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Future implications of China's energy-technology choices

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Abstract

This paper summarizes an assessment of future energy-technology strategies for China that explored the prospects for China to continue its social and economic development while ensuring national energy-supply security and promoting environmental sustainability over the next 50 years. The MARKAL energy-system modeling tool was used to build a model of China's energy system representing all sectors of the economy and including both energy conversion and end-use technologies. Different scenarios for the evolution of the energy system from 1995 to 2050 were explored, enabling insights to be gained into different energy development choices. The analysis indicates a business-as-usual strategy that relies on coal combustion technologies would not be able to meet all environmental and energy security goals. However, an advanced technology strategy emphasizing (1) coal gasification technologies co-producing electricity and clean liquid and gaseous energy carriers (polygeneration), with below-ground storage of some captured CO_2; (2) expanded use of renewable energy sources (especially wind and modern biomass); and (3) end-use efficiency would enable China to continue social and economic development through at least the next 50 years while ensuring security of energy supply and improved local and global environmental quality. Surprisingly, even when significant limitations on carbon emissions were stipulated, the model calculated that an advanced energy technology strategy using our technology-cost assumptions would not incur a higher cumulative (1995–2050) total discounted energy system cost than the business-as-usual strategy. To realize such an advanced technology strategy, China will need policies and programs that encourage the development, demonstration and commercialization of advanced clean energy conversion technologies and that support aggressive end-use energy efficiency improvements.

Keywords: China; Modeling; Technology

1. Introduction

China faces daunting energy challenges: high public health costs from severe air pollution arising mainly from coal combustion; security concerns over growing oil imports for transportation; limited domestic energy resources other than coal; projected demands for energy that will exceed domestic supply capabilities (even coal) within a few decades; and the prospect that China could become the world's largest emitter of greenhouse gases by 2020. We built a MARKAL energy-system model for China and used it for a preliminary analysis of alternative technological strategies China might pursue over the period 1995–2050 to address these challenges (Wu et al., 2001). The main findings of our analysis are reported here.

The technology scenarios we have developed for the evolution of China's energy system are intended not to predict the future, but to provide insights into the implications of energy options that are or could be pursued by China. In particular, we sought insight into the following questions:

(1) How can China meet projected demands for energy services in an affordable manner, given that most projections show a significant shortfall in domestic energy resources by 2050?
(2) Are there plausible scenarios by which China could substantially reduce urban and rural air pollution

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while meeting projected demands for energy services?

(3) Are there plausible scenarios by which China could meet projected needs for liquid fuels, especially for transportation, while not becoming overly dependent on imported energy?

(4) Are there conceivable energy-technology scenarios by which China could meet requirements for lower carbon emissions that may arise from global warming concerns?

2. The China MARKAL model

MARKAL is a linear programming model that identifies the technological configuration for an energy system, subject to user-specified constraints, that minimizes the total discounted energy-system cost (Fishbone et al., 1983). Our China MARKAL model builds on previous MARKAL modeling work at Tsinghua University (Chen and Wu, 2001; Wu and Chen, 2001), primarily by expanding the technology options in the model to include an extensive set of advanced energy technologies. Building a MARKAL model requires the user to specify the costs and maximum available supply of primary energy resources, the cost and performance characteristics of alternative conversion technologies through which the primary energy sources can be processed into final energy carriers, the cost and performance characteristics of alternative end-use technologies that convert final energy carriers into energy services, and the level of energy services that must be supplied by the energy system (Fig. 1). Values for all of these user-specified inputs must be provided at each 5-year time step during the analysis period, which is 1995–2050 in this work. Developing input parameter values was a major part of the work (Wu et al., 2001).

2.1. Simplifying assumptions

We modeled China as a single geographic region. Geographic disaggregation would significantly increase the complexity of the model without providing a commensurate increase in fundamental insights into technology choices. The broad findings presented here provide a useful point of departure for more detailed modeling.

Estimates of commercially mature performance and cost (investment and O&M) are used for all technologies in the model, including for technologies that are not yet

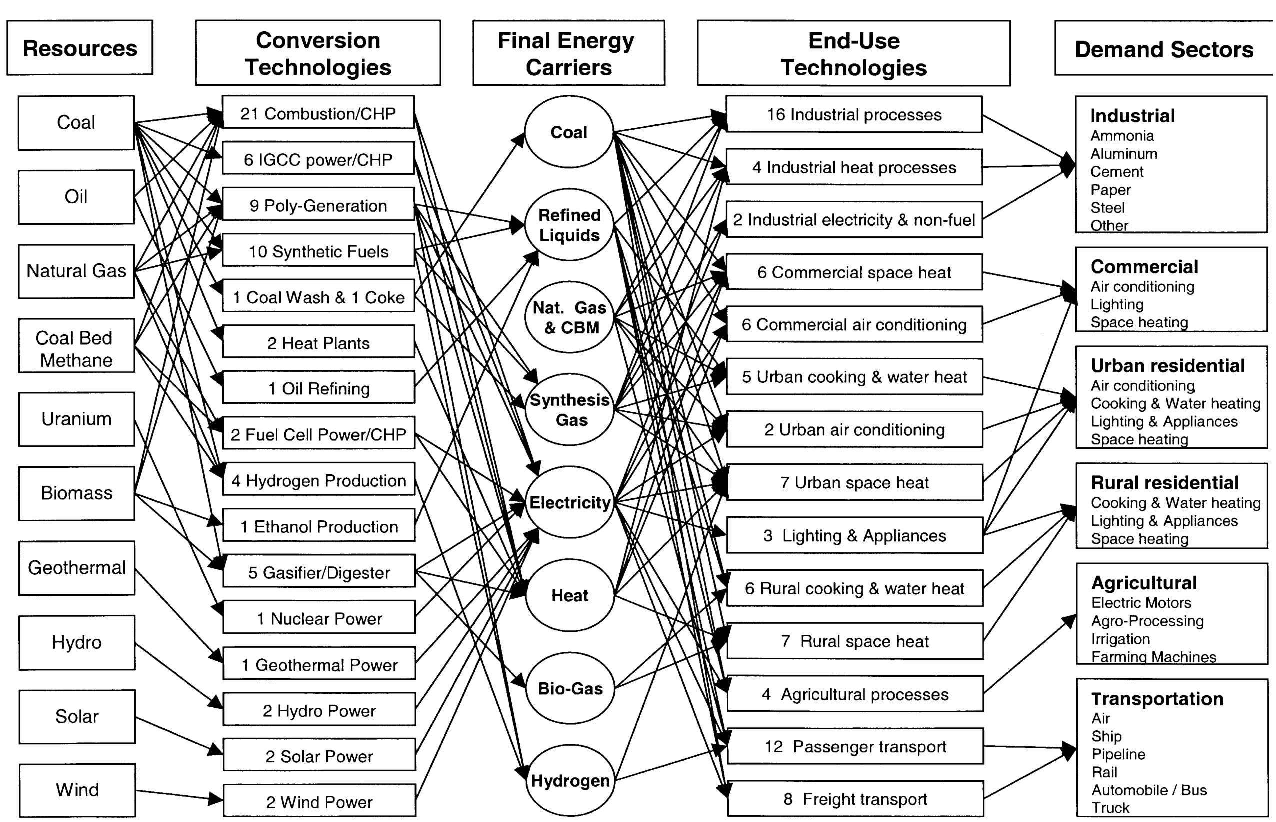

Fig. 1. Interconnections between energy resources, conversion and process technologies, and energy service demands as represented in the China MARKAL model. The numbers in the conversion and end-use technology boxes refer to the number of distinct technologies built into the model for the category represented by that box.

Table 1
General economic assumptions behind energy service demand assumptions

	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Population (billion)[a]	1.211	1.294	1.340	1.386	1.441	1.495	1.528	1.560	1.575	1.590	1.583	1.575
Population GR (%/yr)	1.3	0.7	0.7	0.8	0.8	0.43	0.43	0.2	0.2	−0.1	−0.1	
Urbanization (%)[b]	31.4	34.4	38.4	42.4	46.9	51.4	54.9	58.4	61.7	65.0	67.5	70.0
Urbanization GR (%/yr)	1.8	2.2	2.0	2.0	1.8	1.3	1.2	1.1	1.0	0.8	0.7	
GDP (billion US$)	709	1104	1549	2172	2839	3710	4849	6338	7711	9382	11,414	13,887
GDP GR (%/yr)[c]	9.3	7.0	7.0	5.5	5.5	5.5	5.5	4.0	4.0	4.0	4.0	
Per capita GDP (US$)	585	853	1156	1567	1971	2482	3175	4063	4896	5901	7213	8817
Per capita GDP GR (%/yr)	7.8	6.3	6.3	4.7	4.7	5.0	5.1	3.8	3.8	4.1	4.1	
ppp factor	5.005	4.430	3.930	3.460	3.080	2.730	2.380	2.055	1.830	1.625	1.415	1.230
Per capita ppp GDP (US$)[d]	2930	3780	4542	5422	6069	6775	7555	8347	8958	9586	10,203	10,845
pppGDP/cap growth (%/yr)	5.2	3.7	3.6	2.3	2.2	2.2	2.0	1.4	1.4	1.3	1.2	

[a] State Economic Information Center internal report.
[b] IEA: Link Between Energy and Human Activity, ISBN 92-64-15690-9.
[c] Chinese government social development goal from State Economic Information Center internal report.
[d] World Bank: Key World Energy Statistics.

commercially mature today. Given the 55-year model period, a number of the technologies fall into this category. Assuming commercially mature costs for technologies from the start of market introduction may imply in some cases that actual costs are "bought down" through subsidy of early units introduced in China or elsewhere in the world.

We have imposed caps in the rates of introduction of new technologies. These caps do not necessarily dictate how fast a technology will expand in the market, but for technologies that the model finds especially attractive, the growth rate cap often provides an upper bound on its market expansion. The allowed growth rate caps are often relatively high, especially in the early years of a new technology—generally 20–30% per year in the first couple of decades after introduction. Historically such growth rates have been achieved by technologies such as wind and nuclear electricity.[1] While not implausible, such growth rates do imply policy incentives to augment market mechanisms.

The model accounts for the costs of limiting environmental emissions (by forcing the use of cleaner, more expensive technologies in some scenarios), but the environmental and public health benefits of reduced emissions are not counted. A precise determination of these benefits is difficult, but based on studies that have been done for China (World Bank, 1997) and for other countries (Rabl and Spadero, 2000; Delucchi, 2000), these avoided externality costs are likely to be significant.

A final important assumption is the discount rate used by the model to calculate the total discounted energy-system cost (the objective function that MARKAL minimizes). A discount rate of 10% was selected as appropriate for analyses of China's long-term technological choices (Dadi, 2001).

2.2. Energy service demands, 1995–2050

We developed projections of the demands for energy services to 2050 based largely on comparisons with historical data for various OECD countries at similar levels of per capita GDP. We assumed that by 2050 China as a whole will have developed energy services to the levels that characterized key OECD countries in the mid-1990s. Considerable thought was given to the appropriate choice of the cross-country comparisons in order to minimize differences in economic structure, demographics, geography, culture, development path, etc.

Table 1 presents the general economic assumptions underlying the energy service demand projections.[2] The population projections and GDP projections are based on official data from China's State Economic Information Center and represent their baseline population projection and their lower-bound GDP growth projection. The lower GDP projection was selected as being more consistent with recent trends in China's energy consumption (Sinton and Fridley, 2000).

Overall our assumptions result in a greater-than-tripling in the supply of energy services to the Chinese economy between 1995 and 2050, which falls in the mid-range of energy demand projections made by a number of other analysts (Fig. 2) (Sinton and Ku, 2000).

2.3. Primary energy resources

MARKAL requires that the cost of all primary energy sources be defined along with constraints on their

[1] For example, primarily as a result of government incentives, nuclear power capacity worldwide grew at an average of 37% per year between 1957 and 1977 (Williams and Terzian, 1993).

[2] Unless otherwise indicated, all costs in this paper are expressed in constant mid-1990s level US dollars.

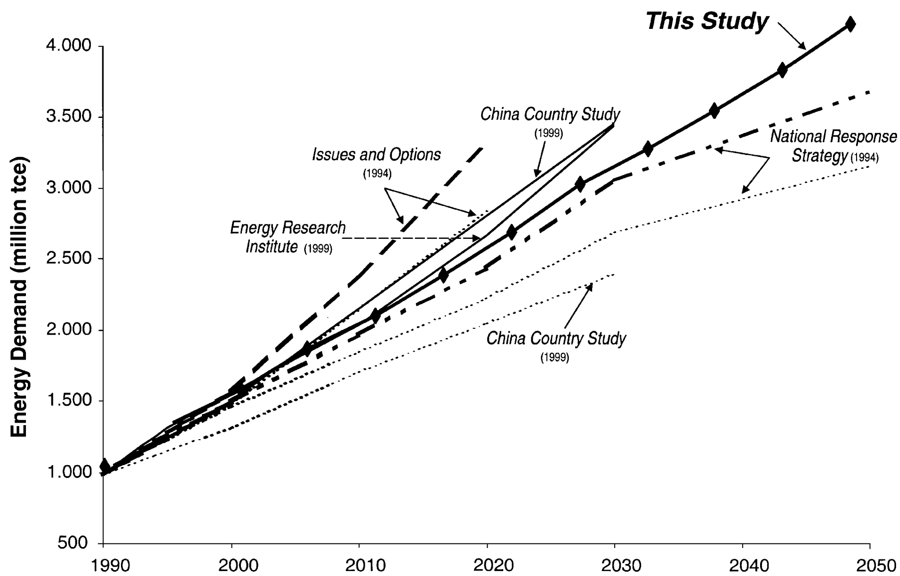

Fig. 2. Comparison of Chinese energy demand assumed in our model with those from other studies, as reported by Sinton and Ku (2000). The units are million metric tons of coal equivalent (Mtce, and 1 Mtce = 0.0293 EJ). Where two lines are shown from the same study, the lower energy demand level is for a scenario that assumes heavier policy interventions.

availability. We provided supply cost estimates and upper bounds on resource availability for fossil fuels (Table 2).[3] For renewable resources the exploitable resource was defined (Table 3), as were maximum rates of technology introduction.

2.4. Technologies

The MARKAL model requires users to create detailed profiles for two sets of energy conversion technologies: one for converting primary energy resources into final energy carriers, and one for converting final energy carriers into energy services. The profiles describe capital costs, operating costs, energy efficiencies, pollutant emissions, availability factors, constraints on market penetration rates, and other characteristics. Using these profiles and the user-specified primary energy costs and availabilities, MARKAL finds the combination of energy resources and conversion technologies that meet the specified energy service demands while minimizing the cumulative discounted energy-system cost for the full period of the analysis. The model monitors capital stock turnover and, as required, it introduces new primary energy resources, new capacity for primary-to-final energy conversion, and new end-use conversion capacity.

We defined 71 technologies for converting primary energy into final energy. For each of these, we specified values for energy input per unit energy output, capital investment per unit of production capacity, fixed and variable O&M costs, plant availability, SO_2 emissions per unit energy output, and the first year in which the technology can be introduced. Two main bodies of literature were drawn upon for the values used to define these technologies. One is China-based (Chen and Wu, 2001; Wu and Chen, 2001) and one is United States-based. The US-based studies by engineering firms, technology vendors, and knowledgeable energy analysts are all available in the open literature. The most reliable studies were selected and evaluated to yield as consistent a set of cost data as possible.

Conversion technologies were categorized as either "base" or "advanced" (Table 4). The base technologies share the common feature of being either commercially available today or at advanced stages of commercial demonstration. The advanced technologies share the common feature of not being commercially mature at present. The technology options include a large number of coal conversion technologies, reflecting the importance of coal in China. A key distinction between the base and advanced coal technologies is that the latter all involve oxygen-blown gasifiers producing synthesis gas, whereas the base technologies are almost entirely based on coal combustion. Synthesis gas can be converted into electricity or clean gaseous fuels or liquid fuels in plants making only a single energy carrier or in plants producing several carriers simultaneously—polygeneration (Williams, 2001; Ni et al., 2001). Several technology options are provided for each of these in the advanced set. Also, several of the advanced technologies have two variants, one with carbon dioxide released to the atmosphere and one with the CO_2 captured for subsurface sequestration from the atmosphere.

[3] The energy contents reported for all fuels in this paper are lower heating values.

Table 2
Assumed fossil fuel production limits and costs[a]

	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	Cum[b]
Domestic coal													
Upper bound (EJ)	29.62	32.0	34.9	38.1	41.5	45.3	48.8	52.5	56.6	61.0	65.7	70.8	2884
(million tons)	1417	1531	1669	1823	1986	2167	2335	2512	2708	2919	3144	3388	138,039
Cost ($/GJ)	0.94	1.04	1.07	1.09	1.12	1.15	1.18	1.21	1.24	1.27	1.30	1.33	—
($/metric ton)	19.6	21.7	22.4	22.8	23.4	24.0	24.7	25.3	25.9	26.5	27.2	27.8	—
Domestic crude oil													
Upper Bound (EJ)	6.27	6.64	7.00	7.36	7.65	7.65	7.65	6.96	6.26	5.57	4.88	4.18	390
(million toe)	150	159	167	176	183	183	183	166	150	133	117	100	9336
Cost ($/GJ)	2.70	2.86	3.04	3.23	3.43	3.64	3.86	4.10	4.35	4.62	4.91	5.20	—
($/bbl)	16.13	17.09	18.16	19.30	20.49	21.75	23.06	24.49	25.99	27.60	29.33	31.06	—
Imported crude oil													
Cost ($/GJ)	3.00	3.18	3.38	3.59	3.81	4.04	4.29	4.55	4.83	5.13	5.45	5.78	—
($/bbl)	17.92	19.02	20.19	21.43	22.75	24.15	25.63	27.21	28.88	30.66	32.54	34.54	—
Imported oil product													
Diesel ($/GJ)	3.99	4.24	4.50	4.77	5.07	5.38	5.71	6.06	6.43	6.82	7.24	7.69	—
Gasoline ($/GJ)	4.86	5.16	5.48	5.81	6.17	6.55	6.95	7.38	7.83	8.31	8.82	9.37	—
Kerosene ($/GJ)	4.62	4.90	5.21	5.53	5.86	6.23	6.61	7.01	7.44	7.90	8.39	8.90	—
LPG ($/GJ)	4.62	4.90	5.21	5.53	5.86	6.23	6.61	7.01	7.44	7.90	8.39	8.90	—
Fuel oil ($/GJ)	2.37	2.52	2.67	2.83	3.01	3.19	3.39	3.60	3.82	4.05	4.30	4.57	—
Domestic natural gas													
Upper bound (EJ)	0.702	1.46	2.19	2.93	3.58	4.24	4.75	5.27	5.71	6.14	6.49	6.84	252
(billion m^3)	18	38	56	75	92	109	122	135	147	158	167	176	6466
Cost ($/GJ)	2.31	2.48	2.65	2.85	3.05	3.27	3.51	3.76	4.03	4.32	4.63	4.96	—
($/1000 m^3)	89.9	96.4	103.3	110.7	118.7	127.3	136.4	146.2	156.8	168.1	180.2	193.1	—
Imported natural gas													
Cost ($/GJ)	2.57	2.76	2.95	3.17	3.39	3.64	3.90	4.18	4.48	4.80	5.15	5.52	—
($/1000 m^3)	100	107	115	123	132	142	152	163	174	187	200	215	—
Conventional coal bed methane													
Upper bound (EJ)	0.023	0.039	0.144	0.360	0.723	1.17	1.63	2.09	2.42	2.80	3.09	3.42	90
(billion m^3)	0.6	1.0	3.7	9.2	18.6	29.9	42.0	53.6	62.1	72.0	79.5	87.8	2300
Cost ($/GJ)	1.60	1.60	1.72	1.84	1.97	2.11	2.27	2.43	2.60	2.79	2.99	3.21	—
($/1000 m^3)	62	62	67	72	77	82	88	94	101	109	116	125	—
Coal bed methane recovered by CO_2 injection													
Upper bound (EJ)				0.124	0.426	1.105	1.82	2.55	3.58	5.02	6.72	8.58	150
(billion m^3)				3.2	11.0	28.5	47.0	65.9	92.4	130	173	221	3863
Cost ($/GJ)				1.20	1.29	1.38	1.48	1.58	1.70	1.82	1.95	2.09	—
($/1000 m^3)				47	50	54	58	62	66	71	76	81	—
Domestic oil recovered by CO_2 injection													
Upper bound (EJ)			0.70	0.74	0.77	0.77	0.77	0.77	0.77	0.77	0.77	0.77	38
(million toe)			17	18	18	18	18	18	18	18	18	18	904
Cost ($/GJ)			1.70	1.82	1.95	2.09	2.24	2.41	2.58	2.77	2.96	3.18	—
($/toe)			71	76	82	87	94	101	108	116	124	133	—

[a] Costs are in 1995 US dollars. Upper bound refers to the limit on annual production specified in the model and is not necessarily the level at which the resource is used in the model.

[b] Maximum cumulative resource utilization allowed in the model, 1995–2050. No limits on imported resources are indicated here, but some scenarios (discussed in the text) involve some limitations on imports.

We defined end-use technologies for converting final energy into energy services in each of six demand sectors: industrial, commercial, urban residential, rural residential, agricultural, and transport. In each sector, the choice of technologies included both those that are commercially available today, as well as technologies that might be commercially introduced in the future. "Conservation technologies," which reduce the final energy needed to meet a specific energy service, were also used to account for efficiency measures, such as

Table 3
Assumed limits on primary renewable and nuclear energy resources[a]

	1995	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Hydro electric capacity (upper bound, GW)												
Small (<25 MW)	17	18	20	23	26	30	35	40	46	52	58	65
Large (>25 MW)	38	57	72	90	115	140	170	200	225	250	275	300
Nuclear electric capacity												
Upper bound (GW)		10	19	30	45	60	80	100	125	150	180	216
Agricultural residues												
Upper bound (EJ)	7.98	7.98	7.98	7.98	7.98	7.98	7.98	7.98	7.98	7.98	7.98	7.98
(million tons)	466	466	466	466	466	466	466	466	466	466	466	466
Cost ($/GJ)	0.52	0.55	0.58	0.61	0.64	0.67	0.70	0.74	0.78	0.82	0.86	0.90
($/ton)	8.7	9.2	9.6	10.1	10.6	11.2	11.8	12.4	13.0	13.6	14.3	15.1
Fuel wood												
Upper bound (EJ)	2.93	2.93	2.93	2.93	2.93	2.93	2.93	2.93	2.93	2.93	2.93	2.93
(million tons)	175	175	175	175	175	175	175	175	175	175	175	175
Cost ($/GJ)	1.37	1.47	1.57	1.69	1.81	1.94	2.08	2.23	2.39	2.56	2.75	2.94
($/ton)	22.9	24.5	26.3	28.2	30.2	32.4	34.7	37.2	39.9	42.8	45.9	49.2
Biogas												
Upper bound (EJ)	0.032	0.033	0.038	0.045	0.060	0.075	0.098	0.120	0.150	0.180	0.207	0.234
Million m^3	1.6	1.7	1.9	2.3	3.0	3.8	4.9	6.0	7.5	9.0	10	12
Wind electric capacity (upper bound, GW)												
Small wind		1.0	1.8	2.6	3.8	5.0	7.0	9.0	11.5	14	17	20
Large remote farms		1.0	5.0	10	20	32	52	84	132	186	237	300
Geothermal electricity capacity												
Upper bound (GW)	0.030	0.040	0.050	0.060	0.080	0.100	0.120	0.140	0.150	0.160	0.170	0.180
Solar energy												
No upper bound specified[b]												

[a] Costs are in 1995 US dollars. Upper bound refers to the limit on annual production specified in the model and is not necessarily the level at which the resource is used in the model.
[b] The installed capacities of solar photovoltaic electricity systems and solar thermal energy systems are allowed to grow at a maximum rate of 30% per year during the full analysis period.

better building envelopes, industrial variable speed motors, etc.

3. Results

The framework for our application of the China Markal model consists of two basic sets of technology scenarios overlaid by one or more of the following constraints: (i) limits on emissions of SO_2; (ii) limits on imports of oil and natural gas; and (iii) limits on emissions of CO_2 to the atmosphere.

One set of model runs used only the Base set of energy conversion technologies. These runs were intended to represent a continuation of current trends in energy-supply technologies: incrementally improved technologies (having higher efficiency and or lower emissions) are available for introduction into the economy, but without the possibility of introducing fundamentally different technologies. For example, in the case of coal-electric technologies, more efficient coal combustion technologies are available in the Base set, but gasification-based technologies are not. The Base set of technologies represents a future in which little incentive is provided for the development and introduction of technologies that would provide "leap-frog" improvements to the energy system.

A second set of model runs added the Advanced set of energy conversion technologies to the Base set, thereby providing technology leap-frogging opportunities. Table 5 summarizes key differences between the Base and Advanced sets of technologies. The model chooses the advanced technologies to meet environmental or energy import constraints whenever they minimize total system cost. While the model chooses these advanced technologies under a variety of conditions, many of the radically new technologies will not necessarily be introduced into the Chinese economy

Table 4
Coal and renewable conversion technologies in the base and advanced scenarios

Base	Advanced[a]
Coal-derived electricity	
Steam thermal plants with capacity 100, 200, or 300 MW (with and without emissions control)	Integrated coal gasifier combined cycle (IGCC)
	IGCC with CO_2 capture and sequestration.
Pulverized coal combustion (PCC), 500 MW	Integrated gasifier/solid-oxide fuel cell with CO_2 capture and sequestration
AFBC, PFBC, and ultra-supercritical steam	"Polygeneration" coproduction of power and dimethyl ether (with and without CO_2 capture), hydrogen (with and without CO_2 capture), or methanol and industrial heat (with and without town gas co-product)
Cogeneration of power and district heat (using traditional or advanced steam plants)	
PCC cogeneration of power and industrial heat	IGCC cogeneration of power and industrial heat
Coal-derived heat	
Boilers (conventional or advanced)	Cogeneration and polygeneration (as above)
Cogeneration (as above)	
Coal-derived solids, gases, and liquids (without co-production of electricity)	
Washed coal	Towngas by modern oxygen-blown gasification
Coke, with co-production of town gas	Fischer-Tropsch liquids (with and without CO_2 capture), methanol, dimethyl ether
Towngas by traditional gasification, with coke co-production	Hydrogen (conventional technology)
	Hydrogen, augmented by H_2 from coal-bed methane obtained by injection of CO_2 captured during H_2 production
Renewable electricity	
Biomass combustion (steam cycle)	Village-scale biomass gasifier microturbine cogeneration
Village-scale biomass gasifier/IC engine cogeneration	Village-scale biomass gasifier solid-oxide fuel cell-microturbine hybrid electricity generation
Small-scale wind farms	Large, remote wind farms with long-distance transmission
Residential solar PV systems	Central solar PV systems
Hydroelectric plants (smaller or larger than 25 MW)	Co-production of electricity with Fischer-Tropsch liquids or with dimethyl ether
Geothermal power	
Renewable gases and liquids (without co-production of electricity)	
Village-scale anaerobic digesters	Ethanol from lignocellulosic biomass
Village-scale producer gas	

[a] In the Advanced-technology scenarios, all technologies (including those listed under Base) are included in the model.

Table 5
Key technology differences between base and advanced scenarios

Base-technology scenarios	Advanced-technology scenarios
Efficient technologies at point of energy end-use	Super-efficient industrial process options added
Coal used primarily by existing or advanced combustion technologies	Coal options extended to include gasification-based technologies for production of electricity and clean gaseous and liquid fuels
Existing and improved gasoline engine vehicles	Vehicles include hybrid-electrics and fuel cells
Currently commercial renewable energy technologies	Advanced renewable energy technologies become available, e.g. large-scale wind farms
No options available for carbon sequestration	Carbon sequestration options available with and without enhanced resource recovery

without focused government policies and support for technology research, development, demonstration, and commercialization.

In all of the model runs the selection of the most-efficient technology options typically minimizes total system cost. As a result, China's economy improves its overall efficiency in all of the scenarios at a relatively aggressive rate. One indication of the aggressiveness of energy efficiency improvements is the rate of decline in primary energy intensity (primary energy use per $ of GDP). Between 1995 and 2050, in most of the cases discussed below, the primary energy intensity falls from 58 MJ/$ to about 8 MJ/$, which is an average of about 3.5% per year. For comparison, over the period

1980–1997, primary energy intensity fell an average of 1.2%/year in Japan (from 8.2 to 6.9 MJ/$), 1.4%/year in the USA (from 18.6 to 15.5 MJ/$), and 1.8% per year in the UK (from 13.1 to 9.7 MJ/$) (EIA, 2001). Given China's high starting point, this level of improvement in primary energy intensity is aggressive, but not implausible.

For the Base and Advanced energy-supply technology sets, we explored the impact of constraining (i) emissions of SO_2, (ii) imports of oil and gas, and (iii) emissions of carbon. Annual SO_2 emissions were capped at declining levels: 24 million tons in 1995, 16.5 million tons in 2020 (official Chinese government target), and 10.4 million tons in 2050 (which would give China an average SO_2 emission per unit of coal consumed that is roughly comparable to the level found in the United States today). The percentages of oil and of natural gas use that could be imported in any single year were each separately constrained to values as low as 20%. For carbon, we considered alternative allowable cumulative (1995–2050) emission caps. Wigley et al. (1996) have estimated that cumulative global emissions from 1990 to 2100 of 380, 750, 1100, and 1400 GtC would stabilize the atmospheric concentration of CO_2 at 350, 450, 550, and 750 ppm, respectively. If we assume that China's share of global emissions is proportional to its share of year-2000 global population (21.5%), then China's allowable emissions from 1990 to 2100 would be 82, 161, 236, or 301 GtC, respectively. In this context, we examined the impact of cumulative emission caps of 80 and 66 GtC for 1995–2050 to help identify possible energy strategies for the first half of the century that would be consistent with stabilizing the CO_2 concentration. With these two scenarios, achieving stabilization at 450 ppm would require China's emissions in the second half of the century to be limited to 81 and 95 GtC, respectively.

3.1. Summary of main results

Fig. 3 summarizes the results for the Base set of scenarios by showing the primary energy mix in 2050 for each scenario. Nuclear, hydro, wind, solar, and geothermal electricity are represented by their primary-energy equivalents (three times actual electricity production). The numbers above each bar indicate the percentage of the cumulative (1995–2050) oil and gas energy that is imported and the total cumulative CO_2 emissions (expressed as carbon). The white inner bars show the change in cumulative (1995–2050) discounted energy system cost relative to the scenario labeled BASE. The discounted energy system cost (referred to hereafter simply as "system cost") represents the total cost for the period 1995–2050 for investments in energy conversion and end-use technologies, for fuel, and for O&M and other costs, discounted to 1995 dollars. Due to the large uncertainties in this kind of analysis, we use the difference in system cost between scenarios as the primary figure-of-merit regarding cost. The system cost for the BASE case is the reference for all cost differences shown in this paper. In the BASE scenario, no external constraints were placed on emissions of SO_2, on oil/gas imports, or on carbon emissions. Scenario B-SO_2 is the BASE case with the SO_2 emissions cap imposed. Scenarios B-S-C80 and B-S-C66 represent the B-SO_2 case with total carbon emissions limited to 80 and 66 GtC.

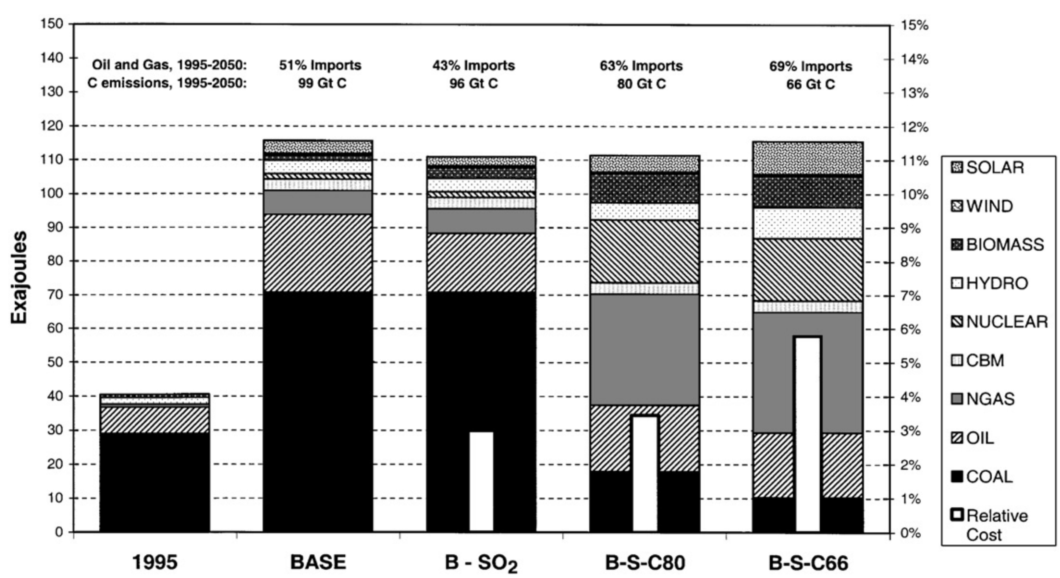

Fig. 3. Primary energy use in 2050 (left scale) and change in cumulative (1995–2050) total discounted system cost relative to BASE cost (right scale) calculated by our China MARKAL model for scenarios involving Base technologies. Above the bar are shown cumulative carbon emissions and percentage of oil and gas use that is imported. See text for explanation of individual scenarios.

For all cases in Fig. 3, primary energy use in 2050 ranges from 111 to 116 EJ. Coal is the dominant energy source in the BASE and B-SO_2 scenarios and is used at the maximum allowed rate throughout the analysis period. Primary energy use is slightly lower in B-SO_2 than in BASE primarily because of substitution of coal by more efficient natural gas use in the industrial sector. In the electric sector, cleaner and more efficient coal combustion technologies such as ultra-supercritical-steam power plants with flue gas desulfurization are selected in B-SO_2 in place of less costly but more-polluting and less-efficient technologies, contributing to a 3% increase in system cost. Oil and gas imports average 280 million tons of oil equivalent per year (Mtoe/yr) in the BASE scenario during the 55-year analysis period, peaking at 450 Mtoe in 2050. (For comparison, China imported about 65 Mtoe in 2000.) Cumulatively, 51% of oil and gas is imported. In the B-SO_2 scenario, oil and gas imports average 203 Mtoe/year and peak in 2050 at 329 Mtoe. Cumulatively, 43% of oil and gas is imported, the lowest achievable oil/gas import level in any Base scenario.

Carbon emissions fall slightly from the BASE to B-SO_2 scenario. To achieve greater carbon emission reductions, coal use must be dramatically reduced, imports of oil and gas must be substantially increased, and contributions from hydroelectricity, nuclear, and biomass resources must be pushed to their limits. In the 80 GtC scenario (B-S-C80), oil and gas imports reach 988 Mtoe in 2050 and hydroelectricity contributions increase by one-third relative to B-SO_2. Hydroelectricity use reaches the maximum allowed in B-S-C66. Nuclear energy increases in the B-S-C80 and B-S-C66 scenarios by an order of magnitude over the B-SO_2 scenario, reaching the maximum allowed installed capacity in 2050 (216 GW) and supplying about 40% of all electricity in 2050. Biomass use also reaches its limit, with most of the biomass being used in village-scale systems co-producing electricity and producer gas for cooking and heating. Solar energy contributions grow significantly in the carbon-constrained cases, reaching almost 200 GW of solar PV capacity by 2050 in B-S-C66. Achieving the 80 GtC emission limits involves a slightly higher system cost than for the B-SO_2 scenario. Reaching the 66 GtC limit involves a larger cost penalty.

Fig. 4 summarizes results for the Advanced set of scenarios. The SO_2 constraint (with no other constraints imposed) can be met with the Advanced technologies (A-SO_2) at a considerably lower cost than for the B-SO_2 scenario, with less imported oil and gas, and with lower carbon emissions. The Advanced scenarios include technology options for converting coal and biomass via gasification into clean substitutes for oil and gas, thereby enabling still lower levels of oil and gas imports to be achieved. For example, in the A-S-O30 scenario, oil and gas imports were constrained to a maximum of 30% of total oil and gas use. In the A-SO_2 and A-S-O30 scenarios, coal is not used at its maximum allowed rate. Increased electricity production from biomass and wind reduces pressure on coal use, and the tight oil and gas import constraints are satisfied by converting coal and biomass into synthetic liquids and gases. Additionally, the use of coal-bed methane (CBM) mined by CO_2 injection further reduces pressure on coal use and natural gas imports.

The wind energy selected in the Advanced scenarios is remote, large-scale wind farms with long-distance

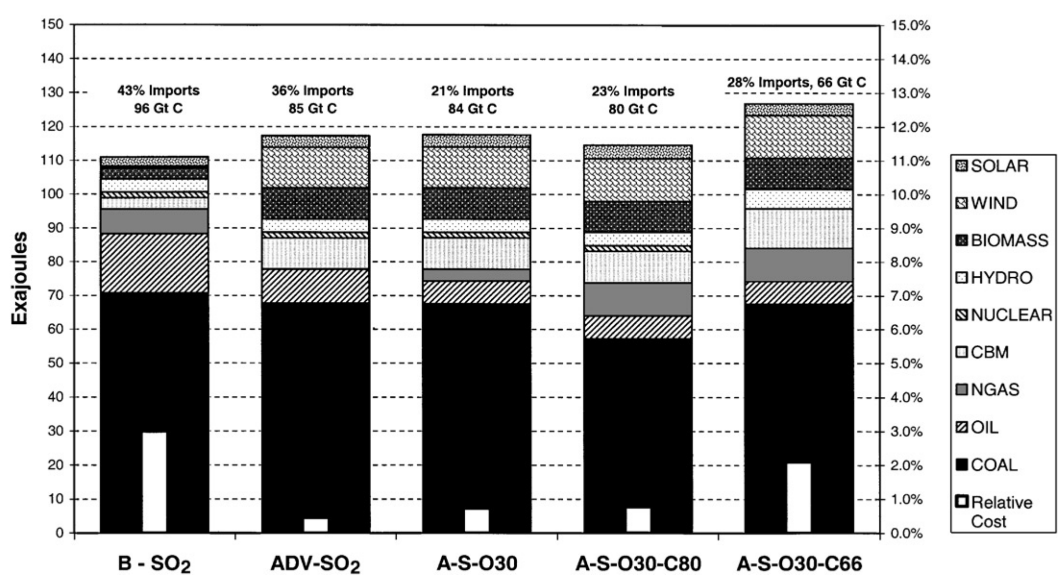

Fig. 4. Primary energy use in 2050 (left scale) and change in cumulative (1995–2050) total discounted system cost relative to BASE cost (right scale) calculated by our China MARKAL model for scenarios involving Advanced technologies. Above the bar are shown cumulative carbon emissions and percentage of oil and gas use that is imported. See text for explanation of individual scenarios.

Table 6
CO_2 sequestered in advanced scenarios with carbon emission limits imposed[a]

	Million tons of carbon per year										Cumulative MtC
	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050	
A-S-O30-C80											
With ERR	0	9	18	36	54	69	86	107	133	169	3404
W/o ERR	0	0	0	0	0	0	0	0	80	186	1330
Total	0	9	18	36	54	69	86	107	213	355	4735
A-S-O30-C66											
With ERR	0	9	18	36	55	75	100	136	186	240	4273
W/o ERR	0	18	69	108	191	240	440	583	666	884	15,997
Total	0	27	86	145	247	315	540	718	852	1124	20,270

[a] With ERR refers to CO_2 storage resulting from CO_2 injection for enhanced resource recovery (oil and coal-bed methane). W/o ERR refers to CO_2 injection for the sole purpose of long-term below-ground storage.

transmission to load centers. The model selects this option up to the maximum allowed level. By 2050, the electricity from these large wind farms is less costly than nuclear or hydro electricity, so the contributions of the latter two options are limited to modest levels. The model also uses the maximum allowed level of biomass, and the preferred use of the biomass is for co-production of electricity and dimethyl ether, a fuel that can be used like LPG for cooking and heating and also as a diesel substitute in transportation.

Notably, without any explicit carbon emission constraint, the Advanced scenarios have between 10% and 15% lower carbon emissions than the B-SO_2 scenario. Some of the reductions come from less use of oil and natural gas, but most are due to the sub-surface injection of CO_2 for enhanced recovery of CBM and oil. Because of favorable economics, enhanced resource recovery (ERR) is used after 2010 at, or close to, the maximum allowed levels in all Advanced scenarios.

The fourth bar in Fig. 4 shows the impact of applying the cumulative carbon emission constraint of 80 GtC. To meet this constraint, coal use is reduced (compared to the A-S-O30 scenario) in favor of end-use efficiency improvements and an increased use of natural gas. Additionally, some carbon sequestration other than sequestration associated with ERR begins in the 2040s in A-S-O30-C80 (Table 6).

The last bar in Fig. 4 shows results for a case with 66 GtC emissions (A-S-O30-C66). Major electrification occurs in the commercial and residential end-use sectors starting around 2035, leading to higher primary energy use in 2050 relative to the other cases shown. The increased electrical needs in 2050 are supplied largely by coal integrated gasifier combined cycle (IGCC) technology that includes carbon capture and sequestration. Carbon sequestration without ERR begins in 2010 at a modest level (0.018 GtC/year) and reaches a maximum of 0.88 GtC in 2050 (Table 6). The system cost increment for the 66 GtC case over the BASE (2%) is greater than for the 80 GtC case (1%), but it is only two-thirds of the cost increment for the B-SO_2 case.

For the 66 GtC case in Fig. 4, we stipulated a phase out of nuclear power by 2025. We ran a second 66 GtC scenario in which we allowed unconstrained nuclear power capacity growth up to a maximum level of 216 GW in 2050. In this case, the model showed a preference for the nuclear option to meet the increased electricity needs during the later part of the model period, which reduces the amount of coal IGCC with carbon capture and sequestration. Even though the electrical generating technology mix is quite different between these two 66 GtC cases, they have essentially the same system cost. This suggests that there are multiple configurations of the energy system that could meet the imposed carbon constraint at similar system cost levels. However, the challenges to implementing these different energy systems are quite different. For example in the case shown in Fig. 4, carbon sequestration (without ERR) must grow nearly 5% per year between 2035 and 2050, from 440 million tC sequestered in 2035 to 884 million tC in 2050. On the other hand, the high nuclear case requires nuclear power capacity to grow nearly 12% per year over the same period, from 41 GW installed in 2035 to 216 GW installed in 2050 (an average of 12 GW of new nuclear power plants brought on line each year).

3.2. Detailed comparison of two scenarios

A more detailed comparison of the B-SO_2 scenario with the A-S-O30-C66 scenario provides a more complete understanding of the fundamental features of an advanced-technology energy-supply strategy as contrasted with features of a ‘‘business-as-usual’’ energy-supply strategy. As a shorthand in this section, we refer to the B-SO_2 scenario as the B scenario and the A-S-O30-C66 scenario as the A scenario.

Primary energy use in the B scenario grows from 41 EJ in 1995 to 110 EJ in 2050 (Fig. 5). Total primary energy growth is similar in the A scenario until the latter part of the analysis period, when primary energy use grows more rapidly due to intensified electrification of the commercial and residential sectors. Total primary energy use in the A scenario reaches 139 EJ in 2050, but fossil energy use is 8 EJ lower than in the B scenario. We next discuss each primary energy source in turn.

In the B scenario coal maintains its dominance throughout the 55-year period. It is used at the maximum allowed level, falling only modestly as a fraction of total energy use from 71% in 1995 to 64% in 2050. The fraction of coal used for electricity production increases gradually from about 30% in 1995 to 41% in 2050. Direct use of coal is reduced over time in the industrial, residential, and commercial sectors (Fig. 6) to help meet SO_2 limits. Coal is increasingly used instead for production of town gas (Fig. 7) for industrial, commercial, and residential uses.

In the A scenario the percentage of coal in the primary energy mix at the end of the analysis period is not markedly different from the B case (Fig. 5). Direct use of coal in industry, commercial, and residential sectors declines, as in the B scenario, but the fraction of coal used in the electricity sector increases to a more substantial level (56%) by 2050 (Fig. 6). The increasing fraction of coal to the electricity sector is primarily a consequence of electricity generation being the least costly means for capturing and sequestering carbon, which is required to meet the 66 GtC cap.

In the B scenario, the share of oil and natural gas in the primary energy mix stays nearly constant over the analysis period, but the absolute consumption of these resources grows from 8.5 EJ in 1995 to 25 EJ in 2050 (Fig. 5). After domestic oil production peaks in 2020, oil imports grow rapidly, reaching 320 million tons in 2050, when they account for 76% of total oil supply. Imports of gas peak early in the B scenario, reaching 97 billion m^3 in 2010, when they account for 56% of total gas use. On average over the analysis period, natural gas is used at half the rate that oil is used, because lower-cost substitutes are available for gas, but not for oil. In particular, the use of town gas from coal increases significantly after 2010 along with a steady increase in the use of coal-bed methane (Fig. 7). As a result of the unconstrained oil imports and the significant use of coal gas, the consumption of natural gas remains flat after 2035 and imports are sharply reduced.

In the A scenario, the oil and gas share of primary energy falls from 21% in 1995 to 13% in 2050, with oil use staying in the range of 160–250 million tons per year throughout the period. The reduced need for oil in the A scenario compared to the B scenario arises primarily as a result of increases in the efficiency of petroleum-fueled vehicles in the transport sector early in the period (with a switch from conventional vehicles to hybrid-electric

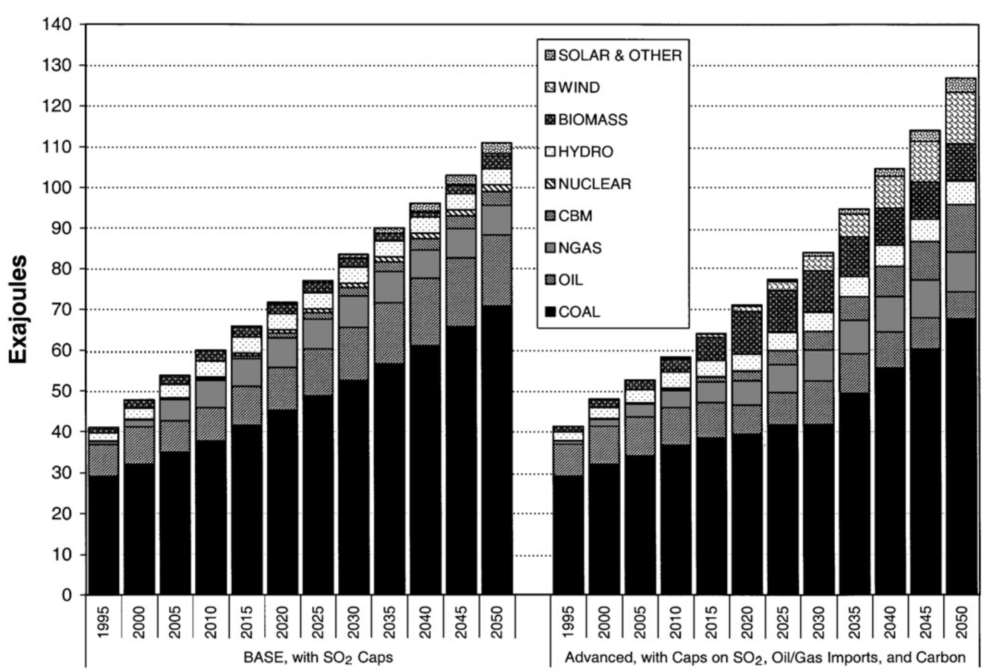

Fig. 5. Evolution of China's primary energy use calculated by our MARKAL model for two scenarios. On the left is a Base-technology scenario with SO_2 emission constraints imposed. On the right is an Advanced-technology scenario with SO_2 constraints, oil/gas imports limited to 30% of total oil/gas use, and carbon emissions limited to a cumulative total of 66 GtC between 1995 and 2050.

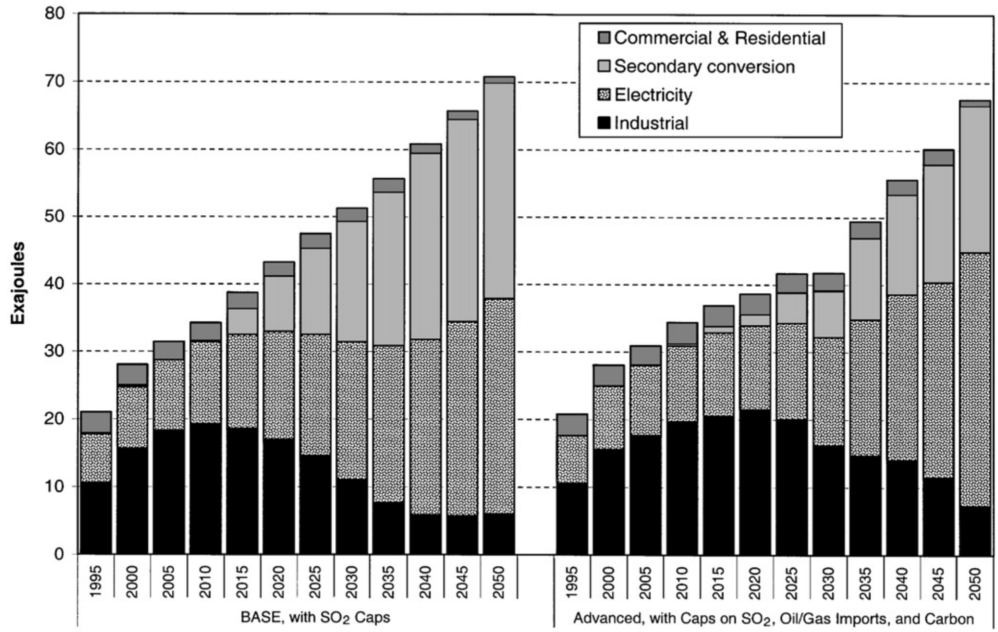

Fig. 6. Evolution of coal use by sector calculated for the two scenarios described in the caption to Fig. 5.

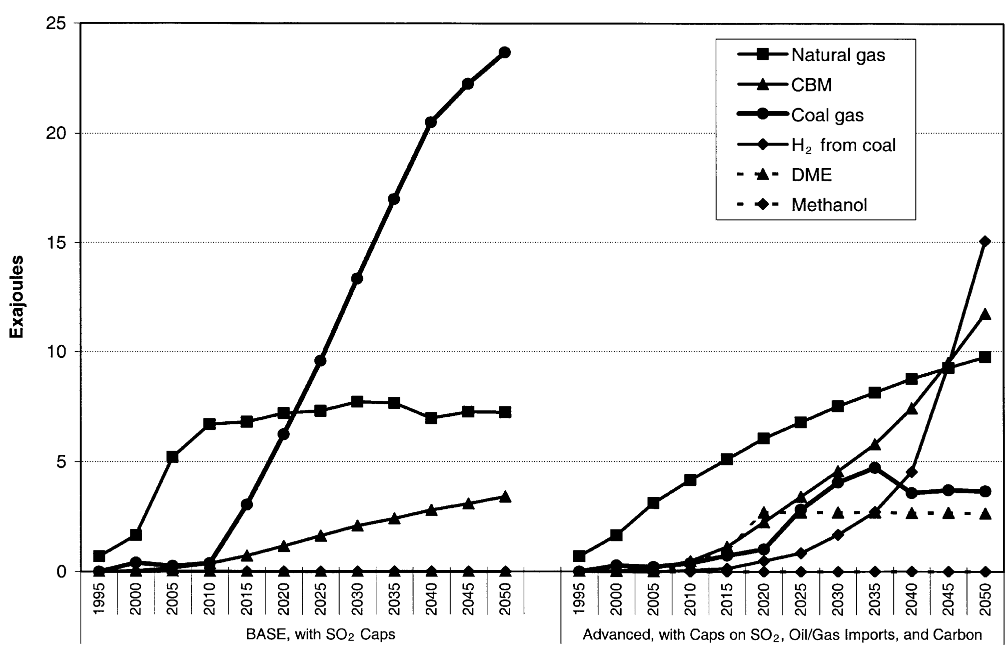

Fig. 7. Evolution of use of gas and liquid fuels calculated for the two scenarios described in the caption to Fig. 5.

vehicles), the increasing adoption of fuel cell vehicles in the second quarter using coal-derived hydrogen, and the availability of petroleum fuel substitutes made from coal or biomass, including DME (Fig. 7).

Natural gas use in the A scenario grows steadily (Fig. 7), and imports account for 30% of use throughout the period. Natural gas supplies are augmented by town gas and conventional CBM (as in the B scenario), and additionally by hydrogen and CBM from ERR (Fig. 7). In stationary applications, hydrogen is used in the second quarter of the century for combined heat and electricity production in distributed fuel cells. In the last decade of the analysis period, these fuel cell power sources account for 7% of all electricity supply in the A scenario in 2040, 15% in 2045, and nearly 22% in 2050.

Fig. 8 shows a full picture of electricity production by fuel and technology class. In the B scenario, electricity production is dominated by coal combustion technologies, which provide 72% of electricity in 1995 (653 TWh) and 78% in 2050 (3225 TWh). Stand-alone coal-fired

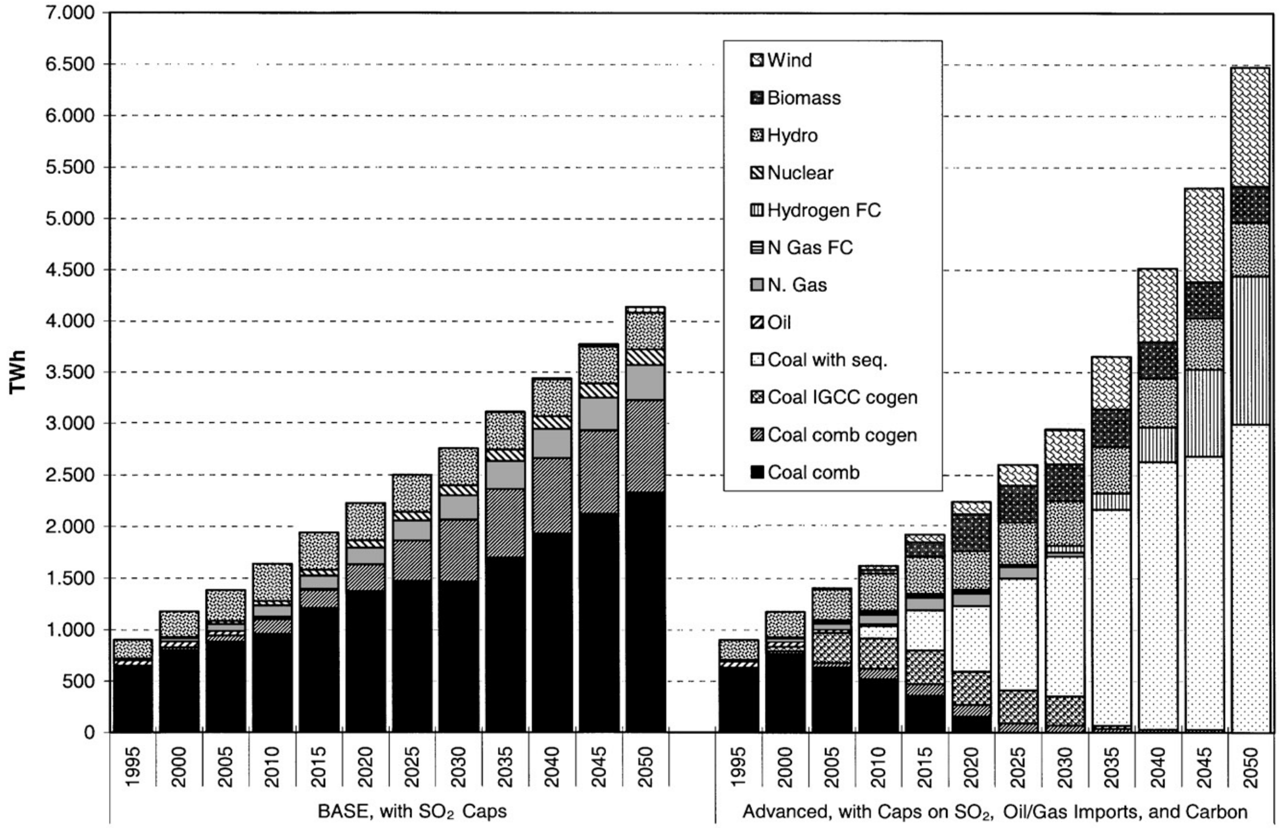

Fig. 8. Evolution of the mix of electricity production technologies calculated for the two scenarios described in the caption to Fig. 5.

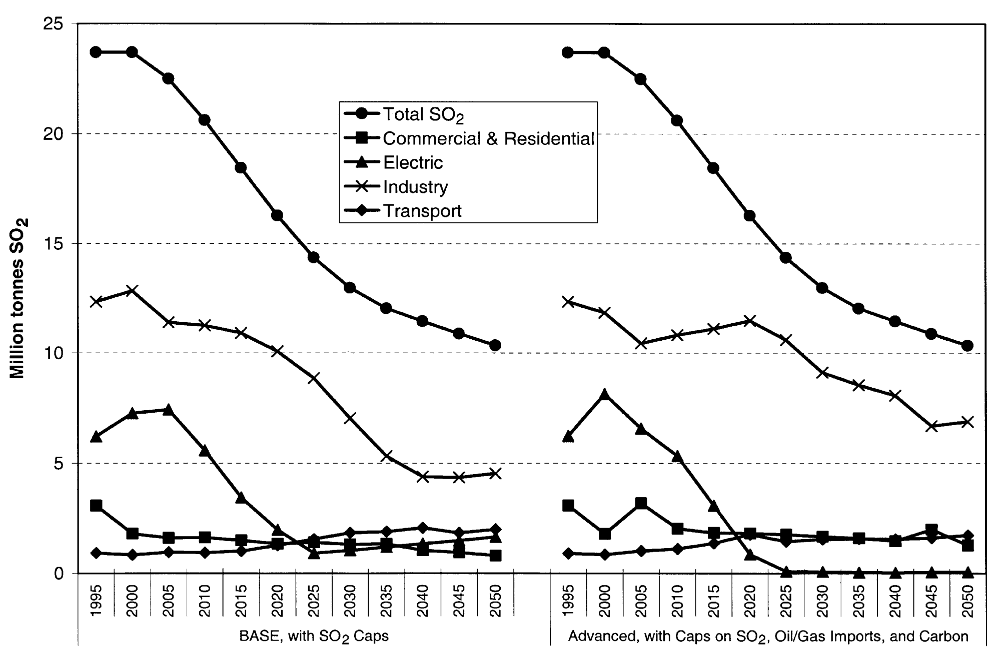

Fig. 9. Evolution of SO_2 emissions by sector calculated for the two scenarios described in the caption to Fig. 5.

power production shifts increasingly over the period from pulverized coal plants to ultra-supercritical or advanced fluid-bed combustion technologies to achieve SO_2 emission reductions. In the second quarter of the century, electric power generation accounts for less than 15% of total SO_2 emissions (Fig. 9). Also, the share of coal-derived electricity that is cogenerated increases from 3% to 28%, reflecting the generally attractive economics of cogeneration and the many available heat loads that could be supplied by cogenerated heat. Coal use is constrained by limits on the availability of coal, so that other electricity sources are required to meet demand. Hydroelectric capacity, a major contributor to electricity supply in the early part of the model period, peaks in 2010 at 87 GW of installed capacity and remains level thereafter. In later years nuclear and natural gas capacity grow. Natural gas combined cycle capacity begins growing around 2020 in proportion to the total supply of natural gas and CBM. In later years, natural gas cogeneration is displaced by coal cogeneration. Installed nuclear power capacity grows from 2 GW in 1995 to 11 GW in 2025 and to 19 GW in 2050.

In the A scenario, the electricity supply mix evolves in a markedly different fashion (Fig. 8). Coal remains the most important fuel for electricity generation, but direct combustion technologies are phased out by 2025 in favor of electricity production from gasification-based systems. The gasification-based systems not only eliminate SO_2 emissions from the electricity sector (Fig. 9), but they also provide the capability for capture and sequestration of CO_2. Either directly or through distributed fuel cells using coal-derived hydrogen, coal provides 69% of the electricity supply by 2050 in the A scenario. In total, nearly 6500 TWh of electricity are generated in 2050, which is 55% more than in the B scenario. The large electricity supply in the A scenario reflects the greater electrification of the economy: by 2050, electricity accounts for nearly 28% of all final energy use in the A scenario compared to 17% in the B scenario.

Relatively little natural gas is used for electricity in the A scenario, enabling gas to displace coal and oil in the residential and commercial sectors. The contribution of hydroelectricity increases modestly relative to the B scenario in the second half of the analysis period. However, it reaches only about 40% of the maximum allowed capacity indicated in Table 3. Biomass and wind resources are used at the maximum allowed levels. Electricity from biomass is produced as a co-product of DME production. A total of 320 GW of wind-electric capacity is operating in 2050, providing about 17% of China's electricity.

Total CO_2 emissions in 2050 are 2.3 GtC in the B scenario and 0.9 GtC in the A scenario, with cumulative emissions over the full analysis period totaling 99 and 66 GtC, respectively. The carbon emissions level in the A scenario is achieved primarily by a combination of more efficient transportation technologies, greater contributions from renewable energy sources, and the sequestering of 20 GtC between 2010 and 2050. Annual carbon sequestration in 2010 amounts to 9 MtC as a by-product of enhanced resource recovery (ERR) and an additional 18 MtC without ERR. Total annual sequestration reaches 1.1 GtC in 2050 (Table 6).

4. Conclusions

Based on our modeling results, we can draw several broad conclusions regarding the strategic technology and energy-resource choices that would enable China to meet future demands for energy services while limiting energy import dependence and environmental impacts.

First, end-use efficiency improvements are the least-costly option for meeting energy service demands and thus should be pursued regardless of what energy-supply strategy is adopted. If energy efficiency implementation falls short of goals for any reason, an advanced-technology energy-supply strategy would likely still enable energy-security and air pollution reduction targets to be met, primarily because several liquid energy carriers made from coal or biomass would be available as clean substitutes for oil.

Second, coal can continue to be the dominant primary energy resource for China. However, to meet environmental and energy security goals, coal use must shift from combustion technologies to gasification-based technologies, which have intrinsic capabilities for removal of SO_2 and offer the option of producing clean liquid and gas fuels as alternatives to petroleum and natural gas fuels. Gasification-based technologies also facilitate lower-cost capture and sequestration of CO_2. While some coal combustion technologies can effectively reduce SO_2 emissions, they cannot produce fluid fuels, and capturing CO_2 from combustion flue gases is more costly than from gasification-based systems.

Third, gas and liquid fuels will need to play increasingly important roles in a sustainable energy future. Coal-derived town gas replacing direct burning of coal in the industrial sector would be one key to achieving SO_2 limits, and natural gas would be an important substitute for coal and oil in the residential and commercial sectors. CBM associated with coal mining and also CBM recovered from deep unmineable coal beds by CO_2 injection could become especially important in meeting residential and commercial sector energy demands. Hydrogen production from coal could provide fuel for fuel cells in vehicles and in combined heat and power plants (CHP) in commercial and urban residential buildings beginning in the second quarter of the century. This would contribute to reducing SO_2 emissions and to limiting the need for oil and gas imports. DME from biomass could grow to become an important fuel in the second quarter of the century.

Fourth, renewable energy sources must take on important roles. Wind power has the potential to be an especially important contributor to electricity supply. Most of the contribution would come from large-scale wind farms located in remote wind-rich areas and connected by long-distance high-voltage DC transmission lines to major load centers. Modern biomass technologies using agricultural residues, such as village-scale producer gas systems and larger-scale systems co-producing electricity and DME, could play an essential role in helping to meet energy needs of rural populations. The biomass contribution could be further expanded if energy crops were grown on degraded lands. (Energy crops were not considered in our analysis.) Solar heating could be an important contributor in the residential sector for water and space heating. Hydropower will play an important role in a sustainable future, but the full exploitable resource may not need to be tapped before 2050.

Fifth, key technologies for achieving reductions in carbon emissions in a coal-intensive energy future that does not rely overly on imported oil and gas, will involve carbon capture and sequestration. Carbon can be sequestered for enhanced resource recovery (ERR), which should provide attractive economics. For storing larger amounts of CO_2 below ground, carbon sequestration without ERR will also be needed.

Sixth, little or no contribution from nuclear power is needed to achieve energy-security and air pollution reduction goals if an advanced-technology strategy is pursued, because coal can be used instead with CO_2 sequestration technologies to meet electricity demands. This is in contrast to following a business-as-usual strategy, in which nuclear power would be much more important to reaching CO_2 emission reduction goals.

Seventh, the long-term cost of pursuing an advanced-technology strategy to reach SO_2 and CO_2 emission reduction goals is not higher, and may be lower, than the cost of pursuing a business-as-usual strategy to achieve the same goals. Moreover, the added goal of energy security (limited percentage of oil imported) can be achieved simultaneously with the emission reduction goals with an advanced strategy, but not by business-as-usual.

Our analysis makes clear that if a ''business-as-usual'' approach to energy supply is pursued (or allowed to happen), relying on the current set of conventional technologies (as represented by the Base scenarios in our modeling), China will be unable to achieve its economic development aspirations over the next 50 years while simultaneously meeting energy-security and local air pollution reduction goals. This is true even if end-use energy efficiency improvements are aggressively pursued and a high level of nuclear electricity enters the economy during this period. Moreover, a business-as-usual energy-supply strategy does not provide the possibility for achieving meaningful reductions in carbon emissions without high levels of energy imports.

On the other hand, with advanced technologies, there are plausible scenarios under which China could continue to meet social and economic development objectives, together with environmental and energy security goals, through at least 2050. Furthermore, with our technology-cost assumptions, there would be essentially no added cost over the long-term to pursue this more-sustainable energy path. The fundamental attractiveness of the advanced-technology strategy arises as a result of interactions between all the energy demand and conversion sectors (not simply the electricity supply sector) and the ability of the advanced technologies to provide a variety of clean final energy carriers.

If China does pursue an advanced-technology energy strategy that allows it to achieve its development aspirations under increasingly cleaner skies and with reasonable energy security, it will need to make significant investments to help develop and commercialize several radically new conversion and end-use technologies within the next 10–15 years. As noted in Section 2.1, these near-term costs were not explicitly accounted for in our analysis. However, the environmental, social, public health, and balance-of-payments benefits that would accrue over the long term from implementation of an advanced-technology strategy were also not included in the analysis. It seems likely that these benefits will outweigh the needed near-term technology and infrastructure development investments, but we have not done a detailed analysis of this tradeoff.

In any case, practical realization of an advanced-technology strategy will require policies in China that (i) encourage utilization of a wider variety of primary energy sources (especially biomass and wind) and secondary energy carriers (especially synthetic fluid fuels from coal and biomass), (ii) support the development, demonstration and commercialization of new clean energy conversion technologies, especially for coal and biomass conversion, to ensure that they are commercially available beginning in the next 10–20 years, and (iii) support aggressive end-use energy efficiency improvement measures.

It is further worth noting that in addition to helping China meet its air pollution and energy security goals, near-term investment in advanced energy technology and infrastructure would lead to some modest near-term reductions in CO_2 emissions and would position China for larger future reductions. Perhaps this insight can provide a new approach to global efforts to rein in future CO_2 emissions, where the investments in absolute emission reductions by industrialized countries are balanced by the investments of developing countries in advanced-technology pathways that set the stage for reduced future CO_2 emissions relative to business as usual.

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