Modeling China's energy future

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1. Introduction

The China MARKAL model, which was originally developed for the Working Group on Energy Strategies and Technologies of the China Council for International Cooperation on Environment and Development (CCICED) during its previous phase (1997-2002, Phase 2), is a powerful tool for analyzing alternative future energy scenarios for China [Wu et al., 2001a; Wu et al., 2001b; Larson et al., 2003a; Larson et al., 2003b]. The work performed in Phase 2 identified the broad outlines of an advanced technology strategy that could allow China to continue its social and economic development while ensuring national energy-supply security and promoting environmental sustainability. The analysis indicated that a business-as-usual strategy that relied on coal combustion technologies (no matter how advanced) would not enable China to meet all of its environmental and energy security goals. However, an advanced energy-technology strategy based on (1) improved energy end-use efficiency in all sectors, (2) expanded use of renewable energy sources (especially wind and modern biomass), and (3) coal gasification technologies co-producing electricity *and* clean liquid and gaseous energy carriers (polygeneration) would enable China to continue social and economic development through at least the next 50 years while ensuring security of energy supply (at reasonable cost) and improved local and global environmental quality. Specifically, this advanced energy-technology strategy would allow China to meet its projected demand for energy services, especially liquid fuels for transportation, largely on the basis of domestic resources and without becoming over-dependent on imported oil and gas. It would assist in reducing urban and rural air pollution, and it would facilitate the meeting of requirements for lower carbon emissions that may arise from global warming concerns.

Significantly, the analysis indicated that the advanced energy-technology strategy offers the opportunity for meeting near/medium-term local environmental improvement and energy security goals at lower cost than a "business-as-usual" approach does. The advanced energy-technology strategies also provide a lower-cost path to deep reductions in CO_2 emissions in the long term.

In Phase 3 of CCICED, the Task Force on Energy Strategies and Technologies (TFEST) defined a set of MARKAL analyses to help sharpen the focus on key strategic issues and to help assess policies and programs for promoting the advanced energy-technology strategy in general, and coal polygeneration technology in particular because of its central role in providing multiple fuels, chemicals, and electricity. The following set of specific analyses was identified to provide an analytical framework for evaluating the impact of implementing advanced energy-technology strategies and facilitating further discussion of these strategies by Chinese and international experts.

- Examine the costs and benefits of the advanced energy-technology strategy compared to a strategy based on coal combustion for electricity generation and direct coal liquefaction to produce liquid fuels for transportation (augmenting petroleum fuels) and residential energy use.
- Assess the impacts that delays in the introduction of polygeneration technologies would have on overall energy system costs and on the ability to meet environmental and energy security goals.
- Explore the impacts of future, crisis-induced oil price shocks.
- Estimate the relative costs of achieving target levels of reductions in air pollution.

2. The China MARKAL model

The China MARKAL model is described in detail elsewhere [Wu et al., 2001a; Wu et al., 2001b]. The model, which is illustrated in Figure 1, requires three basic sets of input information for each time step over the entire period of the analysis: (1) energy service demand, (2) the maximum possible supply and the unit costs of all primary energy resources, and (3) the cost and performance characteristics of both energy conversion and end-use technologies that are potentially available for use in the energy system. The model finds the combination of energy resources, final energy carriers, conversion technologies and end-use technologies that minimizes the overall energy-system cost (including investment and operating costs) for meeting the specified energy service demand throughout the economy over the entire analysis period. The model uses a linear programming solver (GAMS) to simultaneously solve the energy supply and demand balances at each interval over the analysis period (eleven five-year periods between 1995 and 2050 in this work). The model monitors capital stock turnover and it introduces new primary energy resources and energy carriers, and it invests in new energy conversion and end-use capacity as required to meet the specified energy service demand.

The user may also specify environmental or other constraints under which the model must satisfy the energy supply/demand balance. The design of the model enables a wide variety of "what if" analyses to be carried out, e.g., considering alternative sets of policy, technology, or environmental constraints.

2.1. Model updates

Much of the model structure and many of the model inputs were retained from the previous analysis, such as the resource bounds that specify the maximum amount of each energy resource projected to be available in each future year. However, other model inputs were updated as described below.

2.1.1. Energy service demand projections

The baseline energy service demand projection was updated to be consistent with the 16th Party Congress goals (e.g., quadruple GDP from 2000 to 2020). The most significant change to the baseline demand projections was in the area of passenger transport demand. The previous projection was considered by several experts to be low given historical patterns in other developing countries, and the recent trend in private automobile ownership in China. Therefore, an updated transport demand projection was developed that was more consistent with these factors. In addition, a high-transport-demand scenario was developed on the basis of analyses that predict a very high growth in private automobile transport and much lower projected proportion of public transport modes [Beijdorff, 2003].

The projected numbers of private cars that result from all three of these demand projections are shown in Figure 2. The original baseline predicts slightly lower than the actual number of cars reported in the year 2000, and it projects only 130 cars per 1000 people in 2050. The revised baseline is consistent with the 2000 data, and it projects 250 cars per 1000 people in 2050. The high-transport projection predicts almost 425 cars per 1000 people in 2050.

2.1.2. Technology characterizations

The conversion and end-use technology characterizations were reviewed and updated to incorporate newly available information on cost and performance and to ensure a consistent set of technology data. Major updates to the model data base are summarized below.

- Addition of technology characterization for direct coal liquefaction. Specific issues that were addressed included characterization of the liquids produced, the technologies that utilize coal liquids, and the fuels for which coal liquids can substitute.
- Update of the advanced coal combustion and gasification technology characteristics based largely on recent work at Princeton and Tsinghua Universities [Larson and Ren, 2003; Williams and Larson, 2003][1].
- Update of the renewable energy technology characteristics [USDOE/EPRI, 1997].
- Update of the fuel distribution costs for synthetic fuels derived via direct coal liquefaction and via coal gasification.
- Update of the transportation end-use technology characterizations, especially for those that use synthetic liquids and gases.
- Increase of the discount rate for nuclear power (to 18 %) to account for safety, security and other risks

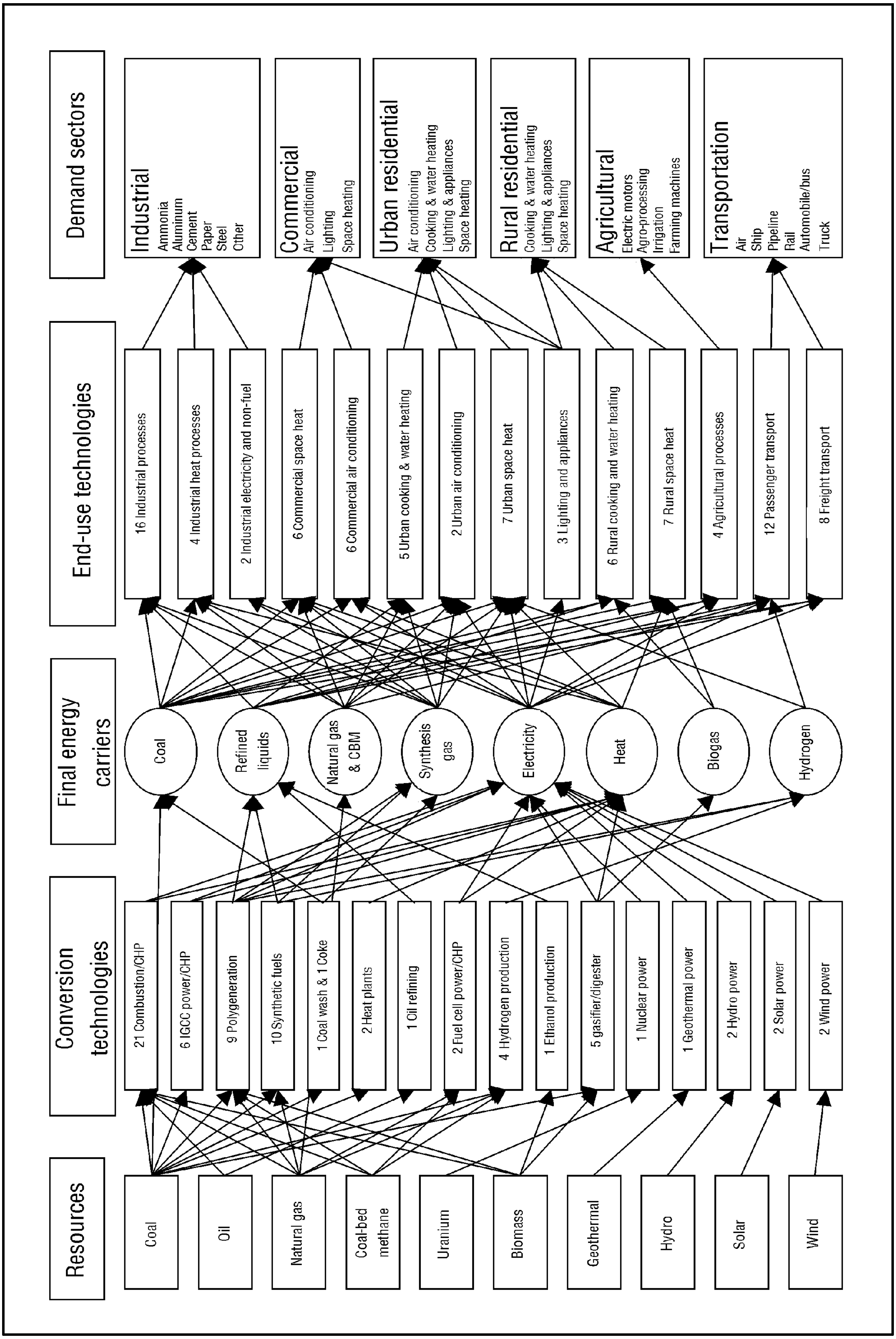

Figure 1. China MARKAL model flow diagram

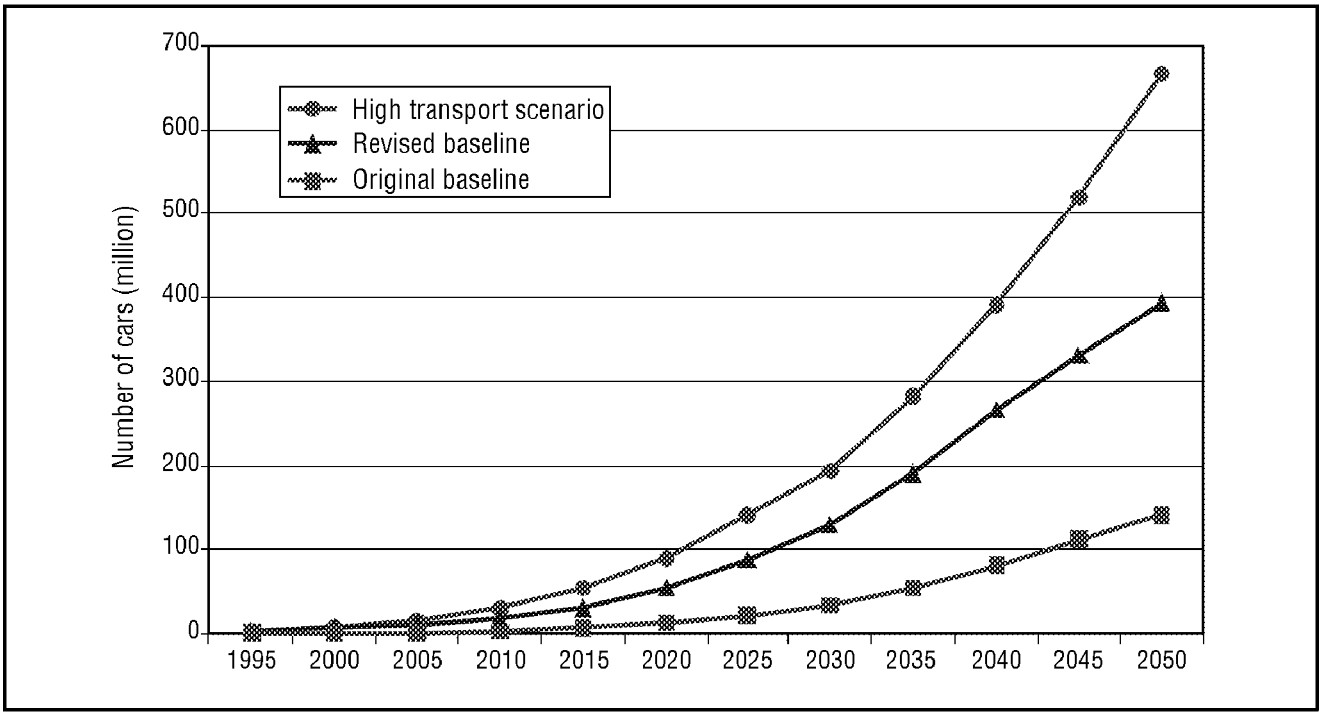

Figure 2. Numbers of passenger cars for alternative demand scenarios

that investors in nuclear power plants need to address. All other technologies in the model continue to use the original 10 % discount rate.

2.1.2.1. Advanced coal combustion and gasification technologies

In this analysis there was no change to the "Base" combustion and gasification technologies from the previous study. Of the set of "Advanced" technologies, several changes were made to update the coal gasification-based technology characterizations. Characteristics for these updated coal gasification technologies are listed in Table 1, which includes costs for mature technology. To approximate the fact that initial plants cost more than mature plants, the capital and O&M costs for the initial plants were increased by 50 % (compared to those in Table 1) in the 5-year period in which they are first introduced in the scenario, 25 % in the second period, and 10 % in the third period before achieving the mature plant costs in the fourth period after commercial introduction. Thus, the technologies only achieve mature cost levels 20 years after first introduction.

2.1.2.2. Renewable energy technologies

During 2002, the Asia-Pacific Economic Cooperation (APEC) Energy Working Group on New and Renewable Energy Technologies funded a study to examine potential market penetration rates for renewable energy technologies using a consistent modeling framework [Goldstein et al., 2002]. The APEC-updated renewable energy technology characteristics were added to the China MARKAL model without deleting the previous technology characterizations. Therefore, the updated technologies compete directly with the existing conventional and renewable technologies in the model. The most significant updates included the following.

- Three new biomass technologies for electricity generation: an advanced direct-fire technology starting in 2000, co-firing with coal also starting in 2000, and an advanced gasification technology starting in 2005.
- Four PV technologies: central station (high and average sunlight) and residential (high and average sunlight) were incorporated into the model. Both were considered available for deployment starting in model year 2000.
- Two solar thermal technologies – power tower and solar dishes – were also incorporated into the model, both available starting in 2010.
- Two new wind turbine technologies (corresponding to Class 4 and Class 6 wind regimes) were incorporated into the model, starting in 2000. These were used as replacements for the local wind-farm technology in the previous China MARKAL model. The remote wind-farm technology with long-distance transmission was retained in the model, and the potential resource (320 GW) was partitioned between the three wind technologies according to data on Class 4-5 and Class 6-7 wind resources [DeLaquil and Larson, 2002].

2.1.2.3. End-use technologies

Among end-use technologies, only the transportation technologies were updated. The cost and performance of automobile technologies was updated to reflect recent estimates [Ogden et al., 2004]. This included a complete set of fuel distribution costs. Also, two new technologies were added: an advanced gasoline car was introduced to reflect potential improvements that could be introduced starting in 2005, and a liquid-fueled fuel-cell car was introduced to provide a direct demand for methanol and ethanol in this sector.

3. Energy system constraints

For this analysis we used a similar set of environmental

Table 1. Updated coal conversion and process technologies[1]

Conversion technology	Year first available	Efficiency (LHV-basis)	Installed capital cost	Fixed O&M cost	Variable O&M cost	SO_2 emission	CO_2 capture
Stand-alone electricity production		kJ_e/kJ_{fuel}	$/kW$_e$	$/kW$_e$-yr	$/kWh$_e$	g/kWh$_e$	kg/kWh$_e$
Coal, IGCC, quench	2000	0.43	1068	21.4	0.0030	0.075	0.0
Coal, IGCC, syngas cooler	2000	0.47	1213	24.3	0.0035	0.072	0.0
Coal, IGCC, quench with CO_2 capture	2005	0.37	1383	27.7	0.0039	0.087	0.737
Coal, IGCC, syngas cooler with CO_2 capture	2005	0.39	1560	31.2	0.0045	0.086	0.680
Polygeneration, electricity + co-products		kJ_e/kJ_{fuel}	$/kW$_e$	$/kW$_e$-yr	$/kWh$_e$	g/kWh$_e$	kg/kWh$_e$
Coal, H_2 & IGCC, quench	2010	0.042	8678	173.6	0.025	0.0	0.000
Coal, H_2 & IGCC, quench with CO_2 capture	2010	0.021	18406	368.1	0.053	0.0	12.99
Coal, H_2 & IGCC, syngas cooler	2010	0.062	7649	153.0	0.022	0.0	0.000
Coal, H_2 & IGCC, syngas cooler with CO_2 capture	2010	0.041	11978	239.6	0.034	0.0	6.32
Coal, IGCC, el + methanol	2005	0.31	1282	25.6	0.0037	0.0	0.0
Coal, IGCC, el + methanol with CO_2 capture	2005	0.21	1975	39.5	0.0056	0.0	0.276
Coal, IGCC, el + DME	2010	0.267	1596	31.9	0.0046	0.0	0.0
Coal, IGCC, el + DME, with CO_2 capture	2010	0.220	1960	39.2	0.0056	0.0	0.397
Production of non-electric energy carriers		kJ_e/kJ_{fuel}	$/GJ/yr	Not used	$/GJ	kg/GJ	kg/GJ
Coal – direct liquefaction	2000	0.511	22.6		2.47	0.0	0.0
Coal – direct liquefaction with CO_2 capture	2005	0.511	23.1		2.48	0.0	55.4
Coal, methanol	2000	0.58	24.69		0.99	0.0	0.0
Coal, methanol with CO_2 capture	2000	0.58	25.54		1.02	0.0	79.4
Coal, F-T liquids	2005	0.53	25.5		1.02	0.0	0.0
Coal, F-T liquids with CO_2 capture	2010	0.52	28.8		1.78	0.0	85.6
Coal, DME	2010	0.55	27.0		1.08	0.0	0.0
Coal, DME with CO_2 capture	2010	0.55	27.7		1.11	0.0	55.6

Note

1. Costs are all in 1995 US$. The performance and cost levels are for commercially mature technology (as discussed in the text). Availability factors are 0.85 for all coal technologies. The model determines the utilization, or capacity factor for any technology. Also see Note 2 to main text.

and energy security constraints as were used in the previous study: (1) limits on emissions of SO_2; (2) limits on imports of oil and natural gas; and (3) limits on emissions of CO_2 to the atmosphere. These are summarized below.

Emissions of SO_2 were used (as in previous analyses) as a general indicator of local air pollution. All scenarios in which SO_2 emissions were restricted used the same profile of reductions over time: annual emissions are capped through 2020 at levels officially targeted by the Chinese government, which plans to reduce emissions from the current level of about 24 million tonnes/year (Mt/yr) of SO_2 to 16.5 Mt/yr in 2020. For 2050, we selected an allowable level of SO_2 emission that 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. We connected the 2020 and 2050 target levels with a smooth curve, and the total allowed annual SO_2 emission reaches 10.4 Mt in 2050.

Under the oil and natural gas imports constraint, we defined oil imports as the ratio of imports of crude oil and refined oil products to total imports plus domestic crude production. Natural gas imports were defined as the ratio of imports to imports plus domestic production of natural gas and coal-bed methane (CBM). In our scenario, the oil and natural gas imports were constrained in any given year to values between 20 % and 70 %. For comparison, oil imports to China in 2000 accounted for about 30 % of oil consumption, and the United States imports about 60 % of its oil today.

The carbon emission constraint was developed from IPCC estimates [Nakicenovic et al., 2001] of cumulative global carbon emissions to the atmosphere between 1990 and 2100 that would enable stabilization of atmospheric concentrations of CO_2 at 450 ppmv (750 GtC cumulative emissions allowed globally). The share of these emissions "allocated" to China over this period was taken in proportion to its share of global population in 2000 (21.5 %). This gives a total of 161 GtC as China's "share" of the 750 GtC allowed globally. We have imposed an arbitrary, but stringent, constraint that at most 41 % of these emissions (66 GtC) can be emitted up to 2050.

In the previous study, we investigated several alternative CO_2 emission constraints, but for this study we used only the 66 GtC constraint because our general approach was to investigate the impact of the specific technology and policy scenarios using a common set of constraints. Therefore, for most of the model runs to be discussed below, the set of constraints consisted of the SO_2 constraint, a 30 % constraint on the import of oil and natural gas (abbreviated as Oil30), and the CO_2 constraint of 66 GtC cumulative between 1995 and 2050 (abbreviated as C66).

4. The technology scenarios

Before describing the specific scenarios, we would like to clarify that the intention of this work is not to predict the future, but to analyze the potential costs and benefits of the following scenarios. These scenarios can represent the results of specific policy choices (or lack of policy choices) that could be made by the Chinese government. All of these scenarios are possible, and are based on generally accepted growth rates for technologies and markets. However, only the Base case (and the Shock scenario) are likely to occur without specific policy intervention by the government. The specific technology and policy scenarios investigated were the following.

- Base. This represents a "business-as-usual" scenario. As in the earlier (Phase 2) work for CCICED, the predominant technology option for coal conversion is combustion. Unlike the earlier work, we have added the possibility of direct coal liquefaction for transportation fuel production into the base set of technologies. (China announced the go-ahead of a major direct coal liquefaction project since the Phase 2 work was completed [Williams and Larson, 2003])
- AdvTech. This represents a scenario in which there is aggressive development in China of gasification-based coal conversion to power and fuels, advanced renewable energy technologies, and capture and underground storage of CO_2 from fossil fuels.
- Delay. This represents a scenario in which China waits for gasification-based conversion technologies (for coal and biomass) to be established commercially elsewhere in the world before adopting them in China. A 20-year delay in the availability of these technologies (compared to the AdvTech scenario) is imposed for the Delay scenario.
- LowEff. This represents a scenario in which the development of new energy supply options (such as coal gasification) are not matched in aggressiveness by development of end-use energy efficiency improvements. In the LowEff scenario, the aggressive energy efficiency goals built into our reference end-use energy demand scenario are not achieved.
- HiTrans. This scenario takes a focused look at the transportation sector, in particular the impacts that high growth in personal automobile use would have on the entire energy system.
- Shock. This scenario represents a situation in which world events lead to an unexpected doubling of the world oil price for a limited period during the first quarter of the century, disrupting the continuous modestly rising oil price trajectory characterizing all of the other scenarios.

4.1. Base technology scenarios

The Base technology case results for the updated model are generally similar to the Base case results for the previous study except that total primary energy use in 2050 is increased (from 115 EJ to 130 EJ) with over half of the increase resulting from the increase in transportation energy (12 EJ to 20 EJ), which is mostly supplied by imported oil. Thus, the various updates made to energy service demand did not result in any significant change in aggregate primary energy requirement.

The Base case results do not change with the addition of the direct coal liquids (DCL) technology to the Base technology set as the model can more cheaply import oil (and there are no constraints in this case on the amount of oil imported). When the SO_2 constraint is applied, the DCL technologies are moderately selected. The primary reductions in SO_2 emissions come from the electric sector and from the use of coal gas to replace direct coal combustion in the industrial and residential sectors.

The Base case cannot achieve import proportions of oil and gas lower than 70 %, even with DCL technologies included. Lower levels of the oil and gas import constraint cannot be achieved because of assumed emission-related limitations on mixing the DCL-derived fuels (primarily gasoline and diesel) with regular petroleum-derived fuels[2].

When the CO_2 constraint is imposed, the Base case does not select the DCL technology because carbon emissions are far higher with DCL fuels than with petroleum fuels [Williams and Larson, 2003]. The CO_2 constraint (in combination with the SO_2 constraint) is achieved by a massive build-up of nuclear power. Even with the large nuclear build-up, the CO_2 constraint cannot be achieved at oil and gas import levels below 80 %.

In summary, the Base Technology scenario, even with the inclusion of the DCL technology, is unable to simultaneously satisfy the SO_2 and CO_2 constraints while also limiting the oil and gas import proportion to less than 80 %.

4.2. Advanced technology scenarios

The results of the Advanced Technology scenario (AdvTech) in the updated model show similar trends as in the previous model. However, several of the renewable energy technologies (primarily biomass and wind) newly introduced into the model result in more significant utilization of biomass and wind, the exact mix of additional renewable energy technologies changes depending upon the scenario, particularly in the biomass area. In the unconstrained cases, the model selects co-firing of biomass with coal, which is relatively low in cost. However, when the SO_2 constraint is imposed, the use of biomass shifts to village-scale biomass gasification CHP and the co-production of electricity and DME.

A comparison of the Base case results (with no constraints) and the AdvTech case (with all constraints) is instructive. Figure 3 highlights the result that advanced technologies can control oil and gas imports. In the Base case oil imports rise to 576 Mt/yr in 2050, while in the

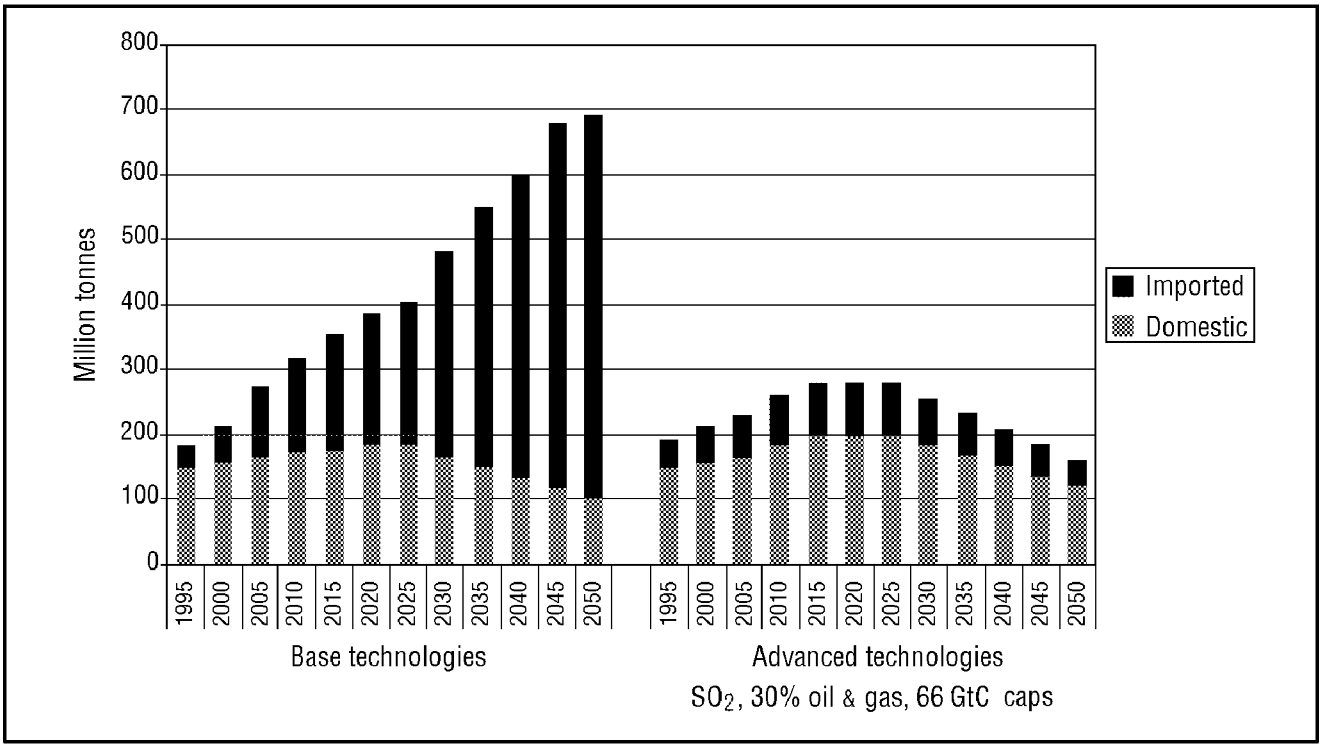

Figure 3. Base and AdvTech scenario oil consumption

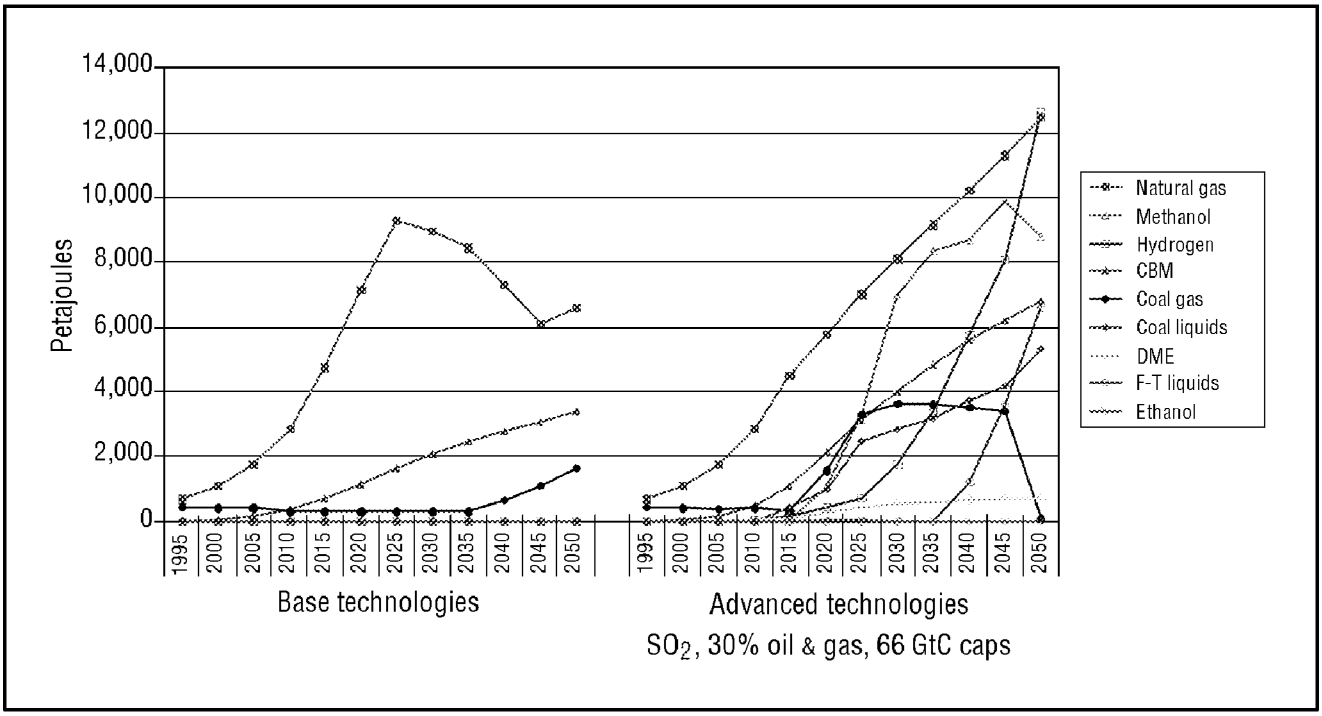

Figure 4. Base and AdvTech scenario gas and synthetic fuel use

AdvTech case oil imports peak at about 80 Mt/yr in 2025. Fuel demand in the transportation sector drives the Base case oil demand. In the AdvTech case, several coal-based liquid fuel options are available.

Figure 4 compares the distribution of gaseous and liquid energy carriers. In the Base case, natural gas is dominant and only coal-bed methane (CBM) makes a significant contribution. Coal gas use generally remains at present levels, and rises only towards the end of the analysis period. Natural gas use peaks and declines partly because of the growth in production of coal-bed methane but also because of unconstrained oil imports, which over time become progressively cheaper than natural gas.

In the AdvTech scenario oil consumption is replaced by methanol, F-T liquids and hydrogen, all of which become significant transportation energy carriers. The use of direct coal liquids in the transportation sector grows rapidly between 2015 and 2025, but grows more slowly after 2030, when gasification-based coal liquids become available. Methanol, hydrogen and F-T liquids are pro-

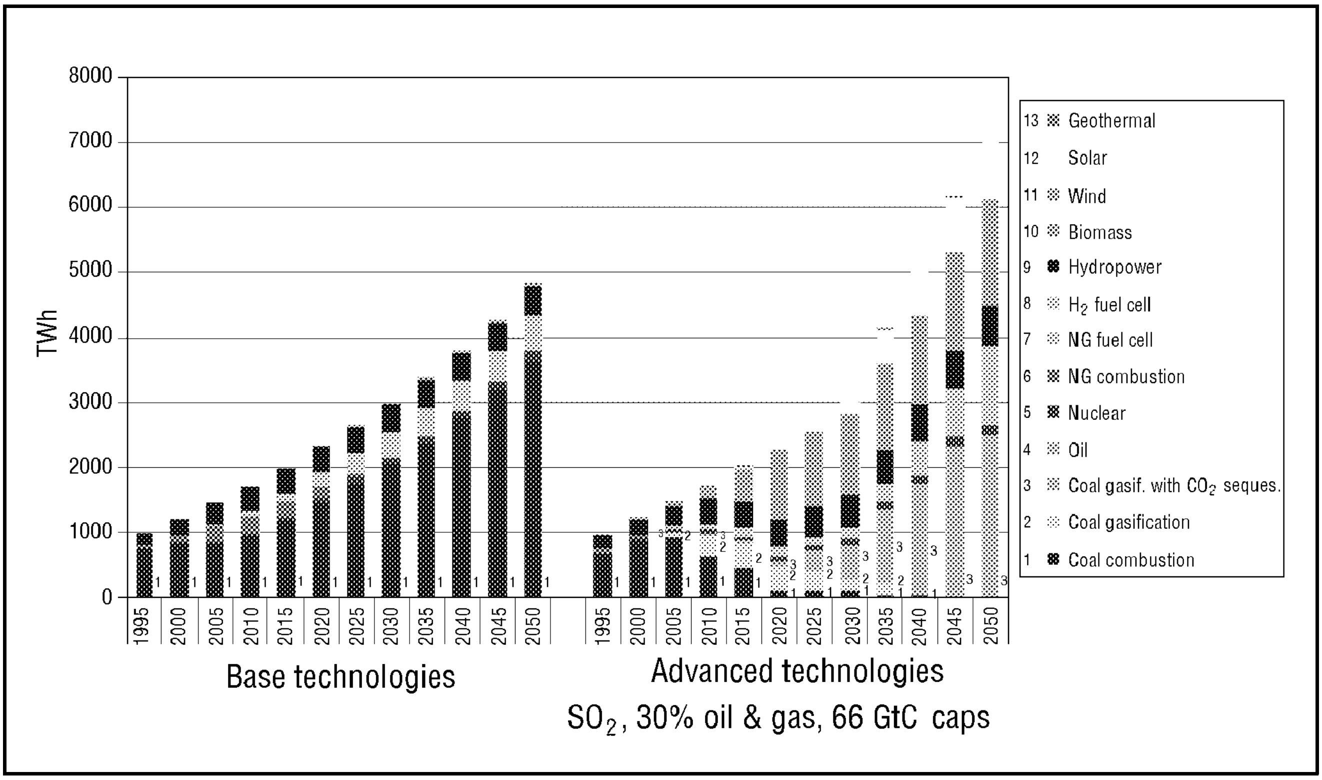

Figure 5. Base and AdvTech scenario electricity production

duced from coal gasification technology with CO_2 sequestration. Coal gas is used primarily to reduce SO_2 emissions in the industrial and residential sectors, and DME is produced from biomass to supply residential heating and cooking demands.

Figure 5 shows that electricity production in the Base case is dominated by coal combustion, while in the AdvTech case, coal combustion is replaced over time by coal gasification and CO_2 sequestration. Only hydro and wind power make renewable electricity contributions to the Base case, but in the AdvTech scenario, biomass and wind power plants make significant contributions, and solar power makes a noticeable contribution in the second half of the analysis period. The total electricity production increases significantly in the AdvTech case because of electrification of end-use demand, especially in the commercial and residential sectors, which offsets direct fuel use and contributes to achieving the CO_2 constraint. The model tends to select the solar power tower technology up to the amount allowed by the resource upper bound. This result has to be viewed in relation to the lack of any organized solar thermal technology development effort in China today. The potential contribution of the solar thermal technologies indicates that a technology development program may be warranted.

Figure 6 shows the development of primary energy supply. Both the Base and AdvTech scenarios use the energy conservation technologies (labeled Efficiency), which indicates their cost-effectiveness. However, the AdvTech scenario shows a very clear investment trend away from coal combustion and towards coal gasification. This trend starts in 2005 and accelerates rapidly after 2020. Interestingly, during the 2005-2020 period the AdvTech scenario invests most in natural gas and renewable energy, which slows coal use slightly.

To test whether the rapid growth in coal gasification after 2020 is due to the high initial implementation cost for gasification technologies or to the costs of gasification relative to renewables and natural gas, we ran a scenario with mature plant costs for the gasification technologies available at the start of implementation. The development pathway selected in that scenario was essentially unchanged from the original AdvTech scenario, indicating that the early investments in natural gas and renewables are more cost-effective and that the slower growth pattern for gasification technologies yields a lower cumulative discounted total energy system cost. This AdvTech scenario result appears to indicate that the 2020 time period is when rapid reductions in CO_2 emissions must begin in order to meet the carbon constraint at least cost.

Fortuitously, this result is consistent with the technological complexity of coal gasification and with carbon capture and storage, which has a relatively long development time, especially compared to most renewable technologies. Although the AdvTech scenario invests more in hydropower, biomass and wind plants between 2005 and 2020 than in coal gasification, the installed coal gasification capacity in 2020 reaches about 50 GW, which clearly represents a significant investment. In the real world this is probably the needed time to develop an industry that is sufficiently robust to deliver 7 to 10 GW of new capacity annually after 2020.

Figure 7 shows CO_2 emission profiles for the Base and AdvTech scenarios in units of elemental carbon. In the Base case, carbon emissions rise from under 1 Gt/yr in 1995 to about 2.4 Gt/yr in 2050, resulting in cumulative

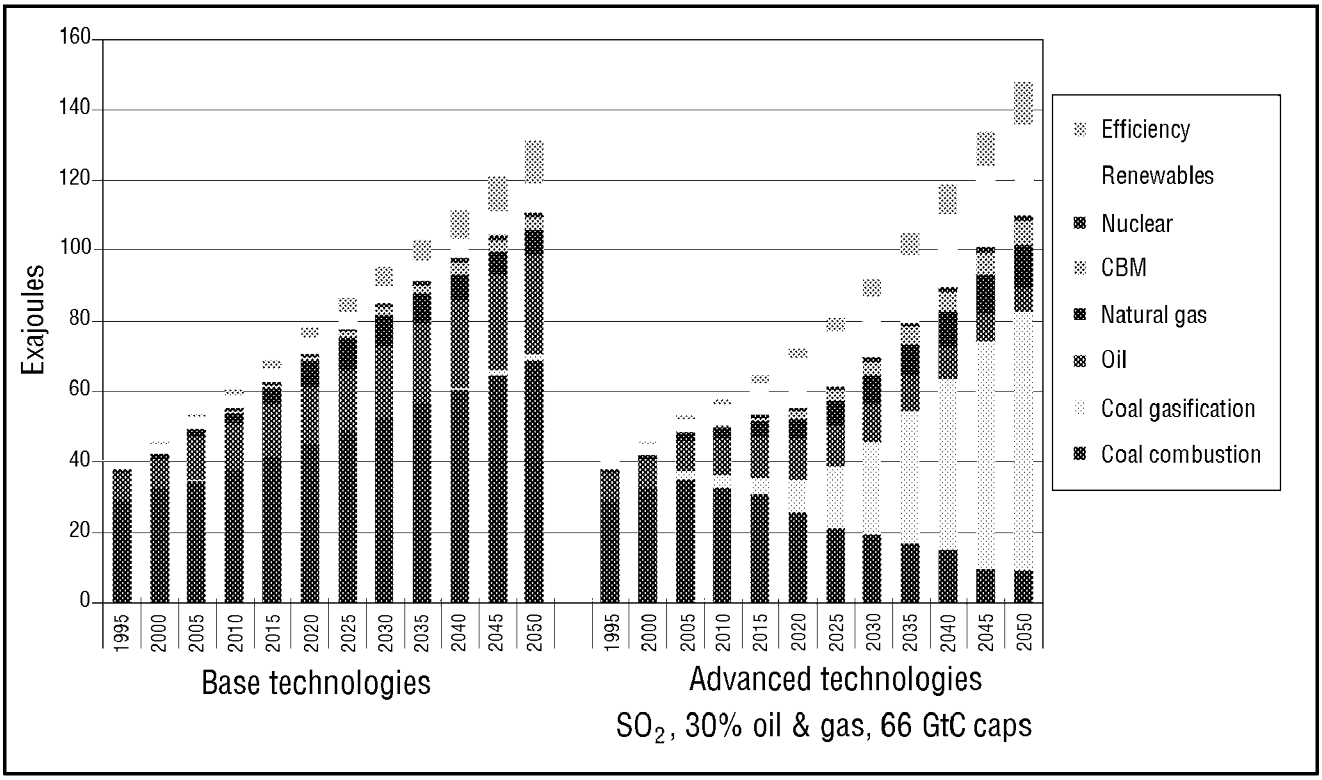

Figure 6. Base and AdvTech scenario primary energy supply

emissions of 98 GtC over this period. In the AdvTech case, carbon emissions rise to about 1.2 Gt/yr (in 2030) and stay relatively constant to achieve the cumulative target of 66 GtC for the modeling period. The largest reductions in CO_2 emissions come from electricity generation through the use of renewables and coal gasification with CO_2 sequestration. Additional reductions come through fuel-switching in the industrial, commercial and residential sectors. Initially, a large portion of the sequestered CO_2 is used for enhanced resource recovery (ERR) of methane from deep unminable coal beds (CBM), but starting in about 2030 sequestration without resource recovery begins, and by 2050 the total amount of CO_2 sequestration is almost 1.3 Gt/yr with only 10 % for ERR. By 2050, more CO_2 is being sequestered than is being emitted.

The impact on the above AdvTech case results of different import constraints for coal and natural gas were explored through additional sensitivity studies. First, imports of coal, which are normally allowed at a 20 % cost premium above domestic coal, were not allowed. Then, two other oil and gas constraints (50 % and 20 %) were run. The resulting costs for imported energy are plotted in Figure 8 along with the import energy cost for the Base case.

Interestingly, coal imports are only needed in the baseline AdvTech case in the last decade of the modeling period. When coal imports are not allowed, significant investments in nuclear power are needed in that period to meet electricity demand.

The reduction in imported energy cost from the Base case (US$ 140 billion per year in 2050) to the AdvTech case with SO_2, Oil30 and C66 constraints (US$ 60 billion per year in 2050) is dramatic. Even if 50 % imports of oil and gas were allowed, the import energy cost would be only US$ 100 billion per year. Even in this case, the cost of energy imports is always less than 1 % of GDP. Of course, the concern over energy imports relates more to security of supply than to energy cost because the impact on the total economy of a disruption in supply could be enormous.

The more stringent case of Oil20 is possible, and energy import costs would be reduced to only US$ 20 billion, but other aspects of the energy system cost increase to offset this reduction, so that the net saving in total discounted energy system cost compared to the Oil30 case is only half the saving in energy import costs.

4.3. Impacts of delaying coal and biomass advanced technologies

In the AdvTech scenarios, coal and biomass advanced gasification technologies for polygeneration and fuel production technologies generally become available for implementation starting in either 2005 or 2010. In the Delay scenarios, the start date for these technologies was postponed by 20 years, but the technologies become available at their mature costs. In addition, introduction of fuel-cell vehicles was delayed by 20 years. The start date for the direct coal liquid technology was not delayed because we wanted to explore whether this technology could substitute for the advanced gasification technologies. The SO_2, energy security and CO_2 constraints for the Delay scenarios remained unchanged from those in the AdvTech scenario.

The impact of the Delay scenario on overall primary energy use can be seen in Figure 9. Relative to the AdvTech scenario (without any delay imposed), total coal consumption does not change, but it is shifted from coal

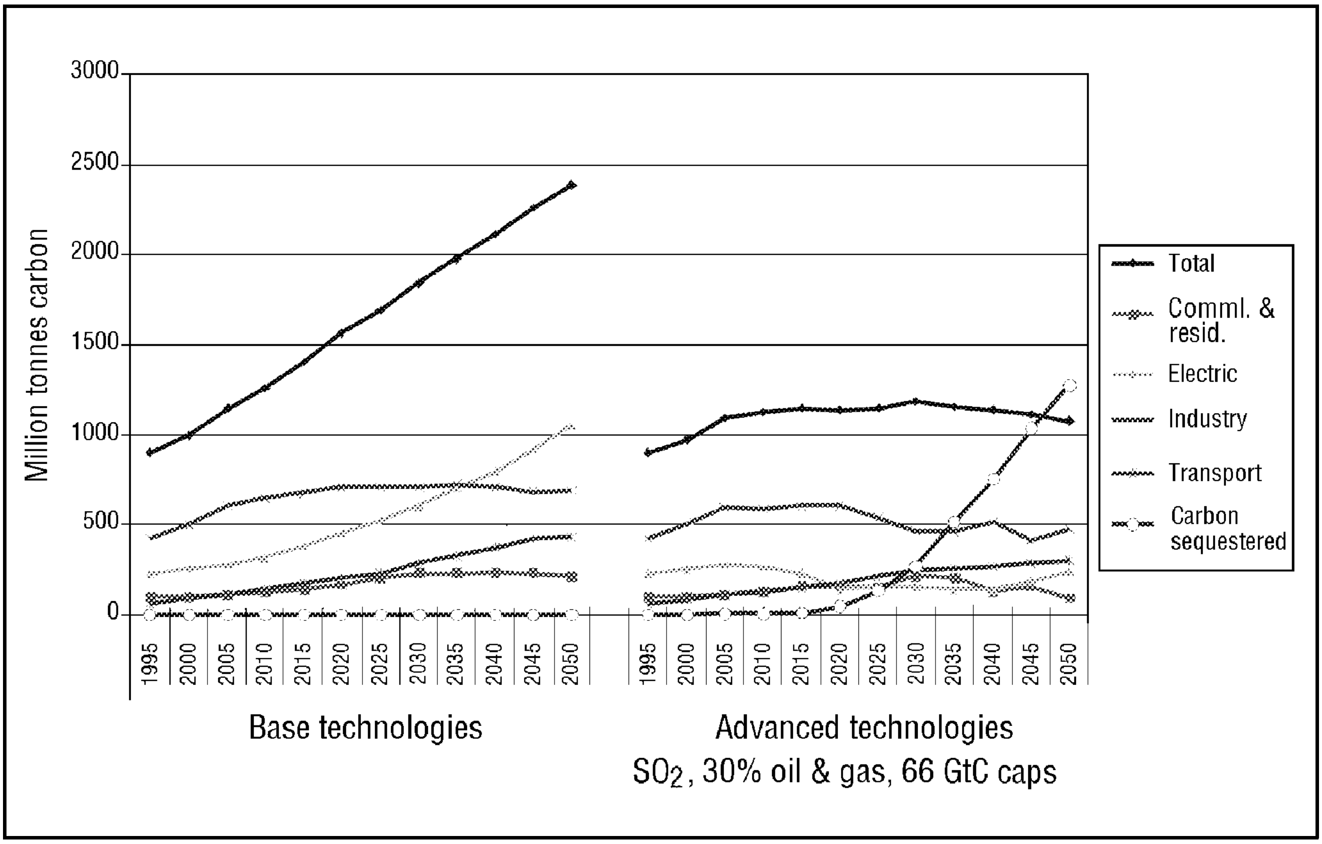

Figure 7. Base and AdvTech scenario carbon emissions

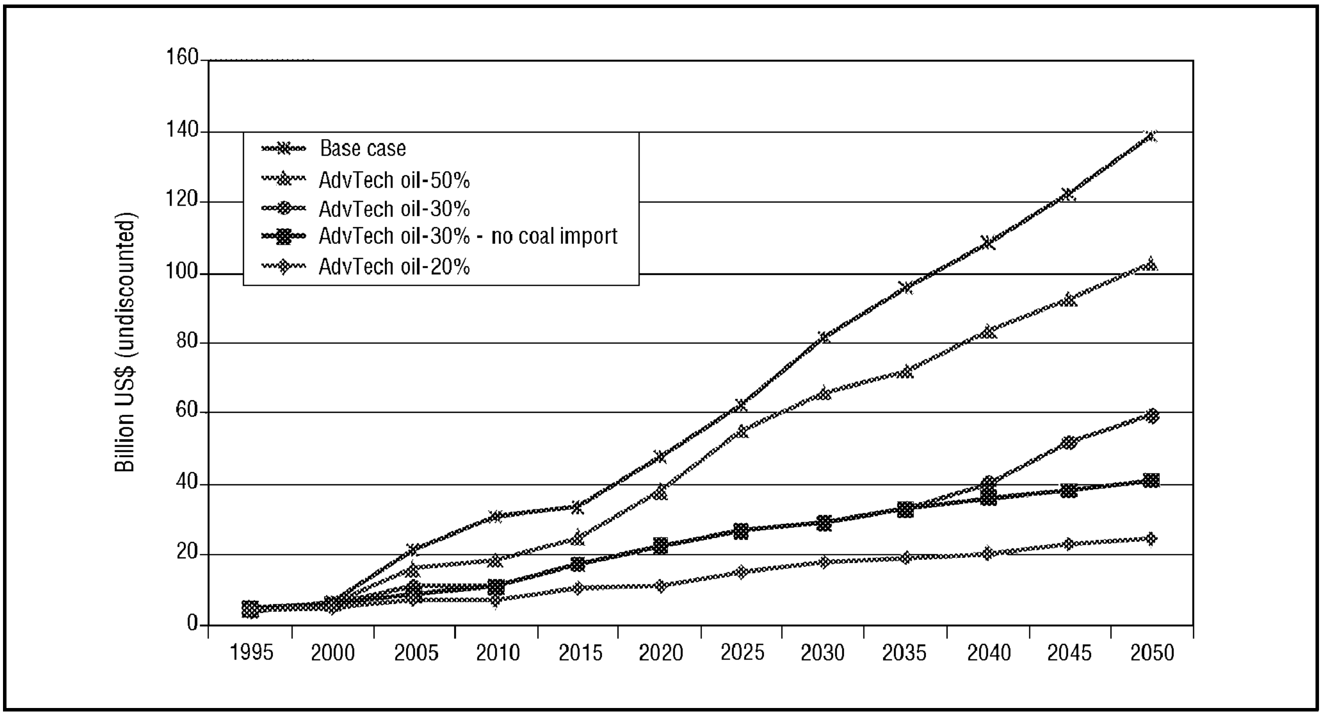

Figure 8. Projected cost of energy imports

gasification to coal combustion technologies. Nuclear power use grows significantly to compensate for this shift to less efficient coal utilization. Renewable energy use also increases (most significantly for solar energy after 2020) because of greater electrification in the commercial and residential sectors.

The Delay scenario also shows significant changes in the mix of energy carriers. Delay increases the use of coal gas, which declines after 2030 in the AdvTech scenario because of the transition to DME, hydrogen and FT liquids, and significantly reduces the use of methanol. The model selects hydrogen to be a dominant energy carrier, initially made from natural gas and then from coal after 2030. The use of direct coal liquids does not change from

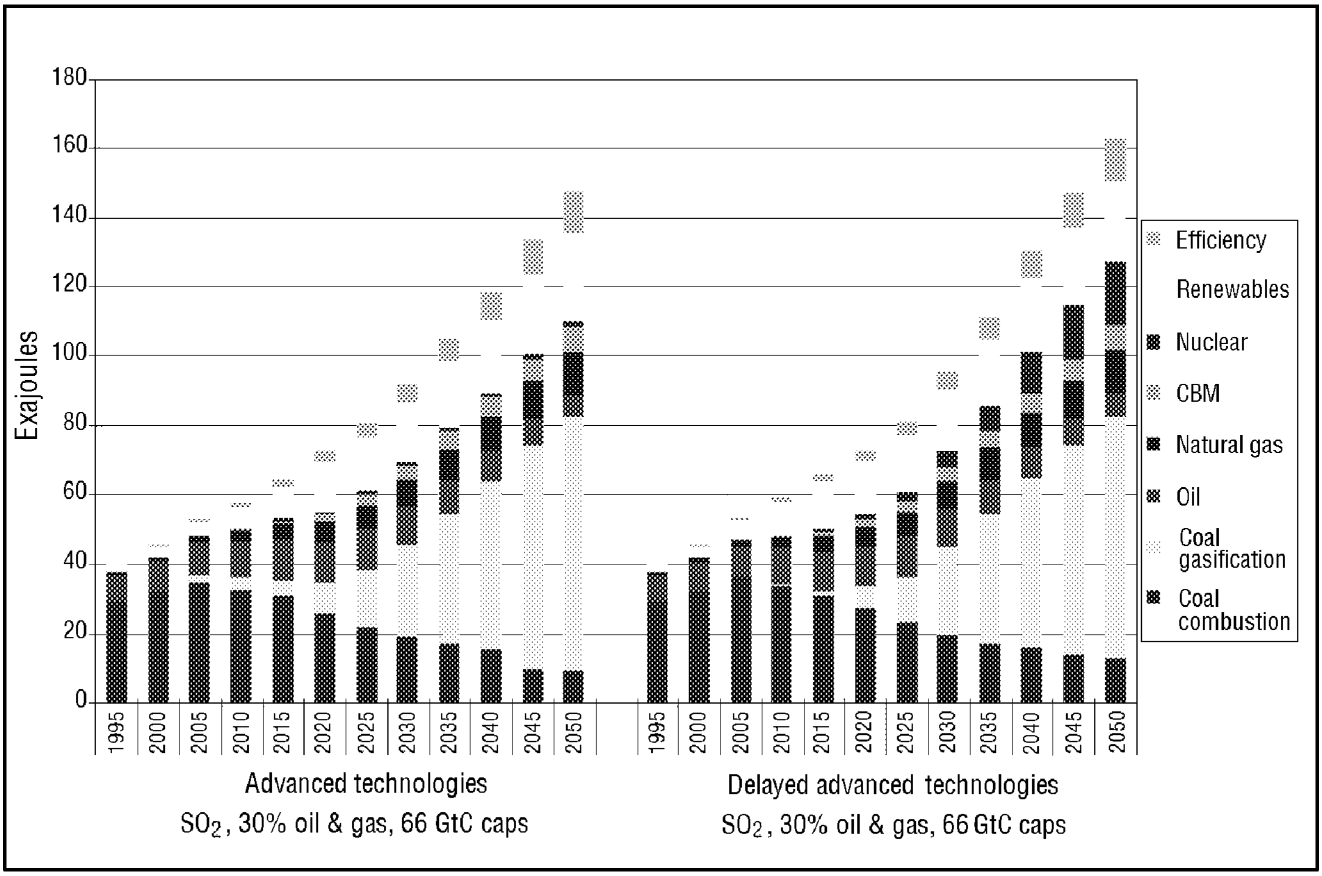

Figure 9. AdvTech and Delay scenario primary energy supply

the AdvTech scenario, indicating that there is little room for growth because of the emission-based limitation of mixing these fuels with conventional transportation fuels.

As can be seen in Figure 10, the Delay scenario results in a requirement for significant increases in the use of nuclear power and hydrogen fuel cells for electricity production after 2020. The use of these technologies is limited by growth rate caps specified as external inputs. The growth in solar electricity generation is entirely in photovoltaic technology used for distributed grid applications.

Very interestingly, the Delay scenario invests early (between 2005 and 2015) primarily in biomass co-firing with coal because neither coal nor biomass gasification technologies are available. As a result, the biomass polygeneration technology for electricity and DME production, which is selected in the AdvTech scenario during this same time-period, never materializes in the Delay scenario. In the 2020 to 2030 time period, the Delay scenario chooses to invest in the production of ethanol for transportation fuel and so when the biomass polygeneration technology eventually becomes available, the biomass resource has already been committed, and, as a result, biomass is phased out of electricity generation when the co-firing plants retire.

4.4. Impacts of low end-use efficiency

In the low energy-efficiency demand scenario, several changes were made to both the level of energy service demand and the mix of end-use technologies. Specifically, the super high-efficiency technologies for the industrial sector were deleted along with all the energy conservation technologies (such as those for high-performance building envelopes) and low energy-use appliances. In addition, the energy intensity projections (energy use per unit GDP) for the commercial, residential, and agricultural sectors were increased by about 20 %. This scenario represents one in which the aggressive energy efficiency goals built into our reference end-use energy demand scenario are not achieved. Instead all the development emphasis is placed on supply-side options.

The low efficiency (LowEff) scenario significantly stresses the entire energy system. The first result is that the 30 % oil and gas import constraint (Oil30) cannot be met even with the advanced technologies. Both the elimination of energy conservation technologies and the higher energy demand result in the requirement for a significant increase in the use of renewable energy and nuclear power (unless massive amounts of coal imports are allowed). Domestic fossil fuel production is at the resource limits and the nuclear and renewable energy technologies are constrained by their growth caps. Therefore, oil imports must increase to 40 %. Figure 11 compares the AdvTech case with the SO_2, Oil30 and C66 constraints to the LowEff case with SO_2, Oil40 and C66 constraints.

Coal gas, hydrogen and methanol continue to be the dominant synthetic energy carriers in the LowEff scenario, and electricity demand grows significantly as more electrification takes place in the commercial and residential sectors. As shown in Figure 12, electricity production from coal combustion gives way early in the century to gasification, but then returns in the form of coal combus-

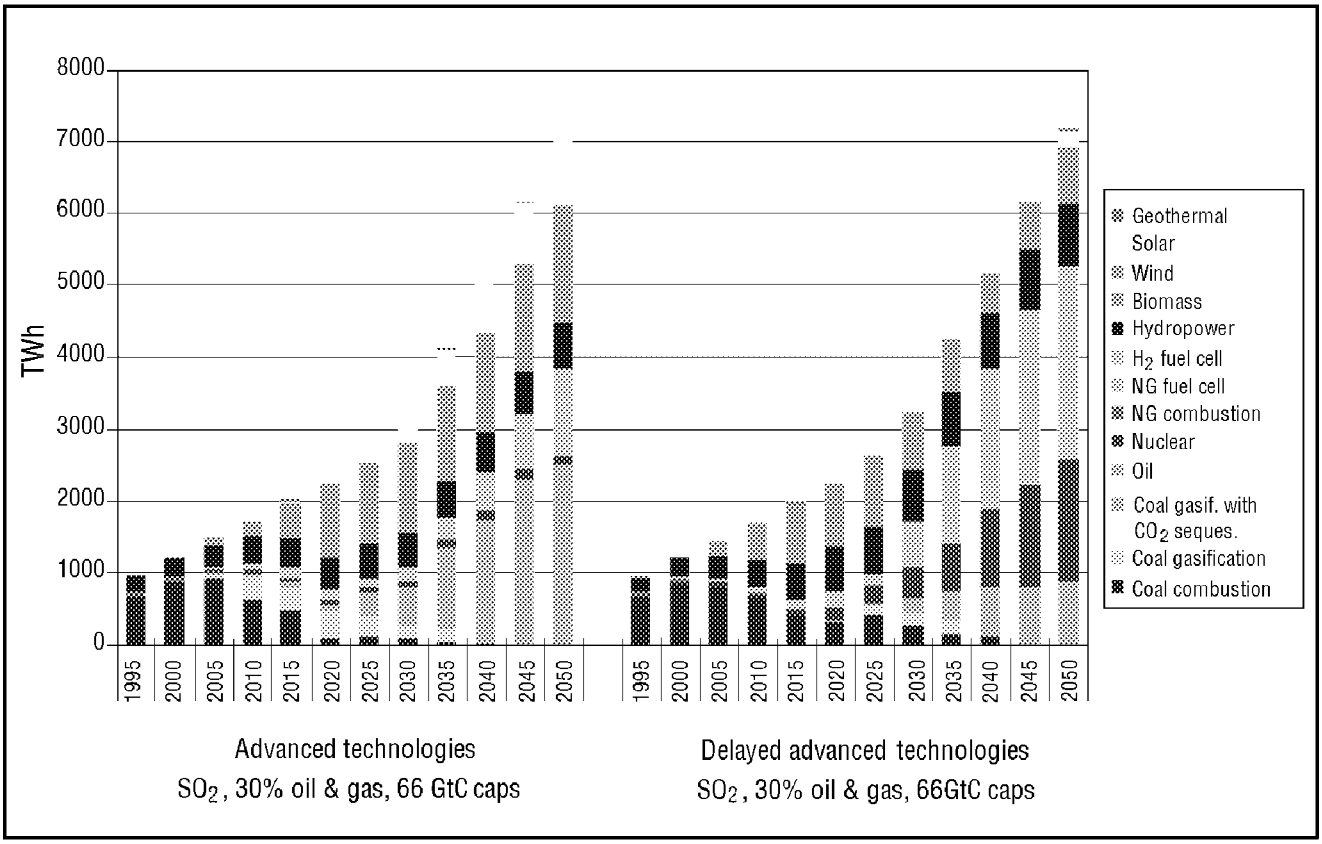

Figure 10. AdvTech and Delay scenario electricity production

tion cogeneration plants needed to supply the greater heating demand in the commercial and residential sectors. Hydrogen fuel cells also show a pattern of growth and decline, as the competing demands for coal shift from hydrogen production to cogeneration. Increased use of renewables and nuclear power compensates for the added CO_2 emissions from the coal cogeneration plants and supplies the increased electrification of the commercial and residential sectors. Most of the added growth in renewable energy comes from solar PV technology, as the other technologies have reached their resource or growth rate caps. We were surprised that a relatively modest increase in energy demand resulted in such a major impact on the energy system.

4.5. Impacts of an oil price shock

The shape of a future, crisis-induced oil price shock was modeled on the basis of similar scenarios that have been generated by the US DOE and others [Patterson et al., 2000]. In the Shock scenario, prices for crude oil, refined oil products and natural gas were increased to twice their baseline price for 2 periods (10 years) followed by one period at 1.5 times the baseline before returning to the baseline. This is illustrated for crude oil prices in Figure 13. The Shock scenario[3] showed little change in technology choices, but major impacts on cost. This highlights the fact that emission and energy security constraints (not system cost, *per se)* are driving the technology choices in the model.

4.6. Impacts of high personal transport demand

The current, very rapid growth of personal transportation modes in China makes projections of future transportation demand difficult. Recognizing this, we have included a high personal transport (HiTrans) scenario in our analysis utilizing the high projection of personal automobile transport demand shown in Figure 2. In addition, road freight transport demand was also increased, and the bus and rail (passenger and freight) projections were decreased. With the Base technologies, the HiTrans scenario can achieve the SO_2 constraint, but the imports of oil and gas cannot be reduced to levels below 70 %, and the 66 GtC constraint cannot be achieved at all. With the Advanced technologies, the HiTrans scenario can achieve the SO_2, 30 % oil and gas imports, and 66GtC constraints. The changes to the energy system are very similar to those seen with the LowEff scenario, in that significant contributions from solar and nuclear power for the electric sector are needed to allow enough coal to be converted to synthetic transportation fuels.

5. Energy system cost implications of the different scenarios

Figure 14 shows the change in total cumulative discounted system cost for a variety of scenarios relative to the Base case. What is striking from this chart is that the AdvTech case with no constraints is 2 % cheaper than the Base case. This result is in contrast to results from the previous analysis for CCICED, which showed the AdvTech case was slightly more expensive than the Base. The reason for the change appears to be the much higher transportation fuel requirement in the updated demand projection. The current AdvTech case has higher investment costs compared to the Base case, but that cost is offset by sig-

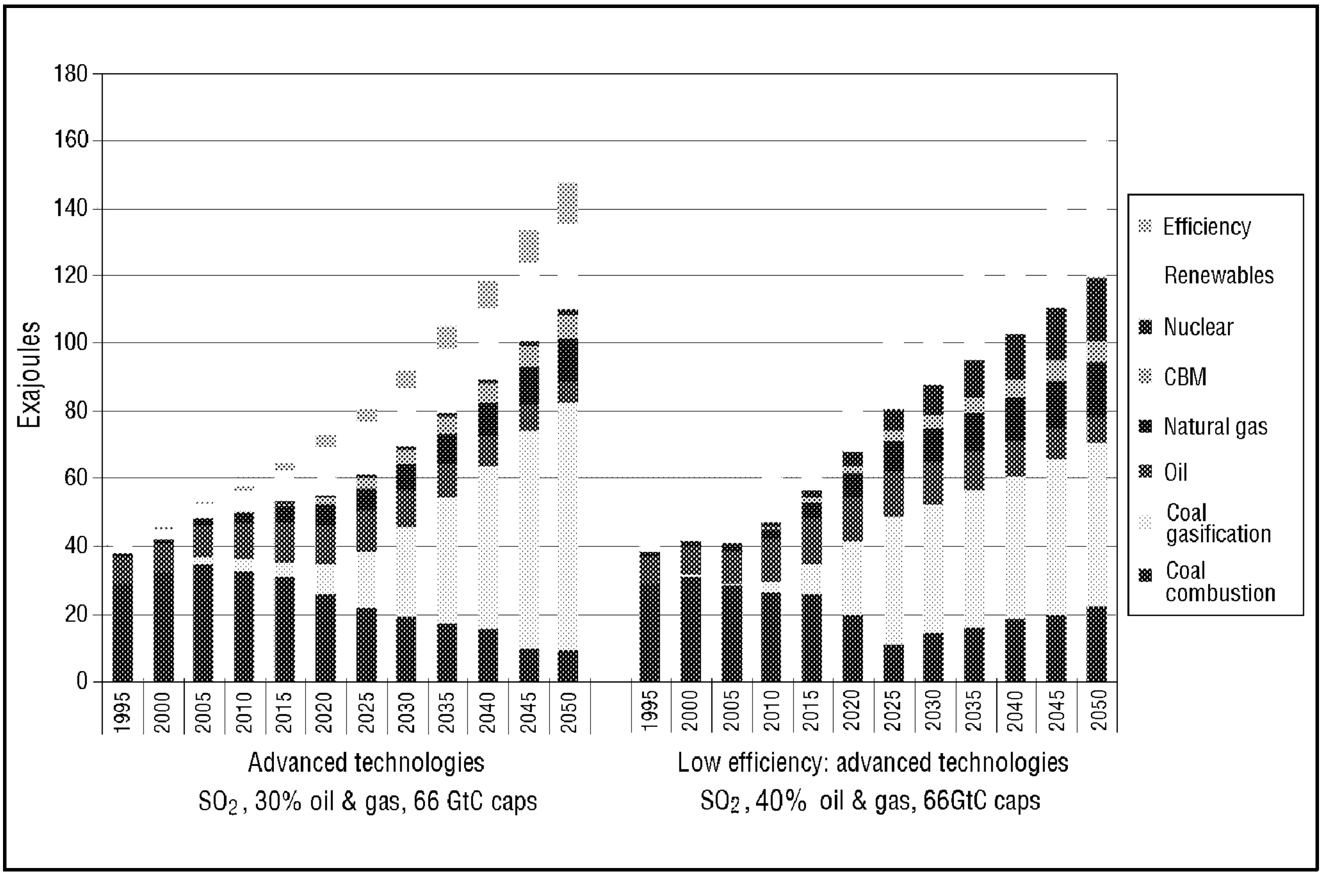

Figure 11. AdvTech and LowEff scenario primary energy supply

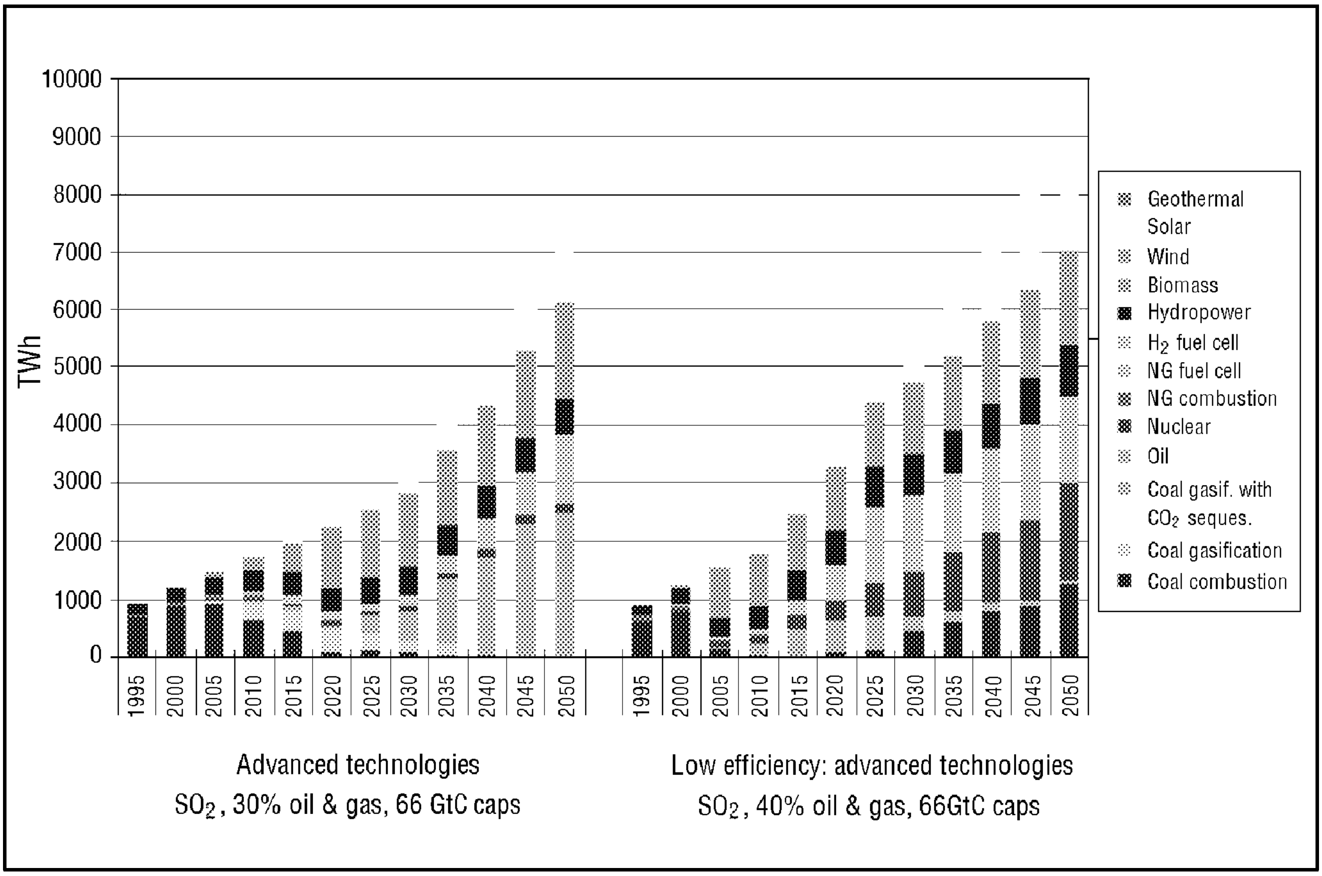

Figure 12. AdvTech and LowEff scenario electricity production

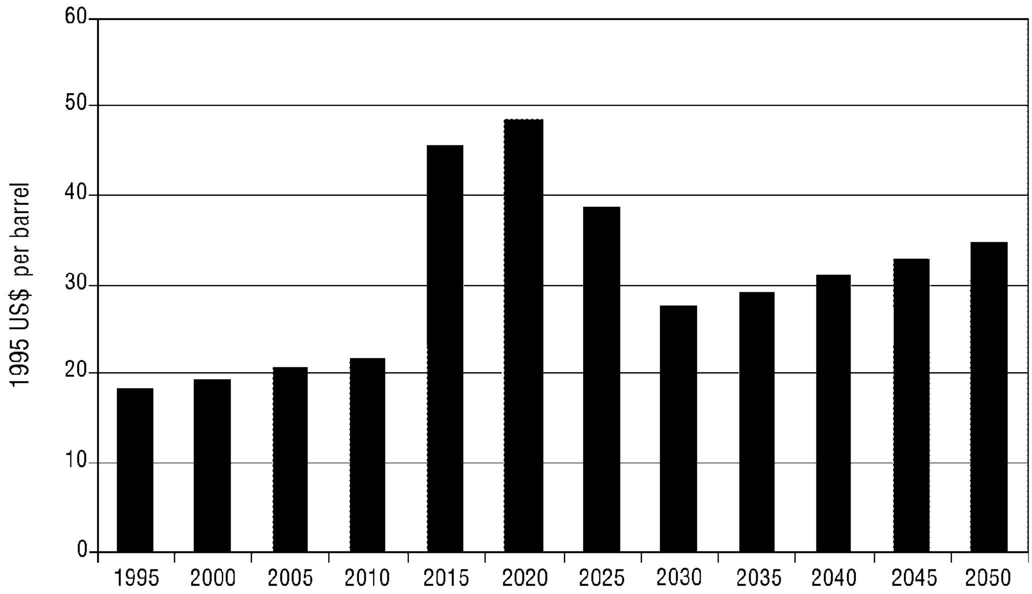

Figure 13. Oil prices for the Shock scenario

nificantly lower fuel costs – especially imported fuel costs.

Interestingly, the AdvTech scenarios can achieve the emission and energy security constraints (AdvTech-SO_2-Oil30-C66) for a lower cost than only achieving the SO_2 constraint in the Base scenario (Base-SO_2). However, even with the advanced technologies, the LowEff scenario (AdvTech-LowEff-SO_2-Oil40-C66) has a dramatically higher cost (along with reduced energy security – the lowest level of imports achievable is 40 %). In the HiTrans scenario (AdvTech-HiTrans-SO_2-Oil30-C66), the advanced technologies can meet the 30 % limit on oil and gas imports, but with a relatively high cost penalty.

In addition to total system costs, we have also examined the added costs to achieve emission reductions with various scenarios. We calculated the average cost of SO_2 reductions as the change in the total discounted system cost (compared to the Base case) divided by the change in SO_2 emissions relative to the Base case (in which no SO_2 constraint was imposed). This average SO_2 reduction cost provides an overall indicator of the effectiveness of energy system expenditures to reduce SO_2 emissions. Figure 15 shows that for various Base technology scenarios the average cost of SO_2 removal starts at almost \$ 70/t and is doubled by the oil price shock. The AdvTech scenarios reduce SO_2 removal cost to about \$ 18/t and \$ 70/t respectively. In the LowEff and HiTrans scenarios, the average cost of SO_2 removal increases dramatically. Note that in all the scenarios used for these results, there are no oil and gas import or CO_2 constraints.

In those scenarios where the SO_2 constraint is already imposed, we calculated the average cost of CO_2 removal as the change in the total discounted system cost divided by the change in CO_2 emissions, both relative to the Base case. As shown in Figure 16, the average cost of CO_2 removal in the AdvTech scenario (AdvTech-SO_2-Oil30-C66) is less than half the cost in the Base scenario (\$ 2.5/t versus \$ 6/t), and the AdvTech scenario limits oil and gas imports to 30 %, whereas the Base scenario cannot achieve an oil and gas import constraint of less than 80 %.

The Delay scenario (Delay-SO_2-Oil30-C66) increases the cost of CO_2 removal by 3 times relative to the AdvTech scenario, and the LowEff and HiTrans scenarios increase the cost of CO_2 removal by a factor of over 10. The impact of the oil price shock generally adds \$ 4/t to \$ 10/t to the cost of CO_2 removal for the AdvTech scenarios.

6. Conclusions

The analyses that we have performed with the China MARKAL model show that the AdvTech strategy can meet all of China's targets for economic development, clean air, energy security and greenhouse gas emission mitigation. The direct coal liquid technology does contribute to these goals, but its contribution is limited because of the emission-related mixing requirements for transportation fuels and the limited ability of DCL fuels to substitute for residential cooking and heating fuels.

The analysis also shows that the Base strategies cannot limit oil and gas imports to levels below 70 %, even with contributions from DCL fuels. The Base strategy can meet the SO_2 and CO_2 emission constraints, but at higher cost than the AdvTech strategy and only with a significant build-up of nuclear power and an increase in the energy system cost.

The AdvTech strategy achieves SO_2 and energy security constraints with only a small (1 %) cost increase over the Base case, and the cost to sequester carbon for climate change mitigation benefits is an additional 1 % increase in the discounted energy system cost case. The primary technology shift to coal polygeneration technologies is made in order to meet the oil and gas import constraint,

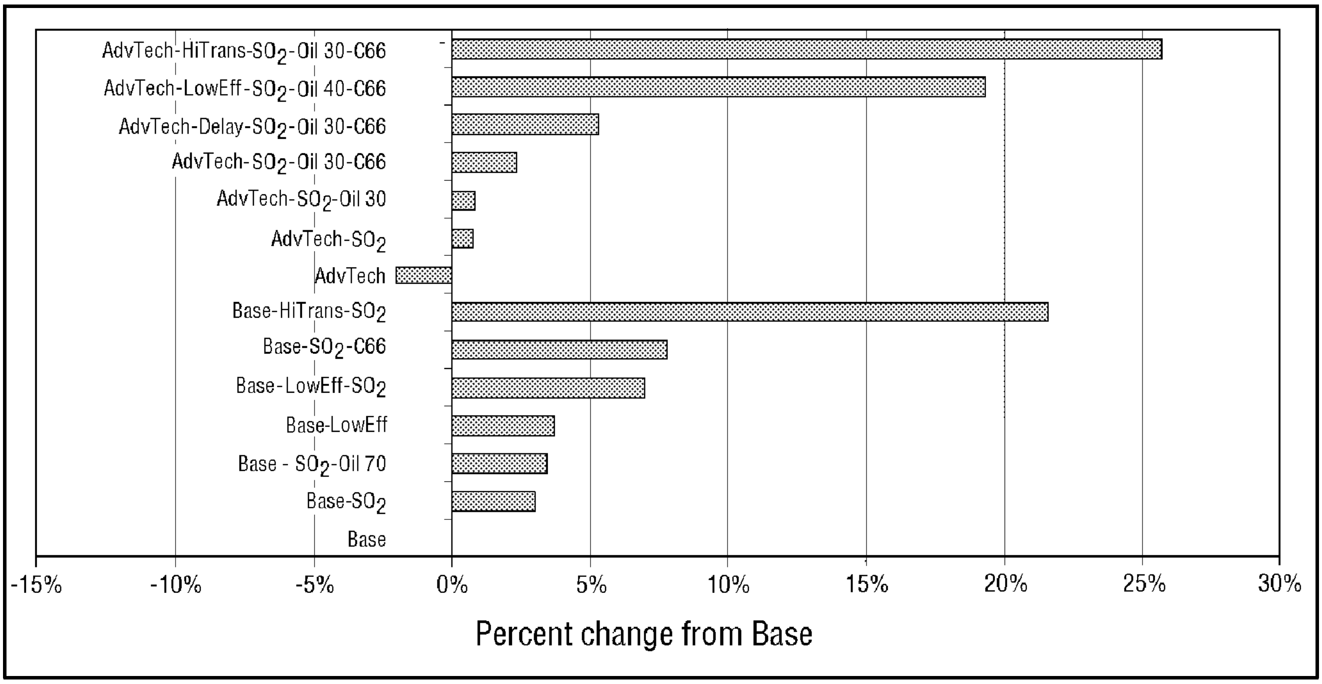

Figure 14. Cost of energy system scenarios relative to the Base case

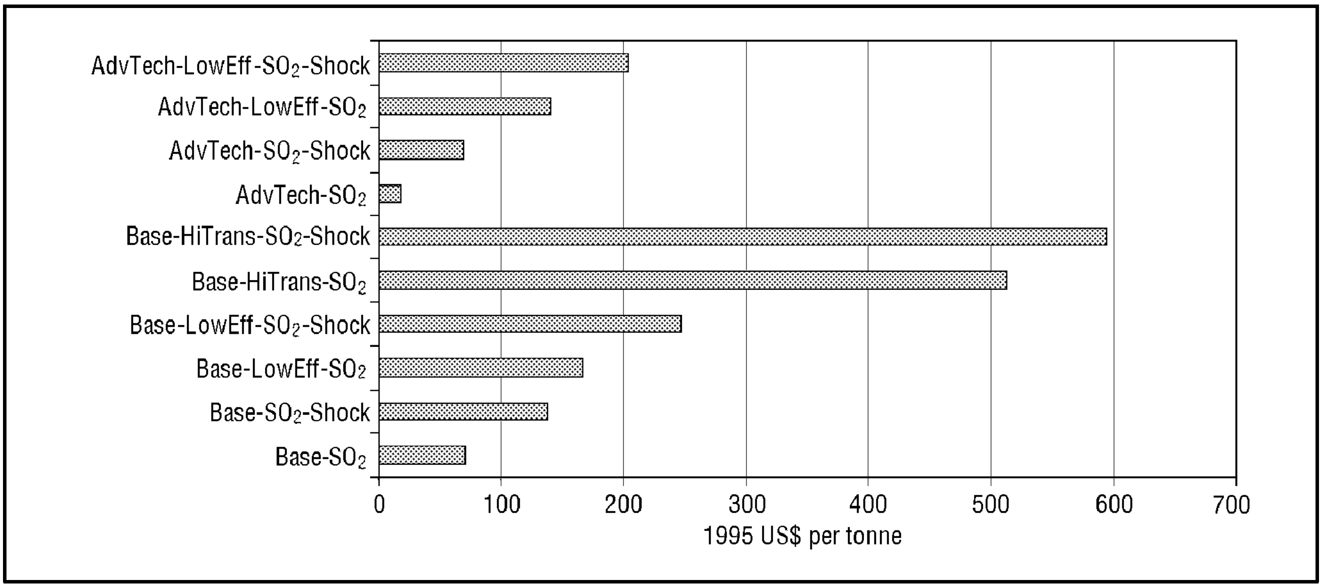

Figure 15. Average cost of reducing SO_2 emissions

and the incremental cost for meeting the CO_2 constraint is due largely to a shift to coal gasification-based technologies with CO_2 sequestration.

The Delay scenario results in a 5 % increase in the system cost needed to meet the emission and energy security goals. This is modest, but Herculean efforts would be required to introduce and build up the coal and biomass gasification technologies starting in the 2030s. The impacts of the Delay scenario are relatively modest because of the following factors.

- Domestic production of oil is not projected to begin declining until 2025, and the oil and gas constraint only begins to force energy carrier technology changes at that time.
- The model finds it more cost-effective to invest in natural gas and renewable energy technologies in the 2005 to 2025 time-period in order to reduce CO_2 emissions.
- The model invests in coal gasification technologies with carbon capture and sequestration from 2030 to 2050 to produce clean liquid fuels both to substitute for oil and gas and to continue reducing CO_2 emissions.

Aggressive technology growth rates (20 %/yr initially, falling to 5 %/yr) allow the coal gasification technologies to be rapidly introduced starting in 2025. However, these are large, capital-intensive technologies, which are not yet commercially ready. It is much more likely that the aggressive growth rates can be realized in practice if commercialization activities begin now.

The LowEff and HiTrans scenarios dramatically increase energy system costs, but the most dramatic impact

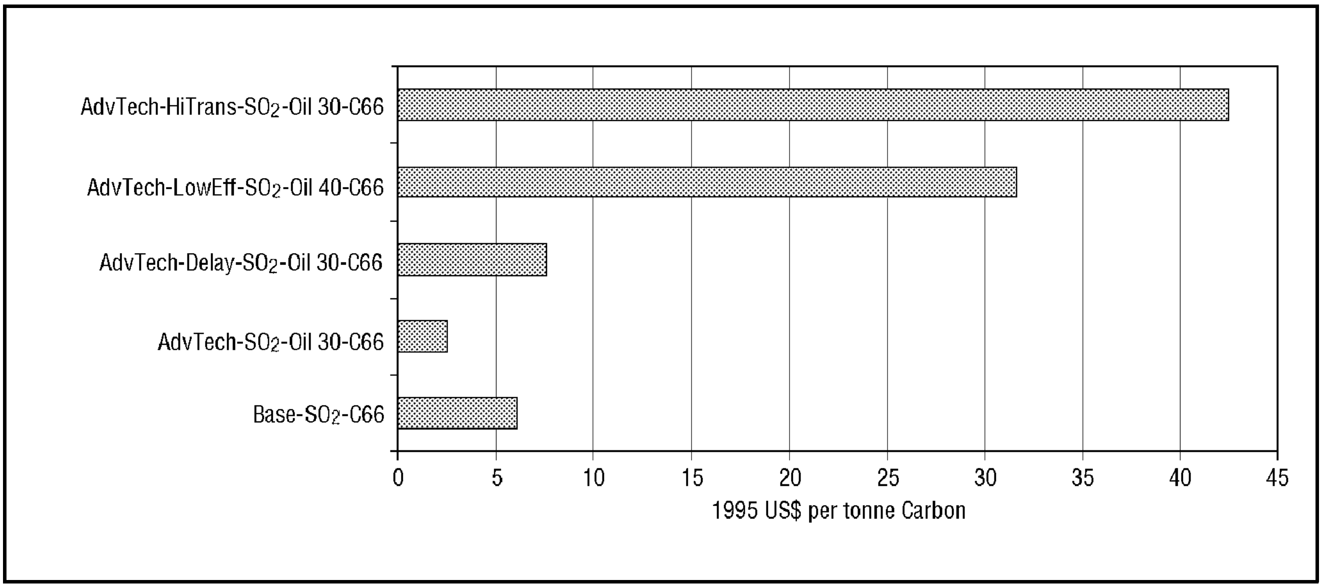

Figure 16. Average cost of reducing CO_2 emissions

of these scenarios is that the energy security targets are impossible to meet with the Base technologies, and much more difficult and costly to meet with the Advanced technologies.

The following conclusions can be drawn from these analysis results.

- The Advanced Technology strategy based on coal and biomass gasification for co-production of electricity and clean liquid and gaseous fuels appears to have significant advantages over coal combustion technology strategies, even if augmented with direct coal liquefaction technology.
- Renewable energy technologies play a significant role, especially early in the analysis period, when the advanced gasification technologies (especially those involving CO_2 sequestration) are passing through their commercialization period.
- Energy efficiency is critical to meeting energy security goals and has a major impact on the total energy system cost and the cost (and, in some cases, even the viability) of meeting emission constraints.
- Delaying the commercial market introduction of coal and biomass gasification technologies results in a requirement for a massive build-up of nuclear power in order to achieve target CO_2 emission reductions.

Our work suggests that China can support its social and economic development objectives for the next 50 years and beyond with clean and renewable energy that is derived mostly from its indigenous resources. This conclusion is notable enough by itself, but what is most remarkable is that it appears there would be essentially no added cost over the long-term to pursue this sustainable energy path relative to a "business-as-usual" energy development strategy (relying on the Base technologies alone) that will be unable to achieve the development, air quality, and energy security goals.

Achieving these promising conclusions will require vision, strong policy supports, and recognition that the higher near-term investment costs implied by this strategy will be paid back in the long run with significantly lower costs for imported fuels and cleaner air, energy security and improved quality of life for the Chinese people.

While the analysis results reported here build upon the previous work supported by CCICED, there is still a need for more detailed analyses to understand the full dimensions and implications of an advanced-technology energy future and to explore and evaluate specific steps that could be taken in the near term. Multi-disciplinary, technology-focused analyses are needed, for example to:

- better understand the spectrum of end-use and energy efficiency technology options in the industrial, transportation, and residential sectors;
- better understand the technical and institutional aspects of co-producing electricity and clean fuels and to explore alternative strategies for delivering these to customers; and
- analyze the regional (province-level) strategies and implications of implementing the Advanced Technology strategy.

Notes

1. This paper and these reference papers were developed cooperatively and in parallel. Some cost and performance values used in this paper are slightly different from the final values in these references because of last-minute changes. However, as the emission and energy security constraints are shown to be the principal drivers of technology choices in the model, these small differences would not change the overall results reported here.
2. Direct coal liquefaction produces a crude-oil like raw product high in aromatic molecules. This product is refined to produce a mix of final liquid products that can be mixed with their equivalent petroleum-derived fuels. To meet automobile tailpipe emission standards, it is necessary to blend the high-aromatic DCL fuels with conventional petroleum fuels. It is not known what blends of DCL and petroleum fuels can meet different emission standards. One study [Lowe et al., 1997; Erwin et al., 1997] found that for a typical existing US refinery, the maximum input share of direct coal liquids (as constrained by processing capacity in specific parts of the refinery) was 37 % on a volume basis, and that the final optimized products from this refinery that met current US Environmental Protection Agency fuel specifications (octane, cetane, sulfur, aromatics, Reid vapor pressure, etc.), contained about 16 % coal liquids in the diesel fraction and 44 % in the gasoline fraction. Emissions from vehicles using these blends were found to be largely indistinguishable from emissions with petroleum fuels. We have specified these blend fractions as limits on DCL blending in the analysis presented here, but it is not known if fuels with higher DCL content might also be able to meet tailpipe emission limits.
3. Variations in timing were investigated, with the shock starting in 2015 in one case and

in 2030 in another case. The results of the two scenario variations were qualitatively the same; the 2030 start simply had a lower total discounted system cost.

References

Beijdorff, 2003. Personal e-mail communications with AF Beijdorff (beijdorf@netvigator.com), September-October.

DeLaquil, P., and Larson, E.D., 2002, *Global Renewable Energy Resource Estimates for the SAGE Model,* final report prepared for the Energy Information Administration, US Department of Energy, November.

Erwin, J., Moulton, D.S., Moses, C., Smith, L., Ryan III, T., and Matteaus, A., 1997. "Refining and end use study of coal liquids: test fuel production and testing – Part II", *Proceedings of the Coal Liquefaction and Solid Fuels Conversion Contractors' Review Conference,* Federal Energy Technology Center.

Goldstein, G., et.al., 2002. *Including New and Renewable Energy Technologies into Economy-Level Energy Models,* APEC#202-RE-01.11, ISBN 0-9726293-0-0, November.

Larson, E.D., Wu Z., DeLaquil, P., Chen W., and Gao P., 2003a. "Future implications of China's energy-technology choices", *Energy Policy*, 31 (12), pp. 1149-1204.

Larson, E.D., DeLaquil, P., Wu Z., Chen W., and Gao P., 2003b. "Exploring implications to 2050 of energy-technology options for China", *Greenhouse Gas Control Technologies,* Gayle and Kaya (eds.), Elsevier Science, Oxford, UK, pp. 881-887.

Larson, E.D. and Ren T., 2003, "Synthetic fuel production by indirect coal liquefaction", *Energy for Sustainable Development,* VII (4), (this issue).

Lowe, C., Erwin, J., and Moulton, D.S., 1997. "Refining and end use study of coal liquids: test fuel production and testing -- Part I", *Proceedings of the Coal Liquefaction and Solid Fuels Conversion Contractors' Review Conference,* Federal Energy Technology Center.

Ogden, J.M., Williams, R.H., and Larson, E.D., 2004. "Societal lifecycle costs of cars with alternative fuels/engines", *Energy Policy,* 32, pp. 7-27.

Nakicenovic et al., 2001. *Special Report on Emissions Scenarios,* Intergovernmental Panel on Climate Change, available at http://www.ipcc.ch.

Patterson, P.D., Birky, A.K., Maples, J.D., and Moore, J.S., 2000. "Future world oil prices and the potential for new transportation fuels", USDOE, OTT, presented at the Transportation Research Board 79th Annual Meeting, January.

US Department of Energy/Electric Power Research Institute (USDOE/EPRI), 1997. Topical Report 109496: *Renewable Energy Technology Characterizations.* Updates to this information were provided by Princeton Energy Research Institute and the National Renewable Energy Laboratory (NREL) on the basis of internal DOE planning documents.

Williams, R.H., and Larson, E.D., 2003. "A comparison of direct and indirect liquefaction technologies for making fluid fuels from coal", *Energy for Sustainable Development,* VII (4) (this issue).

Wu Z., DeLaquil, P., Larson, E.D., Chen W., and Gao P., 2001a. *Future Implications of China's Energy-Technology Choices,* prepared for the Working Group on Energy Strategies and Technologies of the China Council for International Cooperation on Environment and Development, 24 July.

Wu Z., DeLaquil, P., Larson, E.D., Chen W., and Gao P., 2001b. "Future implications of China's energy-technology choices: summary of a report to the Working Group on Energy Strategies and Technologies", *Energy for Sustainable Development,* V (4), pp. 19-31, December.