Developing **countries** & Global **climate change**

Electric Power Options in China

Prepared for the Pew Center on Global Climate Change

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Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

With annual releases of over 918 million metric tons of carbon dioxide into the atmosphere, the People's Republic of China takes center stage among developing countries in the climate change debate. If China could achieve significant emission reductions from the business-as-usual scenario, particularly within the electric power sector, it could be considered a major advance in addressing climate change. Yet the task is daunting. Decision-makers must have a better understanding of the paths that are possible for electric power investment in China, and the impacts of these investments.

This report is designed to improve that understanding. It describes the context for new power sector investments and presents five alternative policy scenarios through 2015. The report presents concrete policy strategies that could enable China to meet growing electricity demand while continuing economic growth, and reducing sulfur dioxide and greenhouse gas emissions.

The principal drivers of the technology choices for the next fifteen years are:

- Growing awareness that under a business-as-usual path, carbon emissions from thermal plants will increase from 189 million tons in 1995 to 491 million in 2015, and sulfur dioxide emissions from 8.5 million to 21 million due to the heavy reliance on coal-fired power generation.
- Increasing demand-side energy efficiency by 10 percent from business-as-usual projections could reduce carbon dioxide and sulfur dioxide emissions by 19 and 13 percent, respectively, in 2015, while lowering cost to 12 percent below the baseline.
- Expanding the availability of low-cost natural gas through market reforms could reduce emissions of carbon dioxide and sulfur dioxide in the power sector by 14 and 35 percent, respectively, and increase cost by only 4 percent relative to the baseline.
- Accelerating the penetration of cleaner coal technologies could help China reduce sulfur dioxide and particulate emissions, but the associated impact on carbon emissions would be minimal and would increase costs by 6 percent relative to the baseline.

Developing Countries and Global Climate Change: Electric Power Options in China is the fourth of a series commissioned by the Pew Center on Global Climate Change to examine the electric power sector in developing countries, including four other case studies of Korea, India, Brazil, and Argentina.

The Pew Center was established in 1998 by the Pew Charitable Trusts to bring a new cooperative approach and critical scientific, economic, and technological expertise to the global climate change debate. We believe that climate change is serious business, and only through a better understanding of circumstances in individual countries can we hope to arrive at a serious response.

Executive Summary

China plays a leading role among developing nations in the field of energy and climate policy. The nation now ranks second in the world in energy consumption and greenhouse gas emissions. The electric power sector alone could consume as much as one billion tons of coal in 2015, and emit 300 million additional tons of carbon per year.[2] Chinese decisions affecting energy development and emissions mitigation will significantly impact world climate. However, China currently has no formal plans to reduce its greenhouse gas emissions for their own sake.

China has changed dramatically since the country adopted economic reforms in the late 1970s. The nation's economy has grown and living standards have improved for over two decades. Although income per capita remains far less than in industrialized countries, its gross domestic product is large enough to affect the global economy.[3] As the country's economy improves, China's influence will continue to grow.

China has fueled this robust growth with plentiful supplies of domestic coal. In 1997, the country consumed nearly 1.3 billion tons of coal, (accounting for three-quarters of all commercial energy demand), the highest in the world. Heavy reliance on coal has also caused severe environmental problems, including acid rain in southern China, deadly particulate levels in most cities, and increasing concentrations of greenhouse gases in the global atmosphere. Yet, for two decades energy use has grown only half as fast as the economy. According to official statistics, China has recently been far more successful than the United States in improving energy efficiency.[4]

The power sector currently accounts for more than one-third of China's annual coal consumption. Coal-fired thermal power plants generate over 75 percent of the nation's electric power and are among the largest sources of air pollution in China. Continued growth in economic output and living standards implies that electric power demand will grow rapidly in the foreseeable future. How to meet demand at least cost — including local environmental impacts — is a topic of great concern for decision-makers in government and the power industry.

This analysis, which explores China's electric power options, has three primary goals:

- Assess the current and future state of the power sector
- Determine the least-cost combination of technologies to meet projected power demand through 2015 under various scenarios
- Evaluate policies that could minimize both economic and local environmental costs.

This report begins with a brief review of China's economic and energy situation, then turns to a detailed account of the nation's electric power sector. The paper assesses available energy resources and generation technologies, and results of regional electric power demand forecasts through 2015. Results are presented from an analysis using a linear programming model to determine least-cost combinations of power supply technologies that meet projected power demand in 2015. The authors constructed a baseline and five policy cases to test economic and environmental policy measures, including sulfur dioxide and carbon dioxide controls, natural gas reform, clean coal investment mechanisms, and increased energy efficiency. The model simulated these scenarios by applying emissions caps, fees, cost reductions, increased fuel availability, improved plant performance, or lower demand estimates that then influence the selection of alternative technologies.

The authors conclude that without a strong environmental policy, China's electric power mix will become even more coal-dependent, with dramatic increases in emissions of sulfur dioxide, oxides of nitrogen, particulates, and carbon dioxide. These emissions would have serious effects on human health, property, and ecosystems.

When policy measures such as fuel availability, technical performance, and full-cost accounting are considered, however, the mix of electric power generation technologies — if not necessarily the fuels — changes significantly. The six scenarios produced the following results:

Baseline case. Power generating capacity and power consumption are expected to nearly triple by 2015 from their values in 1995, requiring some $449 billion in total costs.[5] In the baseline scenario, coal then provides 85 percent of power, and coal use for power generation alone would reach 1 billion tons per year. Emissions of sulfur dioxide and carbon dioxide from the power sector would reach roughly 20 million tons and one-half billion tons per year, respectively. This scenario assumes that the current environmental policy remains the same, which appears increasingly unlikely.

Sulfur emissions control case. Annual sulfur dioxide emissions from the power sector could be cut to 12.7 million tons by 2015 — a 40 percent reduction from the baseline level — by imposing fees ranging from $360-$960 per ton of sulfur released. Total costs using the sulfur fees would rise by 4 percent. Sulfur control policies would reduce total coal use very little but greatly increase coal washing and flue gas desulfurization. These options cost less in China than alternatives such as nuclear power, hydropower, and advanced coal technologies that reduce sulfur emissions by a comparable amount. Achieving sulfur reductions would also require stricter regulatory enforcement. However, greenhouse gas emissions would change little as a result of stricter sulfur dioxide emissions control.

Carbon control case. This scenario tested the effect of reducing carbon emissions in the power sector by 10 percent, or 50 million tons per year, by 2015. The study simulates these reductions by assuming the construction of new, less carbon-intensive power plants; it does not consider alternatives to lower emissions in existing plants. A 10 percent reduction from the baseline would add an additional $20 billion to total costs by 2015, an increase of about 4 percent. Greater reliance on washed coal, hydropower, nuclear power, and fuel switching to natural gas would be the cheapest ways of reducing emissions. Moderate carbon taxes were also tested in this analysis, but they were not found to be particularly effective in encouraging fuel switching. Only very high taxes — over $75 per ton of carbon — produced significant emissions reductions.

Natural gas case. China currently uses very little natural gas for power generation. For change to occur, the government would need to establish new policies and reforms to increase the availability of natural gas. This scenario simulates the impact of policies to boost gas use in the power sector. Increased availability of low-cost natural gas in the power sector — combined with improved turbine efficiency and a $300 fee per ton of sulfur dioxide emissions — could cut carbon and sulfur dioxide emissions by about 14 and 35 percent, respectively, from the baseline. Natural gas power in this scenario is cheaper than coal-fired power only along the coastal regions (where coal is relatively expensive), but gas would need to be available for $3 per gigajoule. This value is lower than some forecasts, but still higher than gas prices in Europe and North America. The power sector would consume approximately 65 billion cubic meters of gas, accounting for roughly half of China's total gas demand in 2015.

Clean coal case. A set of scenarios tested the effect of reducing the cost of advanced coal technologies such as integrated gasification combined-cycle (IGCC) or pressurized fluidized bed combustion (PFBC) to help them capture additional market share relative to the baseline. A 40 percent reduction in capital costs for IGCC and PFBC, combined with a mid-level sulfur dioxide emissions fee of $300 per metric ton, would reduce carbon dioxide and sulfur dioxide emissions by 9 and 75 percent, respectively. However, approximately $140 billion in additional investment — perhaps through international cooperation on technology transfer and clean development — would be required to subsidize the cost of building these plants.

Efficiency scenario. This scenario tested the effect of reducing electric power use by 10 percent compared to the baseline. Such a reduction would lower carbon and sulfur dioxide emissions by 19 percent and 13 percent, respectively, in 2015, and save $55 billion in investment and fuel costs by postponing the need for 52 gigawatts of coal-fired generation capacity. The analysis did not consider the required policies or costs to lower power demand.

These scenarios revealed two important findings:

1. Policy options exist to reduce carbon emissions substantially in the Chinese power sector at relatively low incremental cost. Emissions reductions of more than 10 percent compared to projected baseline emissions in 2015 can be achieved for less than 5 percent of the total cost of power. Continued improvement in demand-side efficiency is a particularly attractive option to lower carbon emissions.

2. Not all of these reductions will be achieved for reasons that are in China's own interest, such as reducing sulfur dioxide emissions. Consequently, cooperation with other countries would be required to achieve more dramatic results.

I. The Chinese Energy Picture

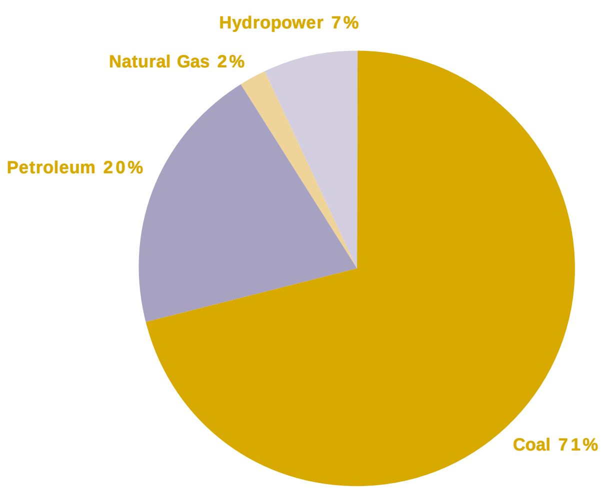
A. The Role of Energy in China's Economy

China's energy economy is defined by three characteristics: rapid growth, low (but increasing) per capita power consumption levels, and heavy reliance on coal. China's economy grew faster than 9 percent per year over the past two decades. But in 1998, the Asian financial crisis combined with the impacts of domestic reforms and record flooding in several regions slowed the Chinese economy. China has dealt with deflation, limited consumer spending, and the serious oversupply of most commodities, including coal and electricity. In 1999, the Chinese government closed many small coal mines, eliminating over 100 million tons of annual production capacity.[6] In the future, China's economic development will again rely more on expansion of domestic demand and consumption than on export growth.

China's primary commercial energy consumption stood at nearly 40 exajoules in 1998,[7] over 70 percent of which is provided by coal. (See Figure 1.) Coal has fueled much of China's economic growth over the past two decades. By the end of 1999, China's coal production was reported to have fallen over 1 billion tons, a decrease of over 250 million tons from the 1997 peak. Statistics on coal supply are controversial, however, and China still leads the world in coal consumption. But China still uses only 40 percent as much energy as the United States, even though the Chinese population is four times larger. Stated another way, China uses one-tenth as much energy per capita as the United States, and only one-thirteenth as much electricity.

Figure 1

Energy Consumption in China, 1998



Source: *China Electric Power Statistical Yearbook,* 1999.

Electric utilities are developing both urban and rural markets and have begun encouraging consumers to use more electricity as a way of expanding economic growth. However, the State Power Corporation has suspended construction of conventional coal-fired thermal power plants for three years due to the estimated overcapacity of about 25 gigawatts in mid-1999.[8] For the first time in decades, the central government does not list power plants among key infrastructure projects. The electric power industry has shifted its priorities to expansion and retrofit of power transmission and distribution systems.[9]

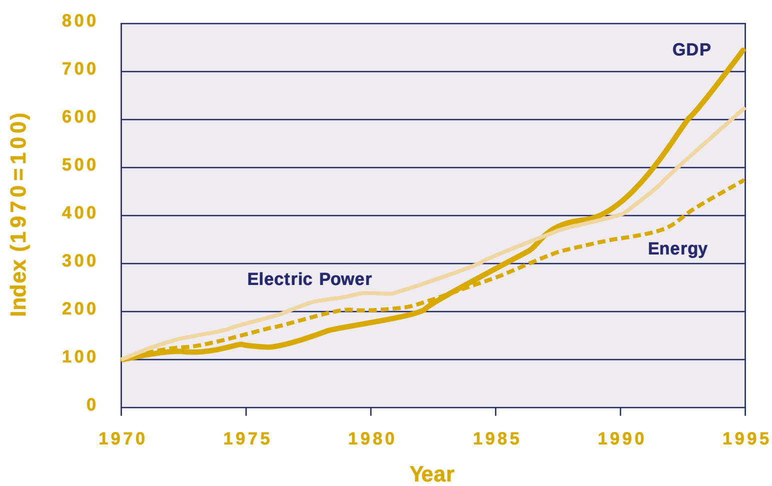
China faces the challenge of maintaining economic growth while implementing effective pollution control policies. The nation ranks first in the world in sulfur dioxide emissions and is exceeded only by the United States in carbon dioxide emissions. The local environmental degradation resulting from burning so much coal — often at low efficiencies with insufficient emissions control — is causing alarm both inside and outside China's borders. Emissions of sulfur oxides, particulates, and nitrogen oxides from coal combustion damage human and ecosystem health, buildings and infrastructure materials, and agricultural output.

Environmental problems associated with heavy reliance on coal would be even worse if China had not initiated a successful energy conservation program in the early 1980s. The program provided incentives for industries to upgrade equipment and manage energy-intensive processes more efficiently so as to ensure sufficient energy supplies for future economic growth.[10] Unlike other developing countries, China has largely decoupled energy growth from economic growth. (See Figure 2.) Still, Chinese industries consume significantly more energy per unit of production than those in developed countries.

Figure 2

Energy and Electric Power Demand

in China's Economy



Source: *China Statistical Yearbook*, 1997.

China generates over 75 percent of its electricity from coal. Because the average efficiency of Chinese power plants lags behind Western rates by approximately 15 percent, carbon emissions are inordinately high. Construction of new hydroelectric plants requires resettling large numbers of people, and has negative impacts on local ecosystems. Power failures, caused by outdated technology and poor operation and maintenance practices, have led to losses in industrial production. Until China begins to account for the full costs of electricity supply decisions, real economic growth will be less than the published estimates indicate.

B. Electric Power Production

China's electric power industry has developed very rapidly over the past two decades as a result of economic development and rising incomes. (See Table 1.) Total installed capacity increased from 116 gigawatts in 1988 to 294 gigawatts in 1999, an average annual growth rate of 9.1 percent. Installed capacity increased by about 15 gigawatts annually, the equivalent of adding a 565-megawatt plant every two weeks.

Table 1

Development of China's Electric Power System

Year	Installed Capacity (GW)	Growth Rate (%)	Power Generation (TWh)	Growth Rate (%)
1988	116	12.2	545	9.6
1990	138	8.9	621	6.3
1993	183	9.8	836	10.9
1995	217	8.7	1,007	8.5
1996	232	6.9	1,075	6.8
1997	254	9.5	1,134	5.5
1998	277	7.9	1,158	2.1
1999	294	7.3	1,230	6.2
Average 1988-99		**9.1**		**8.3**

Sources: *China Energy Annual Review*, 1997; *China Statistical Yearbook* 1999; *Financial Times,* 17 January 2000.

But the impact of this growth on the size and efficiency of plants has varied. Many recently built coal plants have relatively high efficiencies because they use large units of 300 megawatts and higher. This stands in contrast to the many small, inefficient plants built quickly in the late 1980s and early 1990s to meet soaring demand. The share of electric power produced from large units has increased significantly since 1993, although the addition of many very small (less than 50-megawatt) units has offset some of these efficiency gains. (See Table 2.)

Table 2

Installed Capacity of Coal-fired Power Plants (greater than 6MW)

Year	1993			1997		
Unit Size	**No. of Units**	**Total Capacity (MW)**	**% of Total**	**No. of Units**	**Total Capacity (MW)**	**% of Total**
>600	6	3,600	3.0	10	6,000	3.5
300-600	73	22,780	19.1	144	42,980	25.1
200-300	162	32,600	27.4	189	38,000	22.2
100-200	217	23,993	20.1	270	30,118	17.6
50-100	267	13,530	11.4	339	17,310	10.1
<50	1,807	22,583	19.0	2,374	37,073	21.6
Total	**2,532**	**119,086**	**100**	**3,326**	**171,481**	**100**

Note: Rounding off may result in totals other than 100 percent.

Source: *China Electric Power Statistical Yearbook,* 1998.

China is making efforts to close thermal power plants with unit capacity of 25 megawatts or less to improve efficiency, reduce pollution, and stabilize the power supply system. Small thermal plants with a combined capacity of almost 11,000 megawatts are scheduled to close between 1998 and 2000. Shandong province was first to close a plant under this plan, shutting down the Fangzi plant with 42 megawatts of capacity in 1997. All small power plants in eastern China are scheduled to be closed by the end of 2000.[11]

Chinese policy requires new coal-fired units to be 300 megawatts or larger to improve efficiency. Domestically manufactured 300-megawatt and 600-megawatt subcritical units are becoming the backbone of the generation system. The government hopes to raise the efficiency of large, domestically produced coal-fired power generation units to nearly 40 percent early in this century with intensified technology transfer and research and development programs. The current mix of power plants averages approximately 30 percent.[12]

Thermal power plants (fired with coal, petroleum, or natural gas) accounted for over three-quarters of China's installed capacity in 1997. (See Table 3.) Hydropower provided about 24 percent and nuclear power less than 1 percent of capacity. Oil and natural gas combined accounted for less than 7 percent of total power generation in 1997. China uses only about 10 percent of its limited natural gas supply to generate power, and, except in Hong Kong, does not yet operate any large, modern combined-cycle power plants.

Table 3

Installed Capacity and Power Generation 1997

	Thermal	Hydropower	Nuclear	Total
Installed Capacity (GW)	194	60	2	256
Power Generation (TWh)	939	195	14	1,148

Source: *China Electric Power Statistical Yearbook,* 1998.

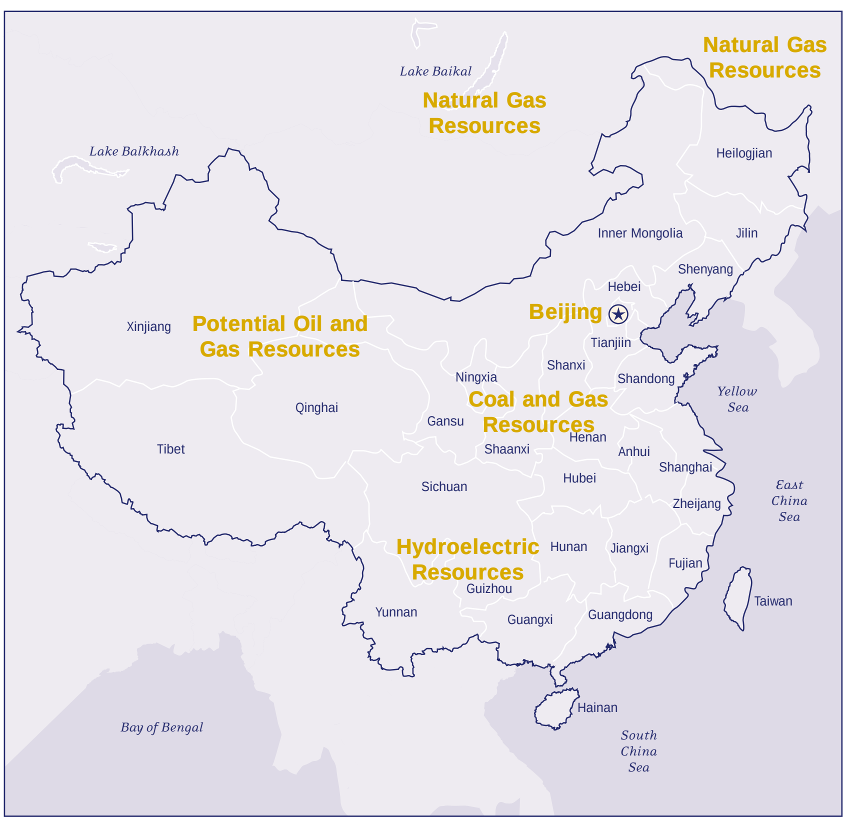
Energy Resources and Power Production

Coal. China's total coal resources are estimated at five trillion tons, with proven reserves of one trillion tons.[13] Even the latter is enough to satisfy China's current demand for over 750 years. Coal imports may become an option in southern coastal areas because of the high costs of transporting domestic coal there from the north, where most coal resources are located. (See Figure 3.)

China's electric power industry is based on low-cost, plentiful domestic energy resources and low-cost, locally made power generation technologies. As a result, China has produced some of the world's least expensive coal-fired power plants. For these reasons, coal now supplies the vast majority of electric power production. Most new coal plants in China rely on domestically manufactured units up to 300 megawatts in size, although imported and joint-venture equipment can be as large as 900 megawatts. Local companies will soon be capable of manufacturing 600-megawatt units independently.

Figure 3

Mainland China's Energy Resources and Population Centers



Note: Most of China's energy consuming markets are located on or near the coast.

Pressurized fluidized bed combustion and integrated gasification combined-cycle systems use coal but operate at higher efficiencies and generate fewer emissions than traditional coal-fired power plants. China began researching pressurized fluidized bed combustion and integrated gasification combined-cycle systems in the 1980s, believing that they would help solve the country's power problems while continuing to use domestic coal. Several countries are collaborating with China on research and development, but so far the costs and technical barriers of these systems prevent their widespread adoption.

The easiest and cheapest pollution control for coal combustion is coal washing to remove ash and sulfur. Less than 20 percent of the coal burned in China is currently washed. The revised Air Pollution Prevention Law prohibits use of coal with sulfur content above 3 percent; the law also requires coal washing at mines producing coal with a high sulfur and ash content. However, compliance is low and enforcement is weak.

Electrostatic precipitators are required on all new coal-fired power plants. This technology is often less efficient at removing particulates than baghouses or filters, which are used on low-sulfur coal and when regulations require collection efficiencies above 99.5 percent.

Post-combustion technologies for removing sulfur and nitrogen oxides from the emission stream play the largest role in clean coal production in industrialized countries. These technologies probably offer the most cost-effective approach in the near term to China, where they are in the testing and demonstration stages. Post-combustion is generally more complex than other types of sulfur control and requires a significant amount of auxiliary power. These technologies include wet scrubbers with SO_2 removal efficiency of 80 to 90 percent, dry scrubbers with SO_2 removal efficiency of 40 to 60 percent, and combined control technologies with SO_2 and NO_x removal efficiency up to 90 percent.[14]

Hydropower. China has the most abundant hydropower resources in the world, with an estimated potential of 380 gigawatts.[15] Hydropower theoretically could supply much of China's needs, but suitable rivers are located far from load centers and are heavily laden with silt. China has an aggressive program to build large hydropower stations over the next 20 years, mainly to diversify power generation, help control flooding, and irrigate farmland. These plants are intended for the middle and upper reaches of the Yangzi, Yellow, and Lancang Rivers.

Most of China's hydropower resources are located in the southwest, where approximately one-third of all hydroelectric power was generated in 1997. (See Figure 3.) China is constructing the world's largest hydro project, the massive Three Gorges Dam, in Hubei province with total installed capacity of 18.2 gigawatts. The plant is scheduled to be fully operational by 2009 after an investment of at least $25 billion. At that time, it will supply about 3 percent of the country's power needs. There is strong domestic and international opposition to the dam in large part due to its size. The project has considerable environmental and safety impacts and will require the forced relocation of over 1 million people. Many opponents believe that the same energy objectives could be achieved for less cost using several smaller plants.

China manufactures all but the largest hydropower turbines, and designs and builds both large and small hydroelectric plants. Hydropower projects are expensive and capital intensive and can lead to mass resettlement of residents, loss of farmland and wildlife, and ecosystem damage. On the other hand, hydropower projects can also help control floods and improve navigation.

Natural Gas and Petroleum. After decades of bypassing natural gas development, planners in China have focused greater attention on gas in the last few years as a relatively clean fuel source. According to a recent resource assessment, China's estimated total natural gas reserves amount to 38 trillion cubic meters (over 1,450 exajoules).[16] Proven reserves, however, range from 1.2 to 5.3 trillion cubic meters (roughly 50 to 200 exajoules).[17] Additional reforms to encourage exploration and development will be needed to further refine this estimate.

China's natural gas is located mainly in the southwest, central, north, and off-shore regions. (See Figure 3.) Gas production will grow most rapidly in the northern region and offshore. International markets may become an important source of natural gas supply for some regions, including gas from Siberia and liquified natural gas from southeast Asia. China has large reserves of coal bed methane, amounting to 35 trillion cubic meters; several major international gas companies recently began identifying the commercial potential of this major resource.[18]

In January 2000, China's State Council gave final approval for construction of the country's first liquefied natural gas terminal project in Guangdong. The project will be complete in 2005 and will include one or two large combined-cycle power plants. More importantly, it may signal a shift in thinking about energy imports and environmental quality that would call for additional terminals in other coastal cities.

Petroleum resources in China are estimated at 89 billion tons, while exploitable reserves are estimated at around 15 billion tons (the latter is about 630 exajoules). In 1996, petroleum production peaked at 159 million tons.[19] Domestic production more recently has stagnated, while demand for industry and transportation has skyrocketed. China thus became a net oil importer in 1993. Imports are expected to continue to grow for decades.[20] However, very little petroleum will be used for electric power generation.

Gas and petroleum-fired plants are rare, limited in the past by domestic supply and policy decisions. Existing plants are outdated, while newer units are more efficient, rugged, and cheaper. Imported combined-cycle gas turbines have efficiencies approaching 60 percent.[21] Higher efficiency and lower capital costs can offset the price advantage of coal over gas, especially in regions where low-cost natural gas is available and coal is relatively expensive due to transportation costs. China has also started researching fuel cell technologies that could use natural gas, or a variety of methane-rich fuels.

Nuclear. Domestic uranium reserves are sufficient for nuclear power development at the scale currently envisioned.[22] Until recently, China had ambitious plans to develop nuclear power, but high cost and financing difficulties have combined with a slowdown in power demand to limit its future growth potential.

China started commercial nuclear power production in 1992 with the 300-megawatt Qinshan station. Chinese engineers designed this plant with international technical support, and many components were imported. The Daya Bay nuclear station, with two imported 900-megawatt units, began operation in 1994. Another 6.7 gigawatts of nuclear power capacity was under construction as of January 2000, with most of it expected to come on-line around 2005. China has emphasized building nuclear plants in the eastern and southern coastal areas where the economy is relatively well-developed, conventional energy resources are deficient, and fuel transportation costs are high. Despite these regional advantages, financial and technical barriers have prevented rapid growth in nuclear power.

China has the capability to manufacture about 70 percent of the components in advanced nuclear pressurized water reactor systems. The country imports the remaining 30 percent to meet technical requirements. High capital costs, waste disposal, and the risk of accidents present environmental challenges of a different magnitude than other technologies. Currently, nuclear power plants are only being considered on the eastern coast, where coal is expensive or difficult to obtain.[23]

Renewables. China also has abundant renewable energy resources, including reserves of 253 gigawatts of wind power and biomass energy resources estimated at an annual supply of 220 million tons of coal-equivalent.[24] Despite the promising resources, these technologies have not been widely adopted mainly because of high costs, market distortions, and technical difficulties.

China had developed about 20 wind power farms with a combined capacity of nearly 300 megawatts by the end of 1999.[25] These turbines offset approximately 150,000 tons of carbon emissions each year had the power been generated with coal. Installed solar photovoltaic, ocean tidal, and geothermal power amounts to 6, 11, and 32 megawatts of capacity, respectively, or together 0.02 percent of the country's total.[26]

China is a world leader in producing micro and small wind turbines and recently announced that it can manufacture rather large 600-kilowatt turbines domestically.[27] It can also produce photovoltaic cells, biomass digestors, and gasification equipment. China continues to develop other advanced renewable technologies, including tidal, ocean thermal gradient, and solar thermal power. It will probably continue to develop these sources to fill demand in niche markets, but only wind turbines and biomass applications are likely to have the potential to make a big impact on greenhouse gas emissions during the time frame of this study. Still, technical and financial barriers need to be addressed for any renewable power option to play a larger role.

C. Electric Power Consumption

By 1995, China was the world's second largest electricity consumer.
Electricity consumption increased at an annual rate of about 9 percent from 1990 to 1997, when consumption surpassed 1,100 terawatt-hours, about one-third the level in the United States. In 1998, consumption growth dropped dramatically to 2.8 percent because of a slowdown in industrial output. Preliminary data indicate that power consumption increased by approximately 6 percent in 1999.[28] Electricity use per capita remains under 900 kilowatt-hours per year, only one-third of the world average and just one-thirteenth the level in the United States.[29]

Chinese industry has long accounted for the bulk of power consumption, although its share of the total has been decreasing as commercial and residential use grows. In 1997, industry still consumed nearly three-quarters of all power, followed by the residential sector at about 11 percent. (See Table 4.) Electricity use in the commercial and residential sectors recently increased by about 16 percent each while consumption in the agricultural sector grew only half as quickly.

Southwest China led the country in power demand growth between 1990 and 1997, averaging over 16 percent annually. Power demand growth in the north, which is struggling to reform its antiquated heavy industrial sector, averaged 4.6 percent over the same period. (See Table 5.)

The GDP elasticity of electricity demand — which indicates the relationship between power growth and economic growth, and helps serve as a signpost for future demand — is surprisingly low in China. This value, defined as the ratio of power demand growth to economic growth, averaged 0.95 between 1980-1999.[30] Most developing countries, on average, have a ratio of 1.3 or higher. Despite China's ability to control growth in energy demand, the physical intensity of power usage — meaning the kilowatt-hours needed to perform a given function — is higher in China than in most industrialized countries.[31]

Table 4

Power Consumption by Sector

	1987	1990	1995	1997
Total consumption (TWh)	490	613	1,002	1,104
Share by sector (%)				
Industry	81	79	74	73
Heavy Industry	65	63	59	58
Light Industry	17	16	15	15
Agriculture	7	7	6	6
Commercial*	5	5	6	8
Residential	6	8	10	11
Other	3	3	3	3

*Includes the so-called "non-productive" sectors of government, education, health, science, and research.

Note: Rounding off may result in totals other than 100 percent.

Source: *China Electric Power Statistical Yearbook,* 1991-1998.

Table 5

Power Consumption and Growth Rates by Region

	1997 (TWh)	Annual Growth Rate 1990-97 (%)
North	335	4.6
East	269	7.7
Central	159	7.7
Guangdong	79	8.2
Southwest	117	16.7
National Total	**1,104**	**8.7**

Note: These regions and Guangdong account for over 85 percent of China's power consumption and comprise the regional breakdown used in the modeling exercises discussed in Chapter II. Several provinces such as Xinjiang, Xizang (Tibet), and Hainan are not included in the regional groupings because of the isolated nature of their power grids. These regions could have significantly different least-cost power needs than the areas with existing electricity networks.

Sources: *Study on Alternative Energy and Energy Supply Strategies in China,* 1998; *International Energy Outlook, 1998.*

Several factors keep power demand growth low in China in relation to economic growth:

- There has been a general shift in the structure of the economy away from primary to higher value-added products, and to a lesser degree from energy-intensive heavy industries to light industry and service sectors.
- Central planners set power supply quotas and imposed higher power tariffs when quotas were exceeded. Government controls, however, have diminished in recent years as the economy shifted to a greater market orientation and as energy supply expanded significantly.
- Government policies and programs, including financial assistance, encouraged technical energy efficiency improvements.
- Enterprise management devoted attention to reducing power consumption to cut costs and improving market competitiveness.
- Managers retired older generating equipment and introduced more efficient power plants.

A major concern for policy-makers and environmentalists is whether China will continue to maintain a low elasticity of power demand. Command and control regulations used in the past are losing their importance in improving energy efficiency. Market-based mechanisms, including energy pricing, tax incentives, and pollution penalties, will need to take their place.

D. Reform of the Electric Power Sector

China's electric power industry was developed under central planning from the 1950s through the early 1980s, although reforms since then have noticeably changed the sector. Power utilities were owned solely by central and provincial governments, which chose the managers, provided all investment funds, and received most of the profits. The government planned and controlled electricity production, and set prices to assist key industries and reduce the cost of living. Because power tariffs covered only generation costs, funding was limited for building new power plants. Supply shortages and outages resulted in economic losses of as much as 25 percent of GDP in the 1980s and early 1990s.[32]

The government also controlled electric power use. Measures included allocation of power supply among users, mandated scheduled regional power supply outages, quotas for both capacity and power demand, and high prices or fines for exceeding quotas. However, the government also made large investments for electricity conservation with considerable success, as the trends in Figure 2 indicate.

Reform of the electric power industry began in the 1980s. It began by diversifying investment sources to include local governments, industrial sectors, and enterprises. This measure diversified ownership and weakened the central government's monopoly of the electric power industry.

Electric power soon came to be regarded as a commodity to be bought and sold on the open market, rather than a product allocated by government. Regulations enacted in 1985 allowed new independent power plants to set power tariffs high enough to recover investments and achieve profits. These producers were allowed to sell power to the grid competitively through established contracts. Existing state-owned producers were reorganized as companies operating commercially in an increasingly market-oriented environment.

These reforms prompted a surge in electric power sector development, and power shortages diminished. Capacity increased annually by as much as 5 gigawatts during the early 1980s and by over 15 gigawatts in the 1990s. In 1997, power sector investment totaled $16 billion, of which only 4 percent came from the central government.[33] Generation owners included central and provincial governments, joint state and local governments, stockholders, sole proprietors, local and foreign enterprises, joint ventures, and cooperative ventures, all operating independently and selling power to the grid. However, all projects remain subject to approval by local and central planning commissions, and projects costing over $30 million must be approved by the State Council, China's cabinet.

The central government drafted the Electric Power Industry Law in 1995 that was enacted in 1996. The law is regarded as the fundamental legal framework of the electric power industry and ensures development of the industry in a transition economy. The law protects the rights and interests of investors, attempts to direct the behavior of players in the electricity market, and encourages fair competition. Supplemental regulations on power supply and transmission grid operation were also issued independently of this law.

The Ministry of Electric Power Industry (MEPI) was disbanded at the National People's Congress in March 1998,[34] a significant step in reforming the administrative system of the electric power industry. The governmental function of MEPI is now under the State Economic and Trade Commission. In 1997, the government created the State Power Corporation to manage, develop, and operate state-owned power grids and their interconnections. This corporation, which performs some of MEPI's functions, acts independently to develop and compete in the market. Currently, the State Council appoints a Board of Supervisors to oversee the corporation on major operational activities. The corporation is the most important body in China's power sector. The government plans additional reforms to allow power producers more independence and loosen constraints on investment.

There has been significant reform of China's electric power industry, but full reform remains a distant promise. State-owned power utilities function as power providers and sector administrators. These conflicting purposes handicap their efforts to apply modern business practices. Non-state utilities are also forced to compete with producers that not only generate power but make the rules for power production and sales. To convert power utilities into modern enterprises, and to create a fair, competitive business environment, the government is attempting to transfer regulatory functions from power generators to governmental agencies. The sector will be restructured by 2005 to allow competition between independent power providers and state-owned utilities, and to horizontally separate ownership of generation, transmission, and distribution. The Sichuan Power Grid is undergoing restructuring as a model for the rest of the nation.[35]

E. Foreign Investment in China's Electric Power Sector and Market Barriers

Foreign investment provides needed capital for power plant construction and helps introduce advanced technologies into China. In 1997, such sources accounted for about 10 percent of total power sector investment. Foreign investors can own enterprises or participate in joint ventures and cooperative ventures with Chinese partners, and they can purchase power company stock issued on domestic and international markets. All projects and foreign partners are selected by open bid. However, hydropower projects with capacity over 250 megawatts and nuclear power plants must be more than half-owned by locals. China also imposes import tariffs of 38 percent on power units smaller than 350 megawatts, while larger units are assessed at only 6 percent. This incentive is designed to accelerate transfer of advanced power technologies, while protecting local manufacturers who produce smaller capacity units.

Although the Chinese government has improved market conditions for investment in the power sector, significant barriers still exist. Foreign investors perceive higher economic, political, and legal risks than the government acknowledges. Although these investors are generally optimistic about the future market in China, they often complain that profitability is higher in other countries. The Chinese government allows a 12 to 15 percent rate of return on investment in infrastructure projects, but foreign investors expect higher rates based on perceived risks. Few foreign companies will invest in any large project if return on investment is less than 15 percent, even in domestic facilities.[36] Moreover, a complex approval process is required, involving many government agencies at different levels, which takes both time and money. Since late 1997, when power supply began to exceed demand in certain markets, some foreign investors reported that Chinese utilities were not honoring the power purchasing agreement defined earlier in their negotiations. Without enforceable contracts or access to legal recourse, the perception of risk in China's power sector will rise.

F. Environmental Protection and the Power Industry

China's dramatic economic growth in recent years has come at a high price. In every major city, particulate levels and oxides of sulfur and nitrogen exceed government standards, often by several hundred percent. Urban air pollution is responsible for millions of deaths and injuries each year.[37] Acid rain has affected about 40 percent of the land area, and air pollution contributes to over 7 million worker-years lost each year to related sickness. Research indicates that total GDP loss due to environmental pollution from all sources exceeds 8 percent.[38]

Coal-fired power plants account for about one-third of sulfur dioxide and particulate emissions.[39] (See Table 6.) According to the Chinese government's environmental protection plan for the electric power industry, particulate emissions in 2000 must be held to 1995 levels and sulfur dioxide emissions in sensitive areas must be strictly controlled.[40] Many hurdles must be overcome to reach these goals, however. Financing of environmental protection projects is insufficient, enforcement of environmental protection laws is weak, and penalties for exceeding emission limits are low.

Table 6

Air Pollution in China

Year	1990			1997		
	National Total (Million Tons)	Power Industry (Million Tons)	Power Industry (Percent of Total)	National Total (Million Tons)	Power Industry (Million Tons)	Power Industry (Percent of Total)
Particulates	13.2	3.6	27	18.7	4.0	21
SO_2	14.9	4.2	28	23.4	7.9	30

Sources: *China Electric Power Statistical Yearbook*, 1991; *China Environmental Statistical Yearbook*, 1998.

The electric power industry has nevertheless made some notable progress in environmental protection. Power generating capacity and coal consumption have increased dramatically while reported pollutant releases — especially particulate matter — increased only slightly. Large power plants are required to install high-efficiency electrostatic precipitators and growth in particulate emissions from power generation has been greatly slowed.[41] Moreover, the power sector has reportedly increased particulate removal rates from 92 percent in 1987 to 96 percent in 1997. While there is still room for improvement in particulate control, China has made rapid progress in limiting emissions of this harmful class of pollutants in the power sector. These reductions resulted from the implementation of environmental protection laws, increased investment in pollution control, and adoption of advanced pollution control technologies. This level of control is far stricter than for industrial combustion and household stoves.

Sulfur dioxide emissions, by contrast, increased along with power generation and coal use in China. Chinese industries have failed to control sulfur dioxide emissions, largely because regulations are not enforced and because there are no incentives to do so. Addressing this problem remains the most critical environmental task for China's power industry.

Large-scale coal-fired boilers, mostly used for power generation, are probably the only coal combustion facilities that can implement sulfur dioxide removal measures cost effectively. The traditional approach to reducing sulfur dioxide pollution was to increase the height of smokestacks. While higher chimneys reduce local ground-level concentrations of sulfur dioxide, total emissions remain the same. Moreover, emissions are lofted higher into the atmosphere, where conditions are favorable for acid rain formation. China has built several pilot plants equipped with flue gas desulfurization facilities to control sulfur emissions. However, the total installed capacity of these power plants totals little more than 1 gigawatt, and they do not yet play a significant role in reducing emissions.

In 1995, the People's Congress revised the Air Pollution Prevention Law to strengthen controls not only for local concentrations but emissions as well. The law requires newly constructed thermal power plants to use low-sulfur coal (which has less than 1 percent sulfur by weight). These plants also must have desulfurization and dust removal facilities or equivalent emission control measures. The Chinese government has yet to develop a specific standard for nitrogen oxide emissions, a pollutant involved in the creation of smog.

The government has also implemented policies to promote use of ash and slag, by-products of power production that were discharged with wastewater into rivers and lakes until 1995. Ash and slag use, mainly in cement and concrete products, increased from 11 million tons in 1987 to 70 million tons in 1995.

Coal-fired power plants are also among the largest sources of carbon dioxide emissions, accounting for one-third of China's total emissions, or about 190 million tons in 1995. However, China has no specific plans to reduce greenhouse gas emissions from power production because they are not required to do so under the international treaties being negotiated. On the other hand, China's energy conservation programs and local environmental controls are reducing the growth in emissions. Energy conservation and efficiency will be key measures in the near term, while renewable energy, including hydropower resources, may play a larger role in the long term.

One option for reducing environmental problems related to China's electric power industry is changing the energy supply structure. Cleaner sources, such as natural gas and renewable energy, could play a much larger role in reducing harmful emissions and waste products. The efficiency of current technology could also be improved by retrofitting or replacing smaller, older units, reducing transmission and distribution losses, optimizing plant dispatch operations, and lowering in-plant power usage. Using higher quality coal — either washed or naturally lower in ash and sulfur — can significantly reduce pollution. In southern and eastern coastal areas, even imported high-quality coal could be cost-effective, but there is also a priority to use the cleanest coals in industrial and residential applications where local pollution is more serious than from power plants.

China could also benefit from adopting advanced energy technologies. The Chinese have been slow to develop flue gas desulfurization to control acid rain. Advanced clean coal technologies, such as integrated gasification combined-cycle and pressurized fluidized bed combustion, are still in the demonstration stage. China also lacks the capacity to produce large, world-class gas turbines for use in the power sector. These turbines can be used with a wide range of fuels and already achieve efficiencies approaching 60 percent in industrialized countries. Other technologies such as fuel cells, photovoltaic cells, and wind turbines may be important means of solving energy and environmental problems in the future.

II. Comparing Alternatives

This section evaluates alternative power generation sources in three steps:

1. Baseline power demand is estimated from existing studies.
2. The annualized cost of new power generation technologies, including capital, fuel, operations, and associated environmental costs, is estimated and converted to U.S. cents per kilowatt-hour.
3. Demand projections and various power supply cost estimates are incorporated into a linear programming model to determine the least-cost combination of technologies under different scenarios through 2015. The scenarios represent alternative policy cases tested for their impact on average generation costs and for changes in fuel supply mix, local pollution impacts, and greenhouse gas emissions relative to present and baseline demand.

A. Methodology and Baseline Assumptions

The authors used a simple linear programming (LP) model to analyze the cost and environmental impacts of possible electric power futures.[42] (See Box 1.) This model is driven by a set of economic growth assumptions developed exogenously (outside of the model). The LP model selects the least-cost combination of technologies based on the details of costs, emissions, and other constraints defined by the modelers. For example, the authors can set limits on sulfur emissions; the model then finds the least-cost set of power sources that will satisfy demand without violating the limits. Cost and performance details are estimated separately in Appendix B. A flowchart of the model is presented in Appendix C.

This approach to modeling and analysis is not unflawed, but is considered to be the best available tool for evaluating the Chinese power sector, especially for the relatively short time period considered. Macroeconomic general equilibrium modeling might have been preferable if the power sector more nearly approached that of a competitive economy, but it demonstrably does not. Market-based models do not simulate heavily distorted markets well. Moreover, any model simulating China's electricity sector is subject to

Box 1

A Guide to Linear Programming for Power Sector Analysis

Analysts use linear programming (LP) models to optimize combinations of inputs whose values are valid only over specific ranges. For example, power planners and electric utilities use LP models to determine the types of power plants required to meet least-cost power demand over time while meeting limitations in pollution emissions, energy sources, and manufacturing capacity. Models can help planners analyze alternatives, but non-quantitative factors must also be considered when designing real-life systems.

Researchers use two classes of models to analyze energy systems. LP models are often called “bottom-up” models because they contain detailed information about technology and costs. They have rich engineering detail and rely on user input to simulate broader economic conditions. “Top-down” models, on the other hand, begin from a higher level of economic reality by simulating the interaction of supply and demand in the main sectors of an economy. While top-down models have less detailed information about energy technologies and costs, they capture the reality of consumer behavior better than bottom-up models. Some models, like MARKAL-MACRO, try to integrate the economic reality of top-down models with the engineering detail of bottom-up models.

Researchers at Battelle created a generic LP model which each of the country teams in this study modified to analyze least-cost power options according to the conditions in their specific countries. The model can choose among 17 different types of power plants (coal, petroleum, natural gas, nuclear, hydroelectric, and renewable) to meet power demand. The model divides the country into as many as five regions to capture the variation in energy availability, fuel cost, and environmental limitations. Simulation begins with a base year (1995) and then determines the amount of new capacity from each type of power plant needed to meet demand over 5-year intervals.

After analysts enter technology and cost characteristics of the power plant options, the model calculates the levelized, or lifecycle, costs of power generation. Levelized cost analysis accounts for all the costs of building, fueling, operating, and controlling pollution from power systems and spreads them out over the economic life of the plant. In this way, the costs of delivering power to users from nuclear plants (with high construction and low fuel costs) can be compared directly with the costs of providing power from combined-cycle plants (low construction and high fuel costs). Analysts also enter the regional power demand over time. These values are calculated separately according to estimates of economic growth and power demand intensity.

The actual linear program will then find the minimum cost combination of power plants needed to meet the demand. Additional constraints can include emission caps on pollutants such as sulfur dioxide, manufacturing limitations for power generation equipment such as nuclear reactors, energy supply limitations such as hydropower capacity, and transmission line characteristics that limit the amount of power that can be sent from one region to another. For a given time period, the LP will choose the cheapest power source available and continue to use that technology until a constraint prevents its use. LP models need expert input to define when constraints are needed to simulate reality.

uncertainty because consumer prices have been subsidized, and specific fuel costs have been affected by cross-subsidies. Optimization programs like this one poorly reflect the reality of consumer behavior. No model can fully account for investor preference, such as risk mitigation or financial guarantees, or ensure that energy security and diversity issues are addressed without input from the modeler. Bottom-up models do provide realistic technical and performance characteristics, but require expert input to define constraints over which specific values may be feasible.

Economic and Social Drivers

Population and labor productivity growth drive economic growth and energy demand forecasts. Due to the government's one-child policy, annual population growth rates have remained relatively low in China, falling from about 1.5 percent in 1990 to 1 percent in 1997. While highly controversial, China's success in controlling population growth has resulted in tremendous energy savings relative to the baseline.

China's economy has grown rapidly since 1979 because economic reforms vastly improved economic efficiency and labor productivity. Real economic growth averaged almost 11 percent a year in the 1990s until late 1997, when domestic reforms and the Asian financial collapse began to slow economic growth. Growth has also been uneven nationwide, with the east generally expanding faster than the west. The eastern coastal area accounts for over one-third of the nation's economy. The northern and western regions have grown much slower than the national average. The Chinese face considerable uncertainty about their prospects for continued rapid economic development, however, without additional reforms.

This analysis builds its baseline power demand projection from the results of recent Chinese studies of electric power demand. Demand is determined by the development plans of the central and regional governments, as well as the physical and economic constraints of China's regions. Forecasts used in this study draw on recent analyses by the Energy Research Institute and other institutions, including Qinghua University and the Electric Power Research Academy in Beijing.[43] (See Table 7.) While these studies anticipate rapid growth in economic and power demand, the electricity consumption estimates used in this analysis are approximately 12 percent lower than the previous forecasts by 2015 due to the recent slowdown in energy consumption. Reasons for rapid growth in power demand include:

- Continued economic restructuring and enterprise reform
- Modernization of agricultural practices
- Rapid growth in demand for petrochemicals and construction materials
- Rapid growth in the service sector
- Rising living standards leading to increased consumer demand
- Substitution of electricity for dirtier, less convenient direct fuel use
- Growth in new end-uses requiring electricity, e.g., computers and other electronic equipment, heating and air conditioning, and environmental controls.

These trends point to greater economic efficiency, which will increase economic wealth, and to substitution of electricity for other fuels because of its convenience, relative cleanliness, and safety.

Table 7

Chinese Power Demand 1995-2015

Year	1995	2000	2005	2010	2015
Electricity demand (TWh)	1,002	1,310	1,670	2,137	2,740
Demand per capita (kWh)	828	1,015	1,280	1,607	1,977

Sources: Adapted from *Long-term Energy Demand Forecast*, 1994 and *Research on Energy Development Strategy*, 1994.

Three countervailing trends could slow the rate of electric power demand growth:

- Advanced demand-side technologies that reduce electricity consumption per unit of economic output are being introduced and are penetrating the Chinese market.
- Structural changes within the economy are boosting the contribution of high value-added light industry and service sectors at the expense of more energy-intensive heavy industry, although energy-intensive industry is still expanding.
- Government policy and market pricing for energy have effectively promoted energy efficiency, which will help check the growth rate of electricity consumption.

B. Scenario Analysis

This section presents the results of six scenarios: baseline, sulfur dioxide control, carbon dioxide control, natural gas, clean coal, and energy efficiency. These scenarios were created to analyze the impacts of different policy measures. (See Table 8.) For example, the natural gas scenario shows how sensitive the penetration of gas-based technologies is to fuel availability and fuel cost. The scenario also estimates the carbon mitigation potential of such actions. Many common assumptions hold true for each scenario.

The model assumes the construction of all hydropower stations currently planned or under construction and does not optimize their potential inclusion in the scenarios on a least-cost basis. By 2020, the maximum hydropower capacity that can be exploited in the southwest will be up to 50 percent of total exploitable resources in that region, and 80-90 percent in other regions.

Table 8

Summary of Scenario Descriptions

Scenario	Major Policy Mechanisms
Baseline	No change in policy; status quo changes in technologies and energy prices.
Sulfur Dioxide Control	Cap emissions at levels up to 50 percent lower than the baseline case by 2015 or separately impose sulfur dioxide fees ranging from $181 to $1,446 per metric ton of emissions.
Carbon Dioxide Control	Cap at 10 percent below baseline by 2015.
Clean Coal	Simulate international investment in clean coal technologies.
Natural Gas	Relax gas availability and price constraints on gas use in the power sector.
Energy Efficiency	Simulate a reduction in power demand by 10 percent by 2015.

Costs to construct transmission facilities for power plants are included when the plants are located far from population centers. In other words, the model accounts for the cost of inter-regional transmission while intra-regional costs are assumed to remain roughly equal for all technologies and provide no economic advantage to one over another. While this assumption tends to favor centralized power plants over small-scale distributed power generation within a single region (which has no transmission costs and low distribution costs), the advantage is not enough to significantly alter the least-cost mix of generation.

Renewable sources of energy, especially wind power, will no doubt play larger roles in China's electric power future. Power from renewable energy currently does not compete with more traditional forms of power generation in cost or convenience, unless, perhaps, all of the environmental factors are taken into account. Nevertheless, there will be some isolated regions and situations through 2015 where renewable energy does provide least-cost power; we assume that these situations will be a small percentage of the total power needed throughout the country.

In the north and southwest, coal for power generation can generally be supplied from within the region. In Guangdong and eastern and central China, coal used for new power plants will need to be transported from the north or imported from abroad.

Fuel costs for power generation depend on the cost of production and transportation. (See Appendix B for all technical and cost assumptions.) Conservative estimates for natural gas prices paid by power generators are used in all scenarios but one. Availability of gas for power generation is also limited in all but the natural gas scenario. These assumptions reflect the debate within China over the role of natural gas in power generation as opposed to its use in industrial and residential applications. Capital costs for power generation and transmission equipment are discounted at a rate of 10 percent.

Results from each scenario described below include the amount of power that each type of supply technology would produce under the least-cost requirement; emissions of sulfur dioxide and carbon dioxide; and capital, fuel, and operating costs.

Baseline Scenario. A baseline scenario with no external constraints was developed as a basis for comparison with other scenarios. The baseline scenario employed here is a conservative projection of China's power future that closely tracks previous Chinese forecasts;[44] the scenario assumes that electric power policies will not change radically, although some technologies are projected to improve gradually. In this sense, it might be considered a business-as-usual scenario, but China may face such overwhelming pollution in some regions that much stricter environmental control measures will be required. Indeed, if the baseline case actually occurred, sulfur emissions alone could devastate major areas of the country.

Conventional coal-fired power is the least-cost option in the baseline scenario. Clean coal technologies have no role in the baseline. Coal-fired plants without flue gas desulfurization supply almost 85 percent of the country's electricity; hydropower provides most of the rest. (See Figure 4.) Even in Guangdong and the east where coal prices are relatively high, coal-fired power generation remains the cheapest technology. This scenario does not incorporate sulfur fees or other environmental externalities.

Figure 4

Baseline Power Generation 2015 (terawatt-hours)

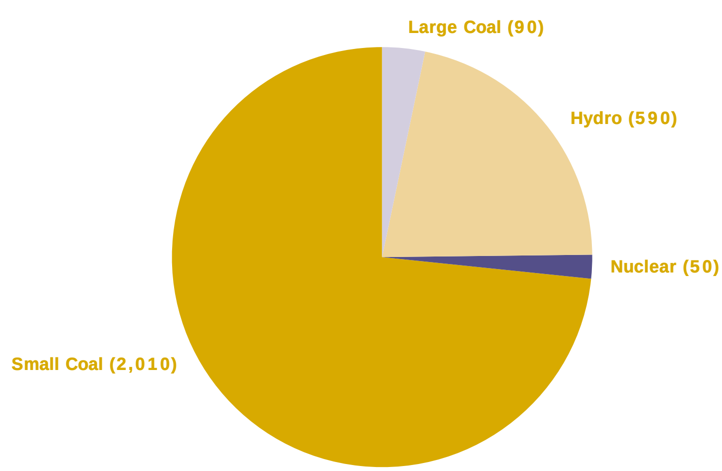


Table 9

Baseline Results

	Units	1995	2000	2005	2010	2015
Generation	Terawatt-hours	1,037	1,311	1,670	2,137	2,740
Capacity	Gigawatts	212	279	358	451	565
Total Cost	Billion USD	—	9	50	138	252
CO_2 Emissions	Million Tons-C	189	210	250	349	491
SO_2 Emissions	Million Tons-SO_2	8.5	9.2	10.4	13.8	20.5

Note: Total cost refers to the discounted capital, fuel, and operation and maintenance costs over the preceding five-year period. Cumulative total costs from 1995-2015 are presented in Table 11.

Cumulative power sector costs between 1995 and 2015 would reach $449 billion. (See Table 9.) Coal consumption for power generation in 2015 would reach 980 million tons. Total sulfur dioxide and carbon emissions from thermal power plants would reach 21 million tons and 491 million tons, respectively — increases of 2.4 and 2.6 times over 1995 levels.

Sulfur Dioxide Control Scenario. Health and property damage due to sulfur dioxide emissions ranks among China's most serious air pollution problems.[45] This analysis evaluates two different ways to limit emissions: first, a cap on sulfur emissions and second, a fee as an alternative policy measure. The limits imposed under the cap amount to reductions of 10, 20, 30, and 50 percent relative to the emissions from the new power plants added in the baseline in 2000, 2005, 2010, and 2015, respectively. (See Table 9 for baseline results.) The model incorporates a cap as a constraint, while the fee increases the cost of power for a technology in proportion to the emissions per kilowatt-hour and the level of the fee.

Even a 50 percent sulfur dioxide emission cap would not end coal's dominance of power generation in China. Instead, tightening the sulfur emissions caps shifts consumption to washed coal, flue gas desulfurization, and, to a minor degree, gas-fired systems. Theoretically, this approach would work effectively, but the model does not reflect potential problems with policy implementation and enforcement. Total costs in this case increase about 5 percent to $471 billion compared to the baseline.

A variation of the sulfur control scenario uses fees to model the effect of applying a market mechanism on sulfur emissions control. The sulfur dioxide fee was set to reflect the estimated environmental damage caused per ton of sulfur released. Though this cost would vary with the level of regional economic development and local meteorological conditions, there was no practical way to incorporate those differences in these results. Consequently, this study chose three sets of sulfur dioxide fees and varied these regionally to match (to the degree possible) the regional impacts of sulfur pollution. The fees range from as low as $181 per ton of sulfur in the north to almost $1,446 in the southwest. (See Table 10.)

The sulfur fees produce little change in the fuel supply mix. Coal remains the dominant source of energy for electricity generation. (See Figure 6.) Coal washing is the cheapest control measure, though when the fees become high enough, scrubbers become the least-cost option in central and eastern regions. Washed coal accounts for about 35 percent of the coal used in 2015. China would need to expand coal-washing facilities considerably to meet this supply need and faces water shortage problems in some regions.

Table 10

Regional SO_2 Emission Fee (USD/Ton-SO_2)

	Low case	Middle case	High Case
North	181	361	542
East and Guangdong	482	964	1,446
Central	361	723	1,084
Southwest	482	964	1,446

Source: *China's Electric Power Options: An Analysis of Economic and Environmental Costs*, 1998.

The mid-level fee reduces sulfur emissions to less than 13 million tons annually by 2015 compared to 20.5 million in the base case. (See Figure 5.) Carbon emissions, however, fall only 7 million tons, less than 2 percent, over the same period. (See Figure 7.) Total costs of the mid-level sulfur fee rise to $512 billion, or 14 percent above the baseline if the sulfur fee is included in the cost of power. If only the shadow sulfur fee is used (meaning that the least-cost supply mix is planned using the fee, but the final price of power does not include the fee), total costs only reach $465 billion — a little less than 4 percent above the baseline. (See Table 11.)

Figure 5

Sulfur Emissions by Scenario

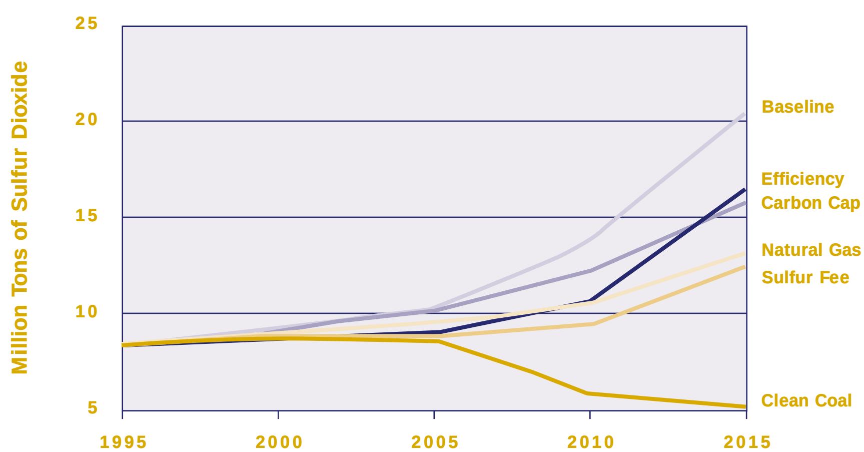


Table 11

Summary Results

Scenario	Cost Billion $	SO_2 (M tons)	CO_2 (M tons)	Capacity (GW)	Coal Use (M tons)
Baseline	449	20.5	491	565	980
Sulfur Fee	465	12.7	484	565	912
Carbon Cap	469	17.3	442	578	857
Natural Gas	466	13.2	422	565	764
Clean Coal	475 +	5.2	448	565	880
Efficiency	394	17.9	396	513	852

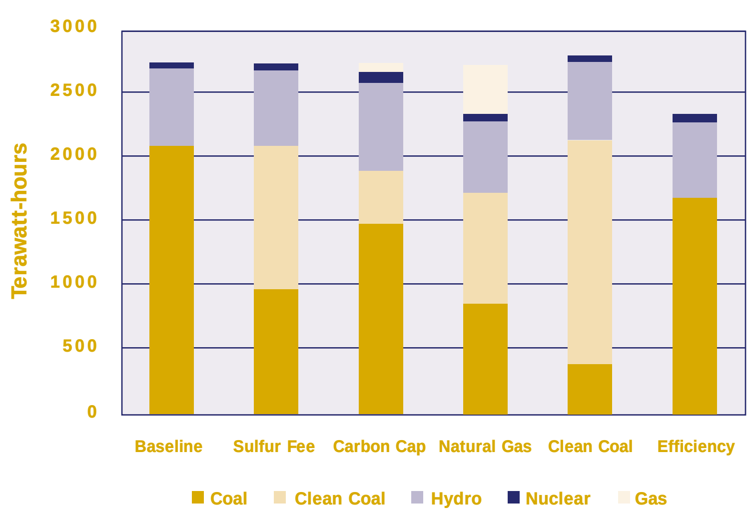
Note: An additional investment of approximately $140 billion is required from outside sources in the clean coal scenario to reduce capital costs. Sulfur fees are mid-level values as shown in Table 10.

Carbon Dioxide Control Scenario. The carbon dioxide control case tests two options for reducing emissions of carbon dioxide in the Chinese power generation sector. One approach places caps on emissions; the other imposes carbon taxes. Both approaches are implemented in the model using the same methods as the sulfur reduction policies, but only the results of the carbon cap are presented in the tables and figures.

The carbon dioxide cap reduces aggregate emissions by 10 percent compared to the unconstrained total in the baseline. The results indicate that the most cost-effective response is substitution of washed coal, hydropower, natural gas, and nuclear power for standard coal. Mitigation options such as use of integrated gasification combined-cycle and pressurized fluidized bed combustion are not selected for solving this problem because their high capital cost and carbon emissions levels make them uncompetitive. But both nuclear and hydroelectric power also have high capital costs, a problem compounded by long lead-time for construction. Washed coal use would grow to provide 8 percent of total generation in 2015 because its higher efficiency results in lower carbon emissions than standard coal. Natural gas use would grow from virtually nothing to 2.5 percent, while hydro and nuclear would respectively increase to 26 and 4 percent of total generation. (See Figure 6.) Nuclear, gas, and hydropower all played more prominent roles in a sensitivity analysis using a stricter 30 percent reduction cap for carbon, but this seems an unrealistic scenario for China at this stage.

Figure 6

Power Generation Mix in 2015



The results of the carbon tax cases reveal that taxes will have no impact on the power generation mix unless the tax is higher than $25 per ton of carbon; the tax has only limited effect until it reaches $75 per ton. A $125 per ton tax, however, would reduce coal-fired power to only 3 percent of total power generation in 2015, with nuclear power climbing to two-thirds of supply. These results are not surprising given the assumptions on limited natural gas availability for power generation.

Total costs of capping carbon dioxide emissions at 10 percent below the baseline by 2015 are $469 billion, about 4 percent higher than the baseline.

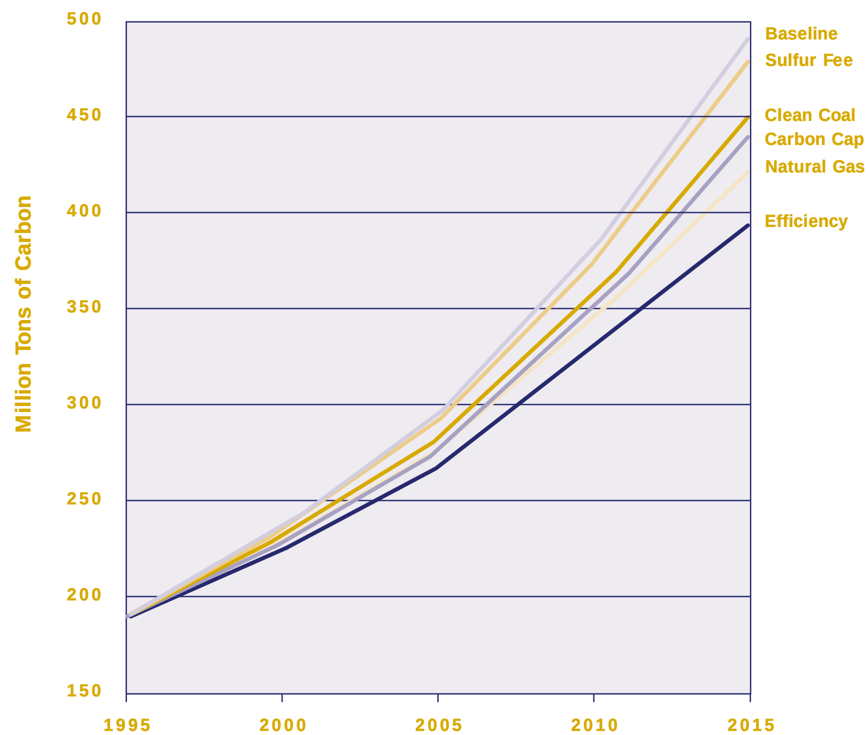
Natural Gas Scenario. The natural gas scenario tests the sensitivity of the availability and price of natural gas in the power sector. In the baseline scenario, constraints are placed on the amount of natural gas available for power generation to simulate the existing policy of limiting the use of gas for power generation. Natural gas has the highest environmental benefit in replacing coal use in domestic cooking, heating, and industrial boilers — not in the power sector — because coal combustion causes the most damage to human health in those applications. It is with good reason, then, that some planners want to restrict use of natural gas in the power sector to reserve scarce resources for other uses. In many countries, however, the power sector is often the driving force behind natural gas projects, but without power plants serving as a strong demand anchor, development of new gas fields or pipelines may never happen.

In this scenario, the constraints on natural gas availability are relaxed. Prices are reduced to simulate market reform and the tendency for power plant gas tariffs to be lower than those paid by industrial and residential consumers. The maximum price to power generators is set at $3 per gigajoule, a value similar to, or slightly higher than, many other countries.[46] Higher efficiencies for combined-cycle systems are also assumed. The baseline uses a constant value of 52 percent through 2015 while this scenario assumes that efficiency will climb gradually to 61 percent by 2015. Cutting-edge plants already are close to achieving this efficiency, but China may be hard pressed to manufacture units with this performance by 2015. An average environmental fee of $300 per ton of sulfur dioxide emissions is also used in all regions of this scenario to account for an average environmental cost of coal use. This fee is included to simulate the environmental benefits that gas would create in offsetting coal use. Use of the fee here differs from the sulfur control scenario, which maintained tight restrictions on gas availability and price.

Results from the scenario show that carbon emissions would decline by 14 percent and sulfur dioxide emissions by 35 percent if policy measures were enacted to achieve the assumptions used in this scenario. (See Figures 5-7.) Gas provides least-cost power only in the southern coastal regions, where coal is relatively expensive. Approximately 64 billion cubic meters would be consumed in combined-cycle power plants in 2015, about half of the country's total projected natural gas consumption that year.[47] Total costs would increase only slightly from the baseline scenario, to $456 billion, mainly because gas prices in the southern coastal regions are held to $3 per gigajoule. With the same gas costs as in the baseline, this scenario would require a total of $466 billion, less than 4 percent above the baseline. (See Table 11.) In both cases, the value of the environmental externality has been subtracted out of the total costs. The shadow costs were used for planning purposes only.

Figure 7

Carbon Emissions by Scenario



Natural gas prices will strongly influence the amount of gas used for power generation. Historically, Chinese gas prices were set below production costs to subsidize the fertilizer and industrial sectors. Now, new pipeline projects set gas prices at market levels, allowing developers to recover their costs and earn a profit. A likely scenario sees relatively high gas prices in the uncontrolled segment of the Chinese natural gas sector, at least until it is more fully reformed and mature. While $3 per gigajoule is considered relatively high for power markets in the United States and Europe, it may take a decade or more for reform to remove the distortions from China's gas sector.

Clean Coal Scenario. The Chinese government has a strong interest in developing clean coal technologies such as integrated gasification combined-cycle and pressurized fluidized bed combustion as substitutes for dirty, conventional coal-fired power. However, these technologies may have difficulties competing against domestically manufactured conventional coal units until they become much less expensive.

This case examines the potential for international cooperation — through something like the proposed Clean Development Mechanism, for example — in sharing capital costs to accelerate market penetration of advanced clean coal technologies. The scenario supposes that this mechanism would enable a host country like China to increase the market share of those technologies at subsidized costs, thereby reducing greenhouse gas and other emissions. This research only considers the potential for carbon mitigation and not the sharing or transferring of credits.

The market penetration of integrated gasification combined-cycle combustion increases to 16 percent of the total national generation capacity in 2015 only when capital costs are reduced by 40 percent. If a mid-level sulfur dioxide fee is added to reflect the improved local environment, the market penetration of integrated gasification combined-cycle and pressurized fluidized bed combustion increases sharply to approximately 60 percent of total national generation capacity.

The results indicate that since integrated gasification combined-cycle and pressurized fluidized bed combustion are coal-based generation technologies, their market penetration will yield fewer effects on CO_2 mitigation. Nevertheless, they will mitigate SO_2 emissions significantly. Sulfur dioxide emissions drop by 75 percent to 5.2 million tons. Carbon dioxide, meanwhile, declines only 9 percent to 448 million tons. (See Table 11.) This puts in question the effectiveness of integrated gasification combined-cycle and pressurized fluidized bed combustion as carbon mitigation measures, especially since an additional $140 billion in outside funding would be needed to lower capital costs by 40 percent, and the domestic costs would be $26 billion more than the baseline.

The team also simulated the reduction in combined-cycle capital costs through a similar scheme of international cooperation. Results did not differ from the baseline case even with a 50 percent reduction. Because combined-cycle power plants are much more sensitive to fuel costs than capital costs, the lower initial cost did not boost penetration of these plants. This case also used the tight baseline constraints on gas availability and the relatively high gas costs.

Efficiency Scenario. Raising demand-side energy efficiency has been demonstrated to be cost effective in China.[48] The energy efficiency case tests the impact of slowing power demand gradually by 10 percent by 2015 compared to the baseline scenario. The results show that carbon and sulfur dioxide emissions could each be reduced by 19 percent and 13 percent, respectively, by 2015. Also, postponing 52 gigawatts of coal-fired generation capacity would save $55 billion in building and operating costs. (See Table 11.) Achieving this reduction in energy demand would likely require additional government incentives, although such a reduction could also be accomplished using market forces such as those employed by energy service companies (ESCOs).[49] These results assume that any costs required to achieve the 10 percent reduction would be balanced by benefits such as energy savings, pollution reduction, capital preservation, and higher power quality.

III. Conclusions and Recommendations

China's electric power demand will increase with economic growth and improved living standards. Power demand is projected to expand almost three-fold, growing from about 1,000 terawatt-hours in 1995 to 2,740 terawatt-hours in 2015. Coal consumption in the power sector would also nearly triple in the baseline case, while sulfur dioxide and carbon dioxide emissions would rise more slowly. Coal ranks as the largest and lowest-priced energy source, and conventional coal-fired power generation remains the cheapest technology in China. Without considering environmental and health costs, China's power would become even more coal-intensive, and pollution levels would increase significantly with damaging effects.

But when some of the environmental costs are accounted for, the electric power mix changes. China has many technological options to reduce sulfur dioxide emissions, including coal washing, flue gas desulfurization, clean coal combustion technologies, and fuel switching to natural gas, hydropower, or nuclear power. Some of these options — like flue gas desulfurization — actually increase carbon dioxide emissions. Others, like integrated gasification combined-cycle and pressurized fluidized bed combustion, could lower carbon emissions slightly. Reducing carbon dioxide emissions significantly would require dramatic changes in the mix of power generation, with low- and non-carbon sources playing a major role in future power supply. The overall cost of power development would increase greatly as a result. Using natural gas for power generation — a controversial topic in China — can address both problems effectively with only slightly higher total costs.

This report provides six recommendations and conclusions to help steer China's electric power industry toward a more sustainable future while fulfilling demand for growth in electric power supply.

1. Using coal without sulfur dioxide emissions controls will worsen already serious environmental problems with potentially damaging consequences. China needs to develop and deploy technologies that lower sulfur emissions to avoid further degradation of the environment.

2. Natural gas can help reduce sulfur dioxide, carbon dioxide, and other pollution from power generation, but gas availability and price are critical components in this scenario. For widespread use of gas in power generation in the near future, China would need to accelerate development of a coherent gas policy and infrastructure. On the one hand, environmental priorities call for gas use in non-electric residential, commercial, and industrial applications, which currently burn coal very inefficiently. On the other hand, the power sector can help anchor investments in natural gas infrastructure development that might not otherwise be possible.

3. Nuclear power is not economically competitive with other electric power options studied. Nuclear could only play a larger role if China chose it in order to reduce sulfur dioxide or carbon dioxide emissions or to improve energy security.

4. China's remaining hydroelectric resources are located in remote areas far from load centers, making their development expensive. The future role of hydropower is constrained, much in the same way as nuclear power.

5. Renewable energy alternatives such as biomass, wind energy, and geothermal cannot compete with other supply options considered in this study. While these energy sources often have unaccounted for benefits — such as little or no associated transmission and distribution costs — costs remain higher than other options. If costs continue to decline, however, renewables will be long-term solutions to economic and environmental problems.

6. China should continue to promote energy efficiency. This emphasis has helped to preserve capital, reduce pollution, and improve competitiveness among Chinese industries.

China can strengthen its research and development of power technologies, focusing particularly on low-cost flue gas desulfurization, low emissions burners, integrated gasification combined-cycle coal combustion, pressurized fluidized bed combustion of coal, advanced gas combined-cycle turbines, fuel cells, large-scale wind turbines, and photovoltaic technology. By learning to manufacture these technologies domestically, China can meet much of the future demand for electric power, and reduce energy consumption and environmental pollution at low cost.

Even without a modeling exercise to consider the potential impacts, China could create a more rational market-based power system by promoting electric power sector reform. Competition in this sector is becoming more common in many countries because it lowers prices and allocates resources efficiently. China has started to introduce competition in power generation, but it is also important to maintain rational nationwide planning to unify and coordinate development of the power sector.

International cooperation remains critically important, especially in introducing advanced electric power technologies and mitigating greenhouse gas emissions. Appropriate mechanisms to enhance technology transfer equitably would benefit both China and the world.

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Appendix B: Assumptions for Cost Analysis

Table A-1

Assumptions used in Power Generation Equipment Cost Estimates

Technology	Capital Cost ($/kW)	Construction Period (years)	Fixed O&M ($/kW-year)	Efficiency (%)
300 MW w/ESP	602.41	2	18.07	37
600 MW w/ESP	662.65	3	19.88	39
300 + dry FGD	686.75	2	20.60	34
600 + wet FGD	801.20	3	24.04	36
IGCC	1,325 (1,024)*	4	39.76	42
PFBC	1,204 (1,024)*	4	36.14	42
Combined-Cycle**	663	1	19.88	52
Nuclear	1,807	5	54.22	33
Large Hydropower	1,325	7	19.88	—
Small Hydropower	843	4	12.65	—
Wind	964	1	19.28	—

* Capital cost after 2005.

** Fueled by natural gas, LNG, or oil.

Sources: Coal-fired capital costs are based on statistically averaged data from 1994-1996. See *China Electric Power Statistical Yearbook*, 1998 and *China's Electric Power Options*. Other data are based on international estimates and modified for China's environment as outlined in *Clean Coal Technologies for Developing Countries, International Energy Outlook, 1998* and *China's Electric Power Options.*

Table A-2

Raw Coal Prices by Region ($/ton)

	1995	2000	2005	2010	2015
Central	14	16	17	19	20
North	14	16	17	19	21
East	30	31	33	36	38
Southwest	12	13	14	16	18
Guangdong	34	35	37	40	42

Source: Staff estimates from the China Energy Research Institute, and *Analysis and Study on the Electric Power Market in China, 1999.*

Table A-3

Washed Coal Prices by Region ($/ton)

	1995	2000	2005	2010	2015
Central	25	28	30	33	35
North	37	40	42	45	48
East	30	34	37	40	44
Southwest	23	25	27	29	32
Guangdong	42	46	48	51	55

Source: Staff estimates from the China Energy Research Institute, and *Analysis and Study on the Electric Power Market in China, 1999.*

Table A-4

Domestic Natural Gas Prices by Region ($/GJ)

	2000	2005	2010	2015
Central	3.83	3.83	3.83	4.15
North	2.56	2.88	2.88	2.88
East	3.20	3.83	4.15	4.47
Southwest	2.56	2.88	2.88	2.88
Guangdong	3.20	3.83	4.15	4.47

Sources: CNOOC/ARCO, *South China Sea Natural Gas Development Study,* unpublished draft, April 1995.

Table A-5

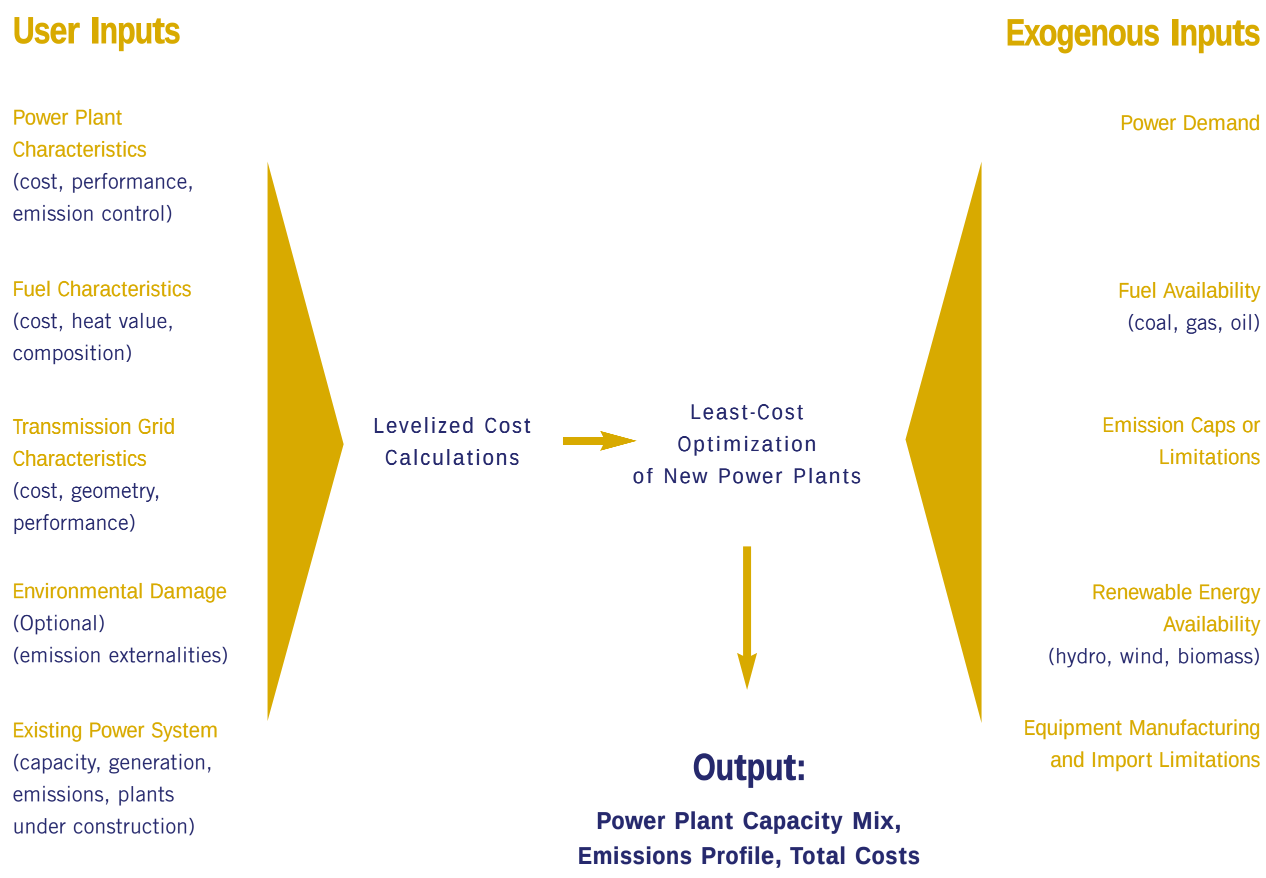
Oil Prices and Imported Natural Gas Prices for all Regions ($/GJ)

	2000	2005	2010	2015
Oil price	4.67	4.91	5.14	5.29
Imported gas price*	4.00	4.00	4.00	4.00

* Imported natural gas price indicates the LNG price in coastal regions and the price of importing natural gas by pipelines in other regions.

Sources: *China's Electric Power Options, International Energy Outlook 1998,* and authors' estimates.

Appendix C: The Linear Programming Model



Endnotes

1. Zhou Dadi and William Chandler directed the project; Guo Yuan and Jeffrey Logan led the modeling work.

2. All units in this report are based on the metric system unless otherwise noted. Currency is based on the 1998 U.S. dollar unless otherwise noted.

3. Per capita income is roughly $700 per year using an exchange rate of 8.28 yuan per dollar. An alternative measure — one that may overstate the standard of living in China as much as the exchange rate method understates it — is the purchasing power parity, which gives a per capita yearly income of approximately $3,000. Assuming $2,000 as an average, China's economy amounts to roughly $2.5 trillion, compared to about $9 trillion in the United States.

4. Over the past twenty years, China's energy consumption per unit of growth in gross domestic product measured in constant local currency has declined by over 4 percent annually, while energy consumption per unit of growth in the U.S. has fallen by slightly over 1 percent. Typical developing countries, on the other hand, exhibit an increase in energy consumption related to economic growth. See Battelle Memorial Institute and the Woodrow Wilson Center for International Scholars, *Climate Action in China and the United States,* Washington, DC, 1999. Official Chinese statistics on economic growth are viewed from abroad with increasing skepticism, however, and real growth may be significantly less than reported. A forthcoming report from Lawrence Berkeley National Laboratory provides a more realistic estimate of China's success in conserving energy based on revised economic growth estimates. See "Energy Trends in China in the 1990s," Berkeley: Lawrence Berkeley National Laboratory, LBL-44283.

5. Total costs include discounted capital, operation and maintenance, and fuel components. Capital costs include the turn-key costs to build a power plant and the transmission infrastructure costs when power will be sent between regions. Within a given region, transmission and distribution costs are not included. While the effects of ignoring these costs would generally be small as they tend to cancel out each other, it does give central power stations a slight advantage over distributed power generation.

6. Songbin Systems International, 1999; *China Energy Watch,* 1999, p. 12.

7. *China Statistical Yearbook,* 1999. An exajoule equals 0.95 quadrillion BTU.

8. *China Energy Watch,* 1999, p. 5.

9. *China Economy Daily (Zhongguo Jingji Ribao),* 15 March 1999.

10. For more background on energy efficiency efforts in China, see Sinton, et al., 1998.

11. *China Economic Times (Zhongguo Jingji Shibao),* 27 May 1999.

12. *China Annual Energy Review, 1996.* In Europe and the United States, the average is approximately 35.

13. *China Energy Databook,* 1996.

14. For more background information on these technologies, see Tavoulareas, 1995.

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16. *International Petroleum Economy [Guoji Shiyou Jingji],* 1997.

17. British Petroleum-Amoco, *Statistical Review of World Energy 1998;* CEDIGAZ, *Natural Gas in the World 1996 Survey,* 1996; Masters, C.D., et al., *World Resources of Crude Oil and Natural Gas: Proceedings of the 13th World Petroleum Congress,* 1992.

18. The China United Coal Bed Methane Corporation has signed formal contracts with at least four international petroleum companies to explore and develop coal bed methane (CBM) resources. Removing the methane from coal mines improves safety, one of the drivers behind CBM development in China. Approximately 2,000 coal miners lose their lives each year in accidents in China's major coal mines. Accidents in the country's numerous small, unregulated mines account for an additional 8,000 deaths. "China Coal Mine Blast Kills 77, Injures Eight," *Reuters,* 30 January 1998.

19. "Output of China's Major Energy Resources Rises in 1996," *Xinhua,* 1 February 1997.

20. Petroleum imports are projected to surpass one million barrels per day by 2000 and three million by 2010. See David Fridley, *China: Energy Outlook and Investment Strategy,* paper presented at the Oil and Money Conference, London, 18-19 November 1997.

21. This is lower heating value (LHV), one of two common measures of efficiency. The lower heating value refers to the direct heat energy produced when burning the fuel. Additional energy is available in the form of the condensation heat of steam present in the combustion gases. When this is added to the LHV, the condensation heat yields the higher heating value (HHV) of the fuel. For gaseous fuels, LHV is about 10 percent higher than HHV.

22. *China Energy Perspective [Zhongguo Nengyuan Zhanwang],* 1997.

23. See "Nuclear Power in China: Slow Breeder," *The Economist Intelligence Unit,* 19 January 1998, for a discussion of financing difficulties in China's nuclear power program.

24. *Research on Energy Alternatives in the Future [Weilai Nengyuan Xuanze Yanjiu],* 1996.

25. Personal communication between Jeffrey Logan and Shi Pengfei of the China State Power Company, 13 July 1999.

26. *Study on Alternative Energy and Energy Supply Strategy in China,* 1998.

27. "China Able to Make 600-kw Wind-Power Generating Units," *China Daily,* 5 January 2000.

28. Sinton, Jonathan E., and David G. Fridley, forthcoming. *Energy Trends in China in the 1990s.* Berkeley: Lawrence Berkeley National Laboratory, LBL44283.

29. Ibid.; *International Energy Outlook* 1998.

30. *China Statistical Yearbook,* assorted years; *China Energy Annual Review 1996.*

31. See *China Energy Annual Review 1996* for comparisons.

32. "China's Power Sector Undergoing Dramatic Change," *Energy Policy,* 1995.

33. *China Electricity Statistical Yearbook,* 1998.

34. A dozen of China's forty-one ministries were disbanded at this Congress. Some of the most important restructuring was in the State Economic and Trade Commission, which absorbed functions of several of the disbanded ministries, including the Ministry of Electric Power Industry.

35. *Analysis and Study on Electric Power Market in China [Zhongguo Dianli Shichang Fenxi Yu Yanjiu],* 1999.

36. *China's Electric Power Options: An Analysis of Economic and Environmental Costs,* 1998; and *Climate Impacts of Foreign Direct Investment in the Chinese Power Sector: Barriers and Opportunities,* 1997.

37. *Clear Water, Blue Skies,* 1997.

38. Ibid. According to this report, over 178,000 premature deaths and millions of illnesses could be avoided each year if China met its Class 2 air quality pollution standards. Class 2 standards are for residential rural and urban areas, and are comparable to those of the World Health Organization. Another World Bank report states that smoke and fine particulate matter causes 50,000 premature deaths and 400,000 new cases of chronic bronchitis in 11 large Chinese cities each year. The cost of air pollution in these cities is calculated to be greater than 20 percent of urban income. See *Can the Environment Wait? Priorities for East Asia,* 1997. Vaclav Smil, an expert on energy and environmental issues in China, reports that environmental pollution may be responsible for eliminating up to 15 percent of economic growth annually. *See Environmental Problems in China: Estimates of Economic Costs,* 1996.

39. Relevant governmental documents include State Council, *The 9th Five-Year Plan on Environment Protection and Long-term Plan for 2010,* State Council, 1996; National Environmental Protection Agency, *National Plan on Total Emission Control in the 9th Five-Year Plan;* Beijing, 1996; National Environment Protection Agency, *National Program for Trans-Century Green Projects (First Phase),* Beijing, 1996-97.

40. See Xie Zhenhua, *Controlling Acid Rain and Sulfur Dioxide Pollution and Improving Environmental Conditions,* Proceedings of the National Workshop on Acid Rain and Sulfur Dioxide Pollution Prevention, Beijing, 1998. Liu Bingjiang, et. al., *Study on Identification of Acid Rain and* SO_2 *Control Regions and Countermeasures,* China Environment Science Research, February 1998. Sensitive areas include acid rain control regions (ARCR) where acid rain problems are serious, and sulfur dioxide emission control areas (SECA), which are cities sensitive to sulfur dioxide pollution. ARCR and SECA cover 11.4 percent of China's territory, and account for more than 60 percent of the nation's sulfur dioxide emissions.

41. The total installed capacity of coal-fired power plants with unit capacities over 6 megawatts was 76 gigawatts in 1990, and particulate emissions totaled 3.6 million tons. By 1997, installed capacity had increased to 171 gigawatts, while particulate emissions increased by only 11 percent to 4.0 million tons.

42. For a review of linear programming, see *Linear and Nonlinear Programming*, 1996, or *Introduction to Linear Optimization*, 1997.

43. *Long-term Energy Demand Forecast [Changqi Nengyuan Xuqiu Yuci],* 1994; *Research on Energy Development Strategy [Nengyuan Fazhan Zhanlue Yanjiu],* 1994.

44. See, for example, *Analysis of Medium-long Term Electric Power Supply and Demand,* 1996.

45. This study does not consider the full range of environmental externalities resulting from coal mining, combustion, and disposal, but focuses on one of the most important from the government's perspective, sulfur dioxide. Particulate emissions are very damaging to human health and have a significant impact on the economy, especially outside the power sector. Nitrogen oxides, carbon monoxide, hydrocarbons, mercury, and carbon dioxide are some of the other pollutants that could be considered in designing a least-cost power sector based on full environmental accounting.

46. In 1997, U.S. power plants paid on average $2.58/GJ for their gas supplies. See U.S. Department of Energy, *Annual Energy Outlook 1999,* Washington, DC: Energy Information Administration.

47. Miao Chengwu, *Development and Forecast of China's Natural Gas Industry,* paper presented at the 2nd Sino-U.S. Oil and Gas Forum, Houston, Texas, 21 June 1999.

48. See, for example, *Energy Efficiency in China: Technical and Sectoral Analysis in China: Issues and Options in Greenhouse Gas Emissions Control*, Washington, D.C.: World Bank, 1994; or IRP and DSM in Beijing Energy Efficiency Center, China: Case Studies, Beijing: Pacific Northwest National Laboratory, 1996.

49. Energy service companies combine finance and engineering expertise to save clients money on energy bills. They typically use "performance contracting" to upgrade their client's energy-intensive equipment. The ESCO typically pays for all the equipment upgrades in exchange for a percentage of the monthly energy savings over an agreed-upon period of time. In China, the World Bank is introducing profit-driven ESCOs that could have a huge impact on energy efficiency in state-owned enterprises.

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