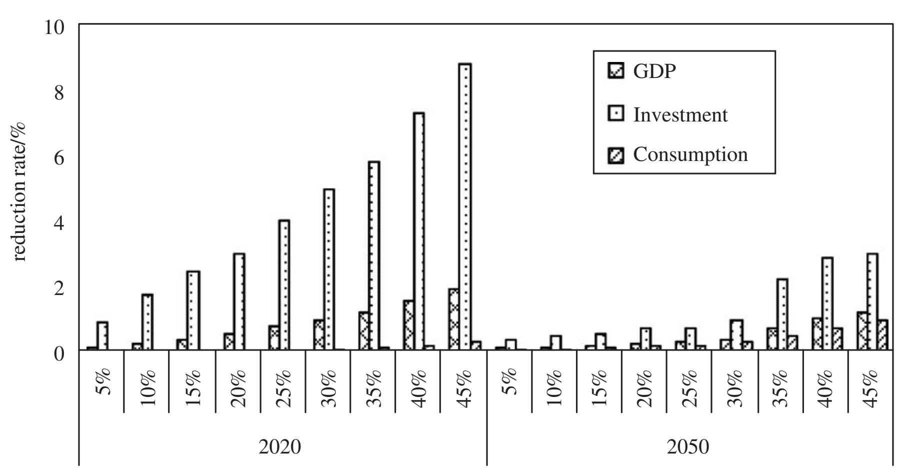

Fig. 14. Reduction rates of three key MACRO indictors, GDP, investment and consumption for different emission reduction rates from 2020 onwards.

37 US$/tC for the MARKAL-ED(−0.5). With additional considering of income elasticity, it further drops to the lowest, only 29 US$/tC. The marginal abatement cost from MARKAL-MACRO in the year 2020 is 63 US$/tC, similar to that from the MARKAL-ED(−0.2). Although the marginal abatement costs in 2020 from different models highly differ from each other, they are almost the same in the other years like 2030, 2040 and 2050 with an average value of around 35 US$/tC and the widest difference of 14 US$/tC. It implies that with the endogenous demands, MARKAL-ED/EDI and MARKAL-MACRO allow a smother transition, whereas MARKAL, a fixed exogenous demand model, has to fully meet the emission reduction targets via the technologies means only.

Fig. 16 compares the marginal abatement cost curves for the year 2020 from different models assuming the emission

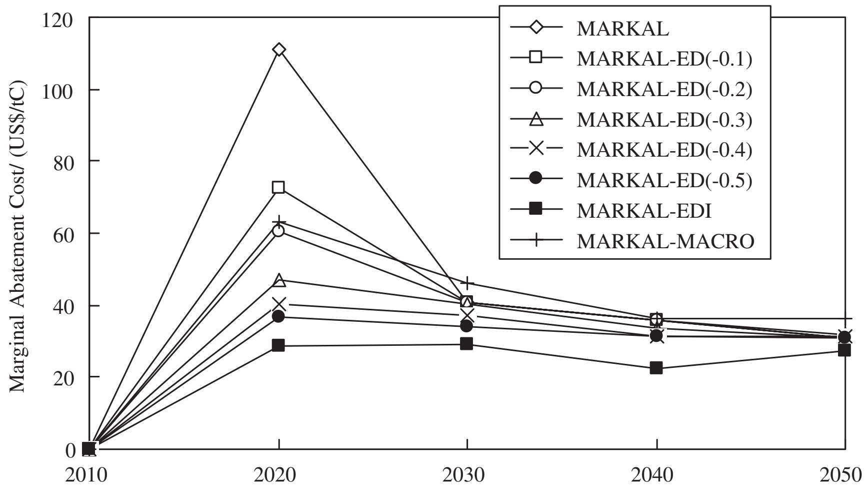

Fig. 15. Marginal abatement costs for emission reduction of 20% from 2020 onwards

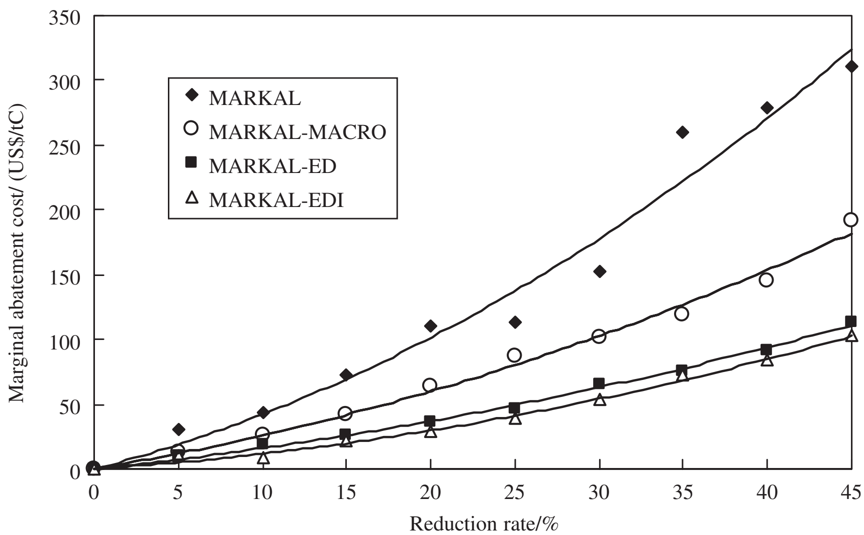

Fig. 16. Marginal abatement cost curves in 2020 from different models assuming emission constraints set from 2020 onwards.

constraints set from 2020 onwards. The curve from MARKAL is the steepest, while that from MARKAL-EDI is the flattest, and the former is about 2 times higher than the latter. The curve from MARKAL-MACRO is nearly in the middle of those from MARKAL and MARKAL-EDI. And the curve from MARKAL-ED is a little bit higher than that from MARKAL-EDI. Taking an example of the 45% reductions, the marginal abatement costs would drop considerably from 311 US$/tC for MARKAL to 191 US$/tC, 113 US$/tC, and 102 US$/tC, for MARKAL-MACRO, MARKAL-ED, and MARKAL-EDI, respectively.

3.4. *Fuel/technology mix*

3.4.1. *Demand side*

Industry sector is the most important energy consumer in China, accounting for as high as 68% of the total final energy consumption in 2000. And over 50% of the energy consumption is the industry sector was from steel, cement, ammonia, aluminum and paper industry.

Increasing steel output has been a top priority in China's industrial development strategy for decades, and China is now the world leader in steel production. Steel production grew at an average growth rate of 6.4% between 1980 and 2000. However, due to the energy efficiency improvement, energy consumed by the steel industry only increased at an average growth rate of 3.1% at the same period. Steel industry consumed 129.6 Mtce in 2000, accounting for 10% of China's total energy consumption. The energy intensity decreased to 1 tce/ton in 2000, but it was still much higher than developed countries' level (around 0.66 tce/ton for Japan, Germany, and USA). Existing technologies, like open-hearth furnaces, basic oxygen furnaces, electric arc furnaces, reduction of iron ore, etc., with continued efficiency improvement assumed for the future time periods, as well as advanced technologies are considered in the model. As energy efficiency improvement for the current technologies, and more market penetration of the advanced technologies, the modeling results show that the energy intensity of the steel industry is expected to improve to 0.5 tce/ton in 2050 for the reference scenario.

Building material industry is another big energy consumer in China, consumed 213 Mtce in 2000, sharing 16.3% in China's total energy consumption. While around 50% energy was consumed by cement industry. Cement production grew at an average growth rate of 11%, while its energy consumption increased at an average growth rate of 9.7% between 1990 and 2000. The energy intensity of the cement industry decreased to 0.172 tce/ton in 2000, but it was still much higher compared to developed countries' level (about 0.1 tce/ton in Japan and Germany). The different kinds of existing kilns with heat efficiency ranging from 17% to 44%, as well as advanced dry processes with heat efficiency of 50–55% are considered in the model. The energy efficiency of current technologies are not expected to improve much, but the modeling results show that the energy intensity of the cement industry is expected to improve to 0.1 tce/ton in 2050 for the reference scenario, as outdated kilns which dominate the current market, are consolidated and/or switch to more efficient processes.

In 2000, the ammonia industry consumed 60.87 Mtce, sharing 45% of the total chemical industry energy consumption, and the energy intensity decreased from 2.9 tce/ton in 1980 to 1.788 tce/ton. The ammonia industry is a composite of the mix of large ($\geqslant$300 kton/a/unit), medium ($\geqslant$50 kton/a/unit, $<$300 kton/a/unit) and small ($<$50 kton/a/unit) manufacturing plants, while the small ones sharing over 50% in the total production. The demand technologies characterized by both plant size and feedstock (coal, oil and natural gas) with different efficiencies are considered in the model. With gradual elimination of small coal-feed plants while more use of large natural gas-feed plants, the modeling results indicate that the energy intensity of the ammonia industry is expected to drop to 1.25 tce/ton in 2050 for the reference scenario.

Carbon emission constrains will cause more energy intensity improvement. Fig. 17 compares the energy intensity improvement for the agriculture, industry, and service (commercial plus transportation) sectors from different models when 20% emission reductions are required from 2020 and onwards. For the reference scenario, China MARKAL, China MARKAL-ED/EDI, and China MARKAL-MACRO provide the same results of annual average decrease rate of 1.3%, 2.8%, and 2.1% during 2000–2050 for energy intensity in the agriculture, industry and service sector, respectively. For the 20% emission reduction constraint, the annual average decrease rate of energy intensity in the industry sector during 2000–2050 will rise from 2.8% in the reference scenario to 2.96%, 2.97%, 2.99%, 3.01%, 3.02%, 3.04%, 3.1%, and 3.01% for MARKAL, MARKAL-ED(−0.1), MARKAL-ED(−0.2), MARKAL-ED(−0.3), MARKAL-ED(−0.4), MARKAL-ED(−0.5), MARKAL-EDI, and MARKAL-MACRO, respectively. However, for both

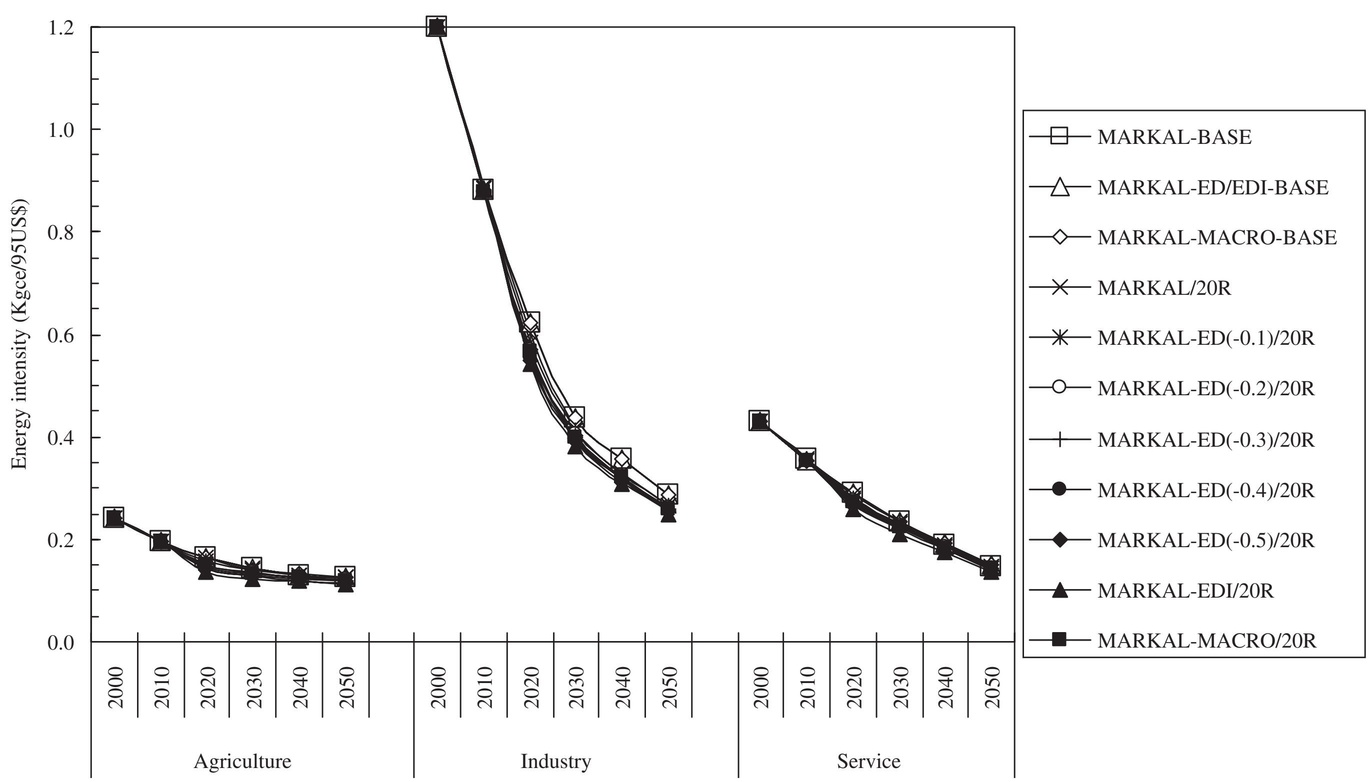

Fig. 17. Energy intensity improvement for agriculture, industry, and service sectors from different models for emission reduction rate of 20% from 2020 onwards.

China MARKAL-ED/EDI and China MARKAL-MACRO, part of the energy intensity reduction is resulted from the energy service demand reductions as displayed in Figs. 8–10.

China MARKAL, China MARKAL-ED/EDI and China MARKAL-MACRO modeling show that the final energy consumption by 2050 is expected to reach 3527 Mtce in the reference case with coal, oil, gas, electricity, and heat sharing 29.6%, 29.7%, 9.6%, 22.3% and 8.8%, respectively. When considering 20% emission reductions from 2020 onwards, the final energy consumption will decrease to 3412 Mtce from the standard MARKAL run, and the percentage of coal will drop greatly to 23.2%, while the percentages of oil, gas, electricity and heat will increase to 31.9%, 10.9%, 22.6%, and 11.4%, respectively. If considering demand elasticity, the final energy consumption will further decrease with the share of coal increasing. For example, it will decrease to 3287 Mtce with coal share of 24.1% for MARKAL-ED, and to 3187 Mtce with coal share of 25.8% for MARKAL-EDI. The MARKAL-MACRO model run shows that the final energy consumption by 2050 will be 3343 Mtce with coal, oil, gas, electricity and heat representing 23.3%, 31.6%, 10.9%, 22.9%, and 11.4%, respectively, and the results are close to those from the MARKAL-ED(−0.2) and the MARKAL-ED(−0.3). Fig. 18 illustrates the details.

3.4.2. Supply side

The primary energy consumption is expected to grow by 2.2% per year from 2003 to 2050, reaching 4816 Mtce by 2050 with coal, oil, gas, nuclear, hydro, and other new and renewable energy accounting for 50.2%, 22.8%, 9.7%, 8.1%, 7.1% and 2.1%, respectively, for the reference case, from China MARKAL, China MARKAL-ED/EDI, and China MARKAL-MACRO modeling (Fig. 19). The percentage of coal is anticipated to drop by 17.4% in 2003–2050, while that of every other fuel will increase, in particular, by 7% for gas, and by 8% for nuclear. Several foreign studies also provide the pictures for China's energy future, e.g., International Energy Outlook from Energy Information Administration, US Department of Energy (EIA/USDOE) [15], World Energy Outlook from International Energy Agency (IEA) [16], etc. However, these studies mainly focus the periods till 2020 or 2030. Energy Research Institute (ERI) of National Development and Reform Commission estimated China's energy demand for the year 2050 with application of Integrated Policy Assessment model for China (IPAC) [17]. Fig. 20 compares the future primary energy consumption trajectory from China MARKAL family models with those from abovementioned sources. Our estimations fall in line with their studies. The reference scenarios from the China MARKAL family models are very close to that from IEA, and lies between ERI-S2 (Conventional scenario) and ERI-S3 (Energy policy intervention scenario), since the reference scenario in this paper is not the Business As Usual (BAU) but with some energy efficiency improvement and development of new and renewable energy considered.

Emission reductions are not only achieved by energy efficiency improvement, but also by fuel switch and by the enhanced utilization of new and renewable energy. The elastic demand version of MARKAL and MARKAL-MACRO with endogenous demand also introduces a demand reduction and hence a supply reduction as well. For the emission reduction of 20% from 2020 onwards, the standard MARKAL shows the primary energy consumption by 2050 will be 4678 Mtce, while MARKAL-ED,

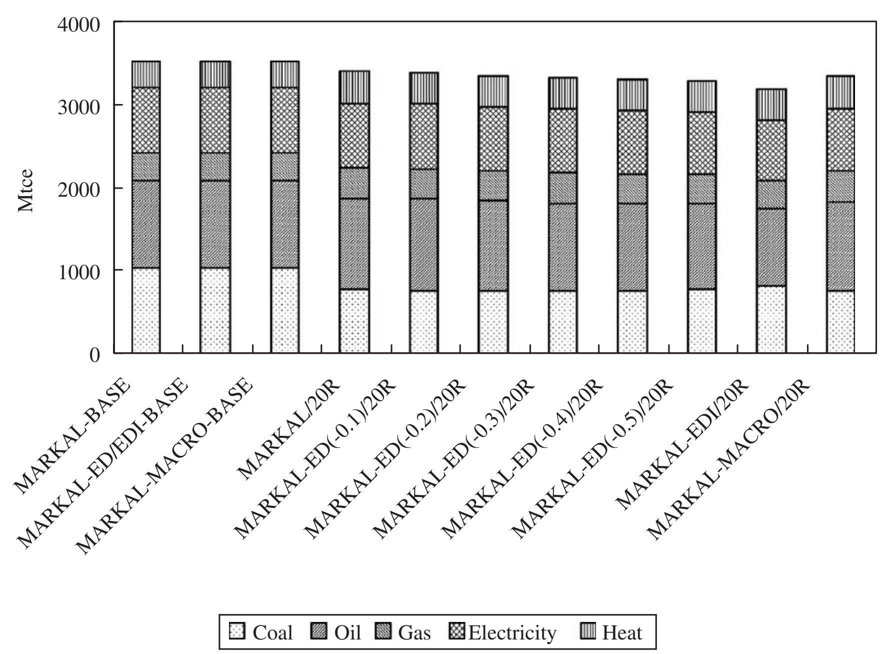

Fig. 18. Final energy consumption in 2050 from different models for emission reduction rate of 20% from 2020 onwards.

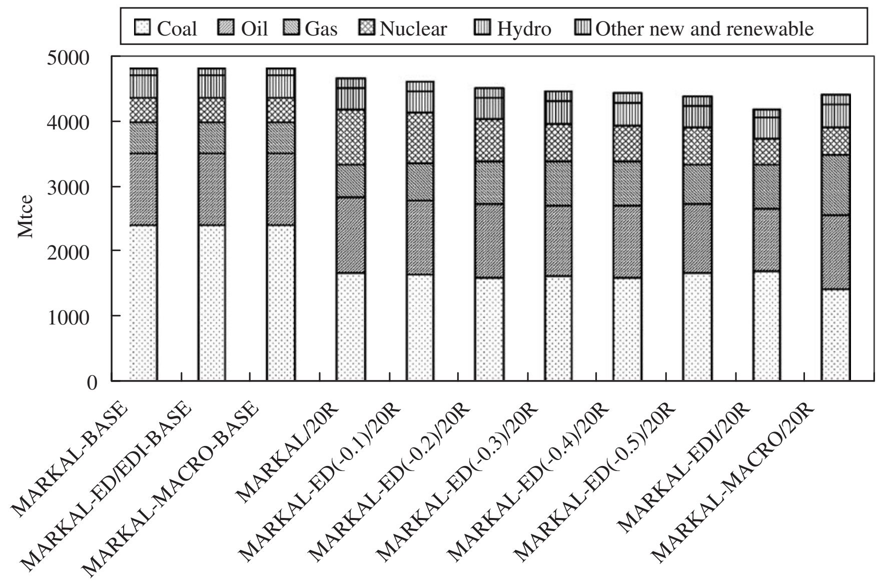

Fig. 19. Primary energy consumption in 2050 from different models for emission reduction rate of 20% from 2020 onwards.

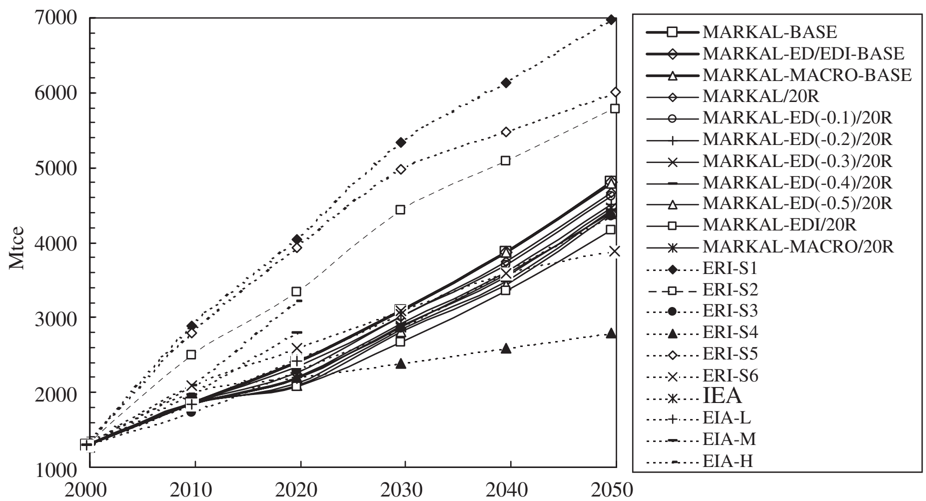

Fig. 20. Comparisons of future primary energy consumption trajectory from different sources.

MARKAL-EDI, and MARKAL-MACRO provides the results of 4404, 4080, and 4417 Mtce, respectively. The emission constraint of 20% reductions will shift the primary energy mix to 36% coal, 24.6% oil, 11% gas, 18% nuclear, 7.3% hydro, and 3.2% other new and renewable energy from the standard MARKAL, with the percentage of coal decreasing by 14% while the percentage of all new and renewable energy increasing by 11% compared with the reference. Elastic demand and MARKAL-MACRO will trail off the fuel mix change due to the lower demand also contributing to some emission reductions. The percentage of coal will increase from 36% in MARKAL to 38.2%, 41.7% and 32.6% while the percentage of all new and renewable energy will decrease from 28.5% in MARKAL to 24%, 20.6% and 21.2% in MARKAL-ED, MARKAL-EDI and MARKAL-MACRO, respectively. Fig. 19 displays the detailed results regarding primary energy and its mix from different models.

China has abundant coal resources, but very limit oil and gas resources. The maximum productions of oil and gas are estimated as around 150 million tons and 200 billion cubic meters by 2050, respectively. The maximum exploitable hydro-power capacity is in the range of 250–300 GW by 2050, and it is assumed to be fully utilized in the reference scenario in order to be consistent with China's sustainable energy development strategy. For the same reason, even in the reference scenario, there are 50 and 160 GW of nuclear power developed by 2020 and 2050, respectively. China's onshore wind resource is estimated as around 250 GW with average 2500–3000 h of operation annually. In the reference scenario, wind power capacity is assumed to be

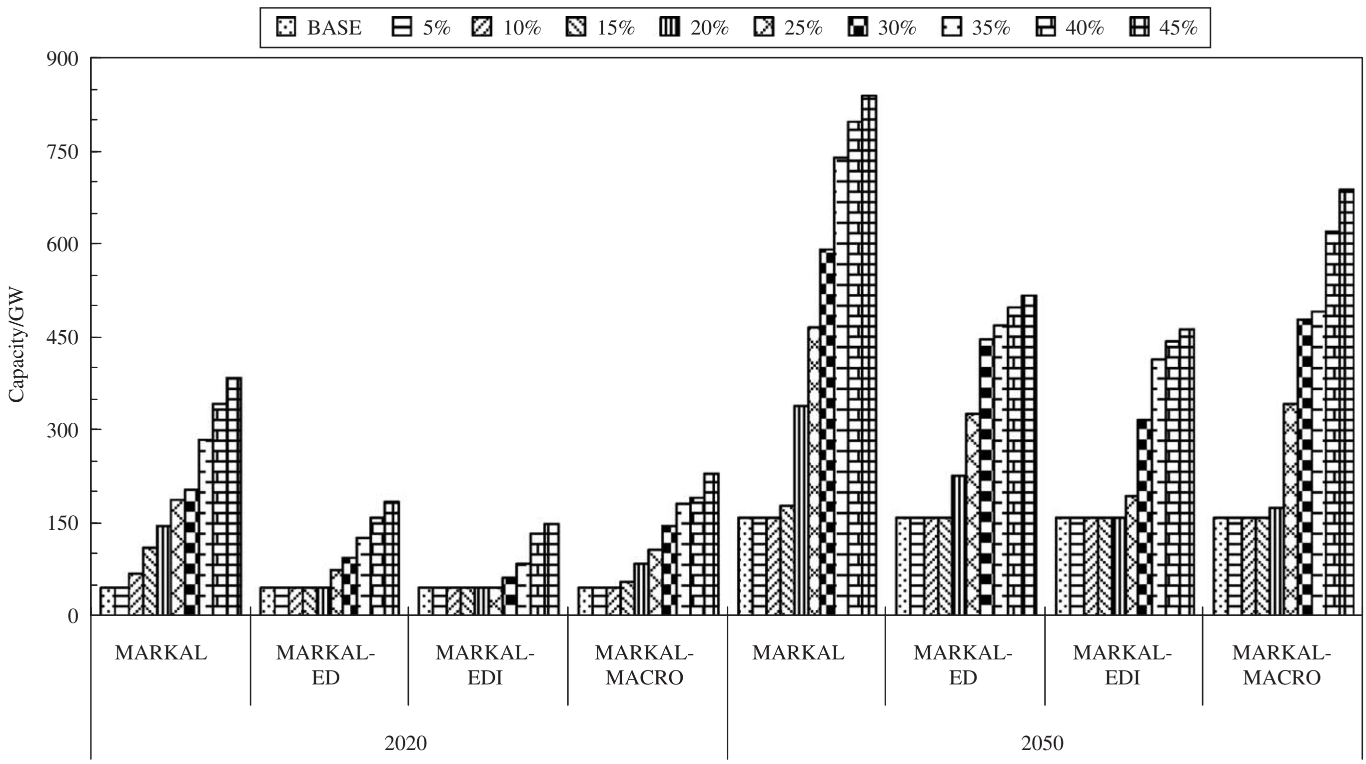

Fig. 21. Nuclear power capacity from different models for emission reduction rates ranging 5–45% from 2020 onwards.

developed to 100 GW by 2050. Large-scale use of solar power is unclear in the future mainly due to its high costs. Consequently, carbon emission reductions in China will heavily rely on the development of nuclear power, in particular for the stringent reduction requirements. Fig. 21 compares the nuclear capacities in 2020 and 2050 for the reduction rates ranging 5–45% from 2020 onwards from different models. The nuclear power capacity for the reduction rate of 45% will reach as high as 387 and 843 GW by 2020 and 2050, respectively, from the MARKAL modeling. Such large scale of nuclear power development will be challenged by the constraint factors like site selection, public acceptance, investment, safety, waste disposal, etc. For the MARKAL-MACRO, MARKAL-ED, and MARKAL-EDI modeling, nuclear power capacity will significantly decline to 231, 186, and 151 GW in 2020; and to 690, 518, and 464 GW in 2050, respectively. The potential role of the demand reductions to abate carbon emissions will greatly help to alleviate the heavy reliance on nuclear.

4. Main conclusions

As the inputs of energy resources, energy technologies as well as energy service demands (they are endogenous in MACRO but calibrated to the same level as the inputs in MARKAL) are the same for China MARKAL, China MARKAL-ED/EDI, and China MARKAL-MACRO, the three kinds of models provide the same modeling results for the reference scenario. Once emission constraints are introduced to the energy system, the results from these three models differ since their diverse model structures enable dissimilar energy service demand responses to the constrains.

Carbon emission reduction objectives, as most policy objectives, are easier to achieve, if more instruments and flexible options can be used. The analysis has simulated three sets of policies. The first set includes investments in technologies and command and control policies at the technological level; it is simulated by the base China MARKAL model. The second set of policies adds to the first set the possibility to transmit the energy price signal to the consumers, at a degree variable by sector; it is simulated by the China MARKAL-ED/EDI models. The third set of policies adds to the first set the possibility to adjust the welfare or purchasing power of consumers and trade-off expenditures on energy verses capital and labor; it is simulated by the China MARKAL-MACRO model.

With comprehensive description of the energy system, the China MARKAL model can provide detailed carbon mitigation technology/fuel mix on both the supply and the demand sides for any carbon abatement scenario. The carbon constraints are solely satisfied via technology/fuel changes to meet exogenous energy service demand in MARKAL. However, in reality the carbon constraints can be satisfied via both technology/fuel changes and energy service demand reductions. With endogenous energy service demand, both China MARKAL-MACRO and China MARKAL-ED/EDI are able to seek for compromise between additional technology/fuel cost and demand reductions while maintaining the technological richness and flexibility of China MARKAL. Compared with China MARKAL-MACRO, China MARKAL-ED/EDI is much easier to use since it is fully compatible with China MARKAL and requires no additional programming of equations.

Modeling with flexible endogenous demand rather than rigid exogenous demand will lower social welfare loss; lessen marginal abatement costs; reduce both final and primary energy consumption; lighten the changes in fuel/technology mix, and alleviate the heavy reliance on nuclear power development for China's future energy system, in particular, for the stringent carbon constraints. Since the emission reductions in the first emission constraint year would more deeply tie to demand reductions while the later years can more rely on higher efficiency and cleaner technologies, the above effects are the most notable in the first emission constraint year after shifting from China MARKAL to China MARKAL-MACRO or China MARKAL-ED/EDI. The China MARKAL modeling shows that the marginal abatement cost in 2020 for the reduction rate of 45% from 2020 onwards is 311 US$/tC, but it would drop by 39%, 64%, and 67% if China MARKAL-MACRO, China MARKAL-ED, and China MARKAL-EDI applied, respectively. China's coal-dominated energy resources character makes it heavily rely on nuclear power development to reduce carbon emission in the future, but the reliance could be lighter if elastic demand is considered to introduce consumers' behavior response to carbon constraints. For the reduction rate of 45% from 2020 onwards, the nuclear power capacity is expected to fall by 40%, 52%, and 61% in 2020; and by 18%, 39%, and 45% in 2050, when shifting from China MARKAL to China MARKAL-MACRO, China MARKAL-ED, and China MARKAL-EDI, respectively. To further reduce the reliance on nuclear power development for future carbon reduction requires large-scale application of other advance energy technologies, such as photovoltaic, hydrogen, carbon capture and sequestration, etc. Policies and programs that encourage the development, demonstration, and commercialization of the advance energy technologies are needed.

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