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EXPLORING IMPLICATIONS TO 2050 OF ENERGY-TECHNOLOGY OPTIONS FOR CHINA

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ABSTRACT

The MARKAL energy-system modeling tool was used to assess potential energy-technology strategies to 2050 for China that would enable continued economic development while ensuring energy-supply security and environmental sustainability. Our analysis suggests that continued reliance on domestic coal, which would help avoid high dependence on imported energy, is not inconsistent with achieving environmental objectives. However, a fundamental shift would be required from coal technologies based on combustion to those based on gasification, which enables the production of clean liquid fuels from coal and which facilitates CO_2 capture. Surprisingly, the total cumulative (1995-2050) discounted energy-system cost for an advanced-technology energy strategy that meets air pollution, energy security, and greenhouse gas emission goals would not be substantially higher than for a "business-as-usual" strategy that is unable to meet all these goals. To realize an advanced-technology future, China will need policies that *i)* encourage use of a wider variety of primary energy sources (especially biomass and wind) and clean synthetic fluid fuels from coal and biomass, *ii)* support the commercialization of radically new clean energy technologies, including those for CO_2 capture and below-ground storage, to ensure that they are available beginning in 10 to 20 years, and *iii)* support aggressive end-use energy efficiency improvements.

INTRODUCTION

China faces daunting energy challenges: high public health costs from air pollution arising mainly from coal combustion; security concerns over growing oil imports; limited domestic fossil fuels other than coal; projected demands for energy that will exceed domestic supplies (even coal) within a few decades; and the prospect that China could be the world's largest emitter of greenhouse gases by 2020. We developed a MARKAL model of China's energy system [1,2], building on earlier work [3,4]. We ran the model to gain insight into alternative technological strategies China might pursue to 2050 to address these challenges.

THE CHINA MARKAL MODEL

MARKAL modeling [5] requires user-supplied values for the efficiency, costs, emissions, and other features of technologies for converting primary energy resources into final energy carriers and of technologies for converting final energy into energy services. The architecture of our model and the included technologies are summarized in Fig. 1. All user-specified parameters are provided at five-year time steps. With user-specified inputs for technologies, primary energy costs and supply availabilities, MARKAL finds the combination of energy resources and conversion/end-use technologies that meet user-specified energy service demands while minimizing the cumulative discounted energy-system cost for the full period, 1995-2050. Externality costs, such as health damages from pollution, are not included in our model, but may be significant [6-8]. The World Bank [6] estimates health damage costs from urban air pollution in China in 2020 under "business as usual" energy development would be $390 billion (in 1995$). This is three times the direct expenditures on energy calculated for 2020 in our reference scenario described later.

We defined six energy-service demand sectors for China (Fig. 1). We projected energy service demands based largely on historical data for various OECD countries at similar levels of per capita GDP. We assumed that by 2050 China will be using energy services at levels equivalent to selected OECD countries in the mid-

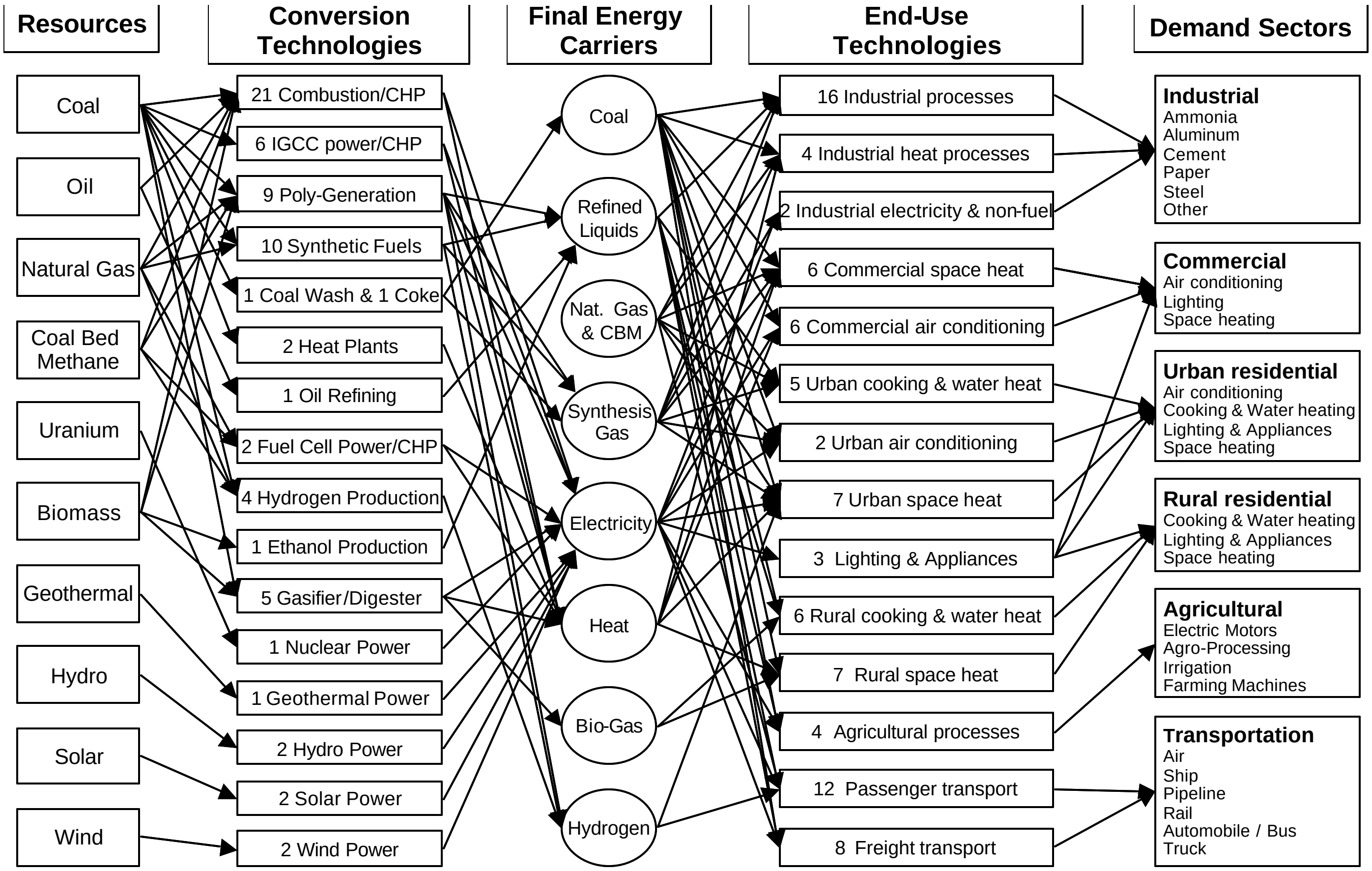

Figure 1: Technologies and energy-system architecture of our China MARKAL model. The numbers of technology variants are shown. For example, among the six IGCC technologies, one makes electricity only, one makes electricity while capturing CO_2, one co-produces heat and electricity, one includes a solid-oxide fuel cell and CO_2 capture, and two use H_2 separation membrane reactors (with and without CO_2 capture).

1990s, which implies a tripling in final energy demand between 1995 and 2050. This projection falls in the mid-range of projections made by several analysts [9]. Final-energy intensities fall from 40 MJ/GDP$ in 1995 to 6 MJ/$ in 2050 in most of our scenarios, reflecting aggressive efficiency improvement rates.

We categorized conversion and end-use technologies as “Reference”, “Base”, or “Advanced.” Reference technologies are already well-established in the market. Base technologies are either commercially available today or at an advanced stage of commercial demonstration. Advanced technologies are not commercially mature today. Commercializing many of the Advanced technologies will require focused government policies and support, the costs of which are not included in our analysis.

In most cases, we assume technologies are introduced with commercially-mature cost and performance. Some technologies are introduced with costs that decline over time. For example the capital cost for large-scale wind farms falls from $1050/kW in 2000 to $580/kW by 2030. We limited the growth rates of any new technology to 20-30% per year initially (and then declining), since MARKAL’s linear programming solution method would otherwise cause a complete shift to a new technology when it is the least-cost option.

Conversion technologies were a main focus of our analysis. We defined 71 of these (Fig. 1). Table 1 gives assumed characteristics of some of these. We included a large number of coal technologies, reflecting the importance of coal in China. A key distinction between the Base and Advanced coal conversion technologies is that the latter all involve oxygen-blown gasifiers producing synthesis gas, whereas the Base technologies are almost entirely based on direct combustion. Synthesis gas can be used directly, or it can be converted into electricity or clean gas or liquid fuels in plants making only a single energy carrier or in plants producing several carriers simultaneously – polygeneration [10,11]. Another key distinction is the availability of CO_2 capture and storage technologies in the Advanced set.

RESULTS AND DISCUSSION

The model chooses from among the various Base or Advanced technologies to meet environmental or energy import constraints in the least-costly manner. One set of model runs uses only the Base technologies.

TABLE 1

2050 CHARACTERISTICS OF SEVERAL ELECTRICITY TECHNOLOGIES. * ARE ADVANCED TECHNOLOGIES.

	Efficiency % LHV	Capital cost $/kW	Fixed O&M $/kW-yr	Var. O&M $/kWh	SO_2 grams/kWh
Coal, pulverized with FGD (500 MW)	36.4	1,090	16.1	0.0020	0.46
Natural gas combined cycle	58.1	600	16.1	0.0015	0
Nuclear power plant	33.0	2,000	40.0	0.0086	0
Wind, large-scale, incl. transmission lines	--	580	5.0	0.0020	0
* Coal, gasification/combined cycle (IGCC)	47.2	1,114	22.3	0.0032	0.075
* Coal, electricity w/CO_2 capture	39.7	1,489	29.8	0.0042	0
* Coal, electricity + H_2, w/CO_2 capture[a]	4.31	10,120	202	0.0289	0
* Natural gas combined cycle w/CO_2 capture	50.8	1,008	18.1	0.0026	0
* Hydrogen fuel cell combined heat/power	41.0	250	10.0	0	0
* Biomass, electricity + dimethyl ether[a]	16.3	2,141	44.8	0.0064	0

a) For this technology "efficiency" is the electricity output divided by total coal (biomass) input, and total system costs are assigned to electricity output. The coal (biomass) technology co-produces 38.5 MJ of H_2 (7.56 MJ of DME) per kWh of electricity generated.

These runs represent a future in which little incentive is provided for introducing radically new technologies. A second set of runs adds the Advanced technologies to the Base set.

For the Base (B) and Advanced (A) model runs, we explored the impact of constraining *i)* emissions of SO_2, *ii)* imports of oil and gas, and *iii)* emissions of CO_2. Scenarios below are named according to which constraints are in place (S=SO_2, I=oil/gas imports, C=CO_2). In the Reference (REF) scenario, no external constraints are imposed. In all scenarios except REF, annual SO_2 emissions are constrained to fall from 24 million tonnes (mt) in 1995, to 16.5 mt in 2020 (official Chinese government target), and to 10.4 mt in 2050 (comparable emissions per unit of coal as in USA today). For all but the nuclear phase-out scenarios (ASIC66 and ASC66) a minimum nuclear capacity is specified, growing from 2 GW in 2000 to 19GW in 2050. In ASI, ASIC80, and ASIC66, imports of oil and natural gas are limited to no more than 30% of total oil and natural gas use in any year—a level of import restriction that is not achievable with Base technologies because China's domestic oil and gas resources are scant and Base technologies do not include options for making synthetic fuels. For CO_2, we consider two allowable levels of cumulative emissions for the period 1995-2050. Wigley, *et al.* [12] have estimated that cumulative global emissions from 1990 to 2100 of 380, 750, 1100, and 1400 GtC (carbon in CO_2) 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, and 301 GtC, respectively. In this context, we examined the impact of cumulative emission caps of 80 and 66 GtC for 1995-2050 (denoted by C80 and C66 in the scenario names).

Figure 2 summarizes our results, showing primary energy in 2050, with nuclear, hydro, wind, solar, and geothermal electricity represented by primary-energy equivalent (three times electricity). Above each bar is the percentage of cumulative (1995-2050) oil and gas that is imported and total cumulative CO_2 emissions in GtC. The white inner bars show the change in total cumulative (1995-2050) discounted energy system cost relative to the $2.86 trillion (in 1995$) cost for the REF scenario, calculated using a 10% discount rate [13]. We use the cost increment (in % of the REF scenario cost) to compare different scenario costs.

For the Base scenarios, coal is the dominant energy source when no CO_2 emission constraints are imposed. For all the Base scenarios (as well as for the Advanced scenarios) wind electricity provided by large-scale wind farms is less costly than other electricity supplies, so that wind power is deployed to the assumed limit of the resource (320 GW) by 2050, providing about ¼ of electricity. Cleaner and more efficient coal combustion technologies such as ultra-supercritical-steam power plants with flue gas desulfurization are selected when the SO_2 constraint is in place (BS), contributing to a higher system cost than for REF. In BS, coal accounts for more than 55% of power generation (as it does in REF), and annual oil and gas imports reach 13.6 EJ (12% of total primary energy consumption) by 2050. For the Base scenarios with CO_2 emission limits in place, coal use is dramatically reduced, imports of natural gas are substantially increased, and biomass use is expanded. All crop-residue biomass is used in village-scale systems co-producing electricity and producer gas for cooking and heating. For BSC80, which involves a modest increment in cost relative to BS, coal use in 2050 is 40% of the 1995 level (with all coal power displaced by nuclear power, of which 300 GW are installed in 2050), and oil and gas imports are 40 EJ (34% of total primary energy – which may be near a worrisome level). In BSC66, for which the cost increment over REF is 1.5 times as high as for BSC80, coal use in 2050 is further reduced to 36% of the 1995 level and nuclear power expands to 480 GW, enabling some reduction in oil and gas imports (to 35 EJ, 28% of primary energy).

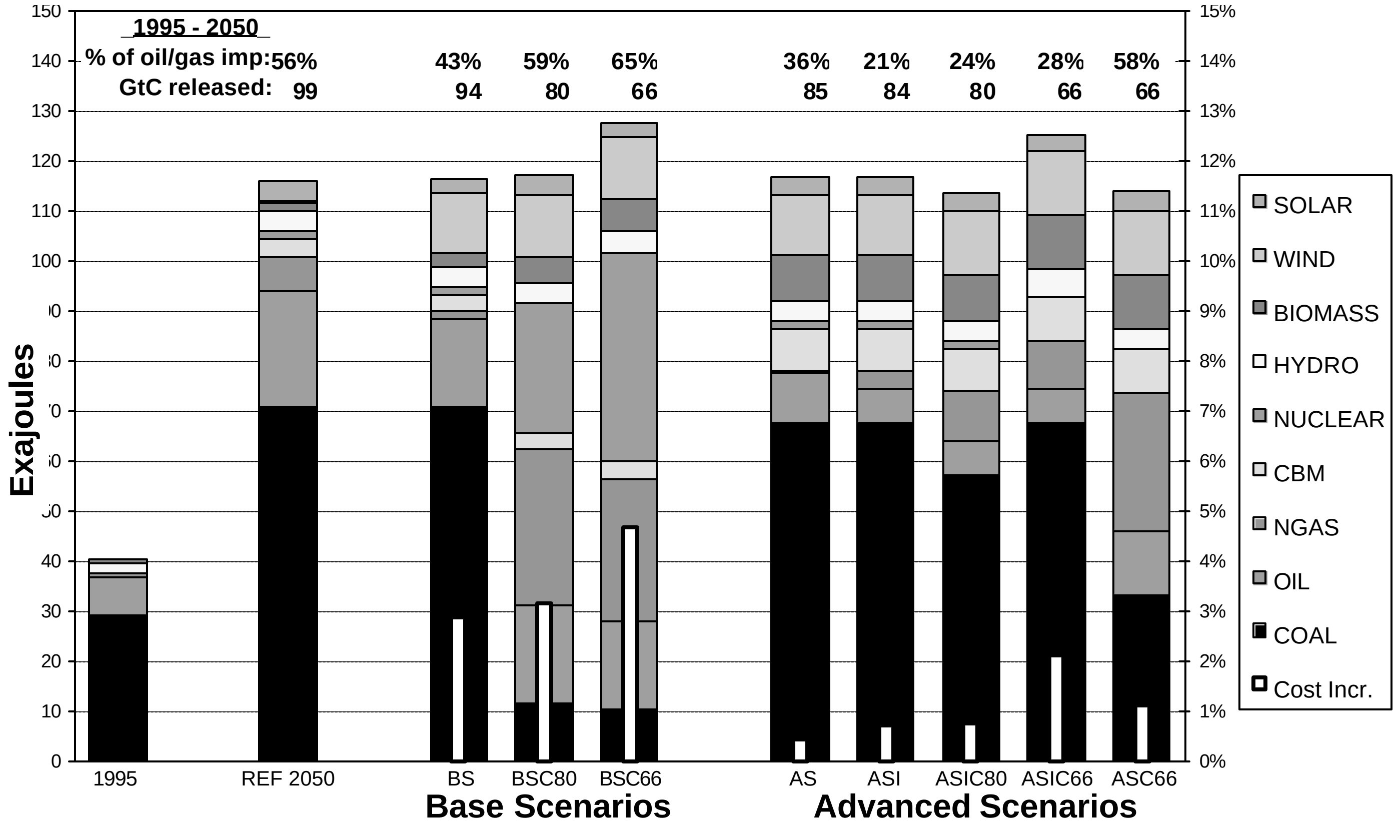

Figure 2: Calculated primary energy use in 2050 for alternative scenarios

With the Advanced technologies, the SO_2 constraint can be met (AS) with considerably lower cost than in BS, with less imported oil and gas, and with lower CO_2 emissions. The Advanced scenarios include technology options for converting coal and biomass via gasification into clean substitutes for oil and gas, thereby enabling low levels of oil and gas imports to be achieved. Biomass is used primarily 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. The use of coal-bed methane (CBM) mined by CO_2 injection further reduces pressure on natural gas imports. Notably, the AS and ASI scenarios have about 10% lower CO_2 emissions than BS. Some of the reductions come from less use of oil, but most are from injection of CO_2 for enhanced recovery of CBM and oil, which entails favorable economics.

The three right bars in Fig. 2 show the impact of explicit CO_2 emission constraints with Advanced technologies. For ASIC80, coal use is reduced slightly in favor of greater end-use efficiency improvements and natural gas use in increased, relative to ASI. Additionally, some CO_2 sequestration other than for enhanced resource recovery (ERR) begins around 2040. The right two bars show scenarios for achieving the 66 GtC limit with a tight oil and gas import constraint (ASIC66) and with no oil and gas import constraint (ASC66). In ASIC66, major electrification occurs in the commercial and residential sectors starting around 2035, leading to higher primary energy use in 2050 than in other cases. At the margin, capture of CO_2 from coal during electricity generation is the most cost-effective option for reducing CO_2 emissions since imports of oil and natural gas are constrained, and wind and biomass supplies are deployed at their maximum allowed limits. The increased electrical needs in 2050 are supplied largely by coal IGCCs with CO_2 capture and sequestration. Sequestration of CO_2 without ERR begins in 2010 at a modest level (0.018 GtC/year) and reaches a maximum of 0.88 GtC in 2050. As a result, CO_2 emissions in 2050 for ASIC66 are only 40% of the level in REF, for which coal use is about the same, while the cost increment for ASIC66 (2%) is lower than for all Base scenarios. Because imports of oil and gas in 2050 in ASIC66 total 4.7 EJ, or just 4% of primary energy, the import restriction we have used might be more severe than needed to address energy supply insecurity concerns.

ASC66 explores the implications of relaxing the import constraint. By 2050, imports in this scenario are 25% of primary energy and expenditure on imports account for about 1.2% of projected GDP—up from the 0.7% of GDP that China spent on oil imports in 1995. But notably, oil imports, which pose a greater energy insecurity risk than pipeline gas imports, account for only about ¼ of total imports and are 40% less than in BSC66. Reduced oil imports in 2050 in ASC66 are realized in part by a shift from gasoline and diesel hybrid electric cars and buses (in BSC66) to fuel cell cars and buses using coal-derived H_2. Each EJ of oil imports reduced this way requires 0.64 EJ of H_2 due to the higher efficiency of the fuel cell vehicles. The cost increment for ASC66 is half of that for ASIC66, and non-ERR carbon sequestration requirements in 2050 are almost halved (0.47 GtC). For ASC66, coal use in 2050 is only slightly more than in 1995 (though the energy services provided by coal are much greater than in 1995 due to a shift to more modern energy carriers and more efficient conversion and utilization technologies—e.g., direct coal combustion for heating and cooking is reduced 37%, and electricity generation from coal increases 3-fold, 1995-2050).

For ASIC66 and ASC66, we stipulated a phase out of nuclear power by 2025. In two sensitivity runs, we relaxed this constraint and kept nuclear power as an option beyond 2025. In the sensitivity run on ASIC66, the model preferred nuclear to coal during the later part of the period, reaching 258 GW of installed capacity in 2050. Without imports constrained, nuclear capacity grows more slowly, reaching 108 GW in 2050. Although the electricity generation mix is quite different without and with nuclear power, the system cost with nuclear power in 2050 are nearly identical to the costs without nuclear power in 2050, indicating that there are multiple system configurations that could meet CO_2 emission targets for similar costs.

In Fig. 3 we consider heuristically the implications of the Fig. 2 energy scenarios relative to meeting alternative global atmospheric CO_2 stabilization targets. The trajectories after 2050 are consistent with the indicated stabilization levels but are otherwise arbitrarily sketched. The figure suggests a plausible continuation of the trajectory of the BS or AS scenario could be consistent with meeting a 500 to 550 ppm stabilization target if CO_2 emission limits are imposed after 2050. Achieving 450 ppm would be considerably more challenging for these scenarios—requiring sharply downward sloping emission trajectories after 2050. If GDP were to grow at 2-3% per year from 2050 to 2100, then meeting the 450 ppm target with the BS scenario implies a decarbonization of the economy (measured in tC emitted per $ of GDP) at a daunting average rate of 4.8-5.7% per year from 2050-2100. But if China's CO_2 emissions are constrained before 2050, as in the C80 and C66 curves in Fig. 3, post-2050 emissions trajectories consistent with stabilization between 400 and 450 ppm are plausibly achievable. For GDP growth of 2-3%/yr after 2050, the flat CO_2 emission trajectories after 2050 imply a rate of decarbonization of the economy of 2-3%/yr. This could be realized if all growth of energy capacity after 2050 utilized zero-emission technologies.

CONCLUSIONS

If only modest changes in energy technologies occur (as represented by the Base scenarios), 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. Moreover, meaningful reductions in CO_2 emissions cannot be achieved without high energy imports.

On the other hand, with the Advanced technologies, there are plausible scenarios under which China could

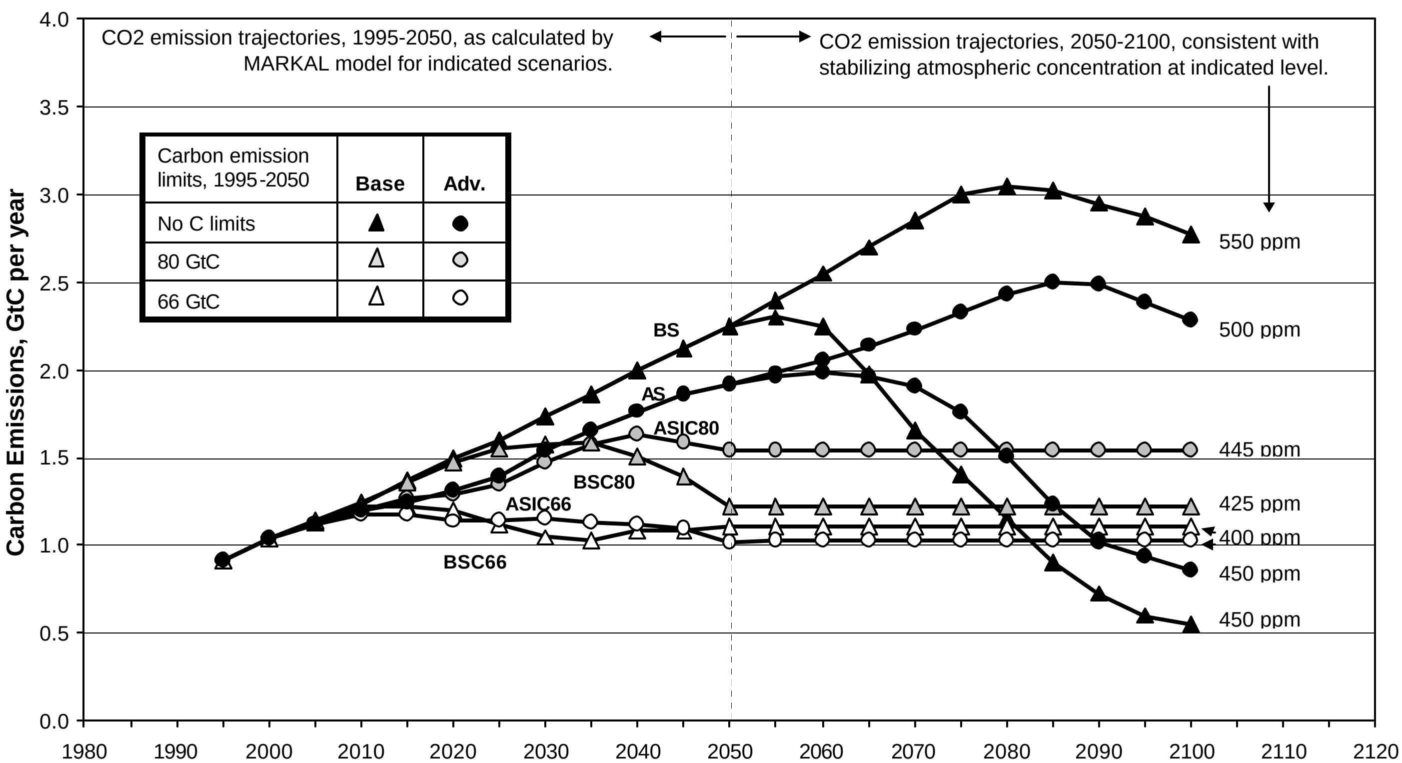

Figure 3: Carbon emission trajectories, 1995 to 2100

meet economic development objectives and environmental and energy security goals through at least 2050. Furthermore, with our technology-cost assumptions, the extra direct cost over the long-term to pursue this more-sustainable energy path would be tiny even with the imposition of severe CO_2 emission limits. 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, it would need to make significant investments to help develop and commercialize several radically new conversion and end-use technologies within the next 10 to 15 years. These near-term costs were not explicitly accounted for in our analysis. However, the value of 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. These benefits may outweigh the needed technology and infrastructure development costs.

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 clean synthetic fluid fuels from coal and biomass, *ii)* support the commercialization of radically new clean energy technologies, including those for CO_2 capture and below-ground storage, to ensure that they are available beginning in 10 to 20 years, and *iii)* support aggressive end-use energy efficiency improvements.

In addition to helping China meet air pollution and energy security goals, investment in advanced energy technology and infrastructure could reduce considerably the longer-term challenge of achieving CO_2 emission levels to 2100 that are consistent with China playing a role proportional to its size in stabilizing the atmospheric CO_2 concentration, even at levels as low as 400 ppm. 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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