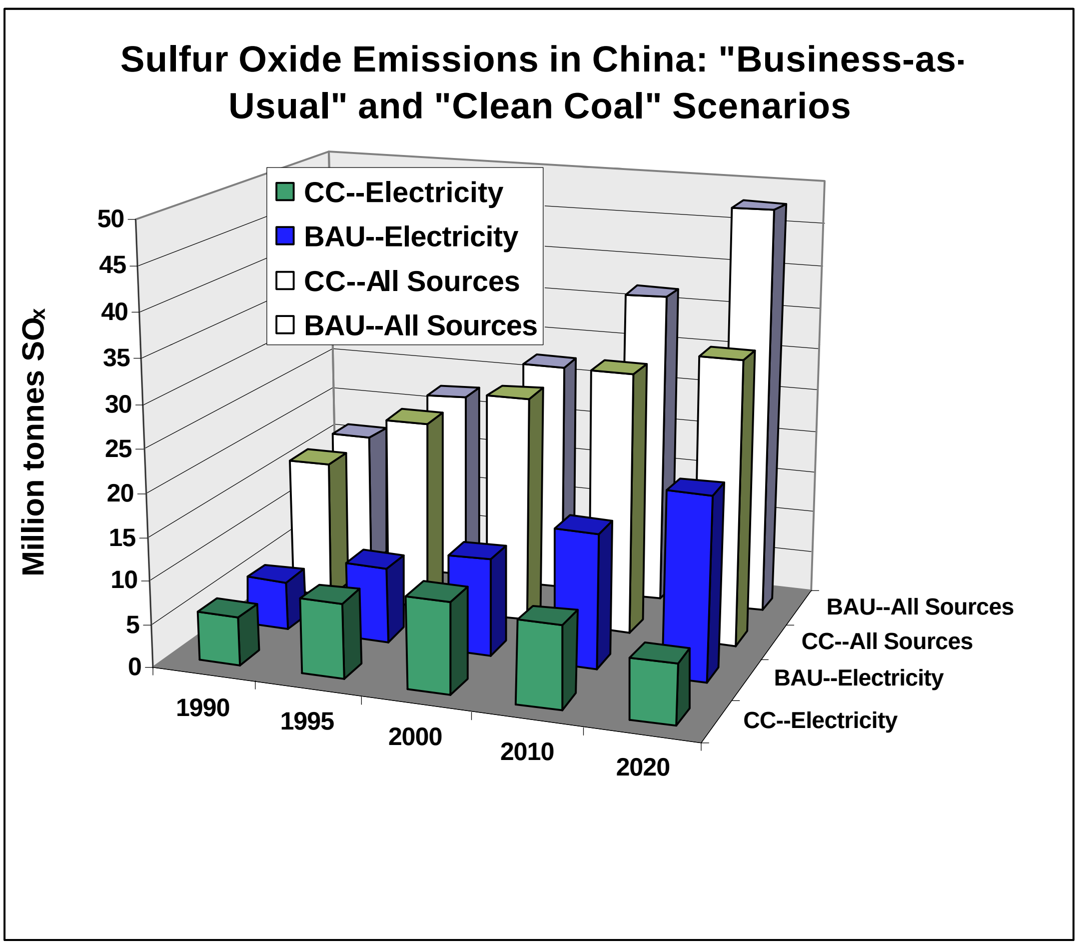
# Modeling of Clean-Coal Scenarios for China: Progress Report and Initial Results

**DRAFT** [October 13, 1999: David Von Hippel]

(Please note that this is a draft paper and will be revised upon the suggestions of reviewers.)



***Nautilus Institute for Security and Sustainable Development***

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**DRAFT**

[October 11, 1999: David Von Hippel]

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# Modeling of Clean-Coal Scenarios for China: Progress Report and Initial Results

## EXECUTIVE SUMMARY

Continued economic development in China will require a significant share of the world's resources—physical, financial, environmental. Different paths of energy-sector development in China will have different global, regional, and local environmental ramifications. Different energy paths will also have different implications for how energy sector investments in China are financed. In this paper, we begin a study of alternative energy futures in China by elaborating an energy demand scenario for China, then present two different visions of how supplies for energy —and specifically electricity—might be developed to meet future energy demand over the next 20 years. The focus here is on sketching two cases; a Business-as-Usual Case, and an Alternative case that stresses the implementation of so-called "Clean Coal" technologies and other electricity generation technologies designed primarily to reduce emissions of sulfur oxides without markedly affecting fuel supply patterns in China. The relative environmental and cost impacts of the two scenarios are then compared. This work has built upon on a number of past and ongoing Nautilus Institute initiatives.

A demand-driven model with substantial sector, subsector, end-use and fuel detail was used to provide a methodologically simple, transparent, and convenient framework for assembly and testing of alternative energy futures. Base year (1990 and 1995) data from a variety of sources were used to create a data set that describes the flows and end-uses of fuels in the Chinese energy sector. Using a combination of analysis of recent trends and conjectures about changes in the consumption of energy services in China over the period through 2020, a Business-as-Usual scenario for energy demand was developed. The supply of resources, and the capacity to transform primary resources into fuels (including the stock of power generation facilities), was built up to meet final fuel demand.

The Business-as-Usual (BAU) demand scenario is an extrapolation of the performance of the Chinese economy over the last 15 years or so, tempered somewhat by consideration of the recent crisis in the Asian financial markets and its impacts. As such, the BAU scenario postulates continued strong economic growth through the end of the 1990s and into 2000, with growth gradually slowing as the Chinese economy begins to mature. The commercial sector and lighter industries are assumed to show the strongest growth of the different sectors of the Chinese economy, with the growth in the output of heavy industries slowing, as recent trends already seem to show. Residential energy consumption is assumed to increase markedly, though household size declines and population growth slows. Personal travel is also assumed to expand markedly, with particularly rapid (continued) expansion in the stock and use of private vehicles. Energy intensities for demand-side devices continue to improve, but not at a rapid rate, as a combination of the desire to keep most production in-country and a lack of capital for high-efficiency investments tend to keep energy intensities higher than in the United States, Europe, and Japan. The type of economic evolution outlines here is consistent with a continued, but

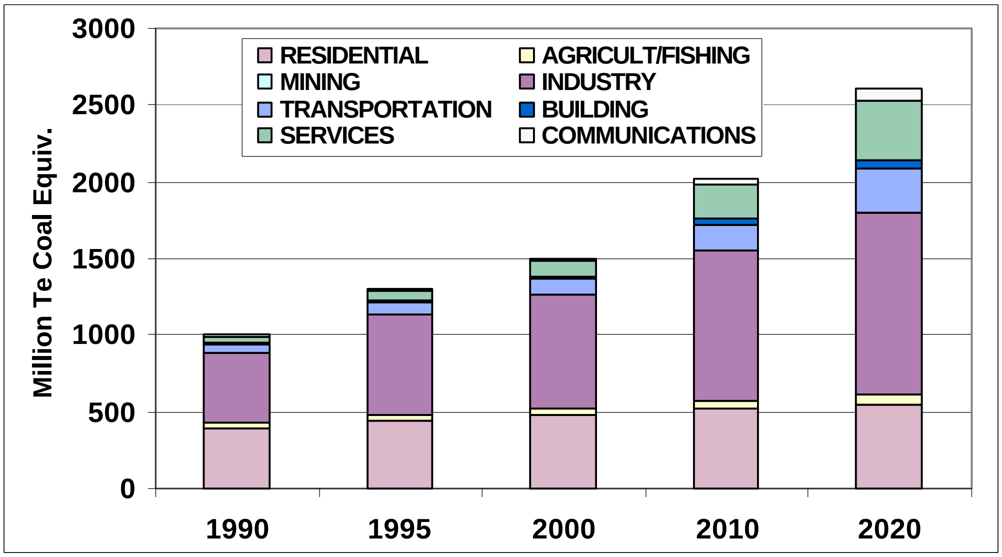
controlled and not abrupt, opening to the market economy model by China, with a reduction in materials use (cement and iron and steel, in particular) as domestic materials-use efficiency improves.

On the energy supply/transformation side in the BAU scenario, lack of capital means that coal-fired generation facilities continue to provide the great bulk of power supplies, with most of the expansion of coal-fired capacity being domestically-produced units. Progressively larger fractions of coal-fired power plants have domestically-produced scrubbers to remove sulfur oxides, however, though the scrubbing efficiencies are not as high as for new coal-fired power plants in North America, Europe, or Japan. Washed coal is used for power generation in increasing amounts. Nuclear power continues to expand, but modestly. The share of total primary supplies provided by natural gas use expands as well, but remains relatively minor through 2020. The use of renewable energy sources for electricity and other uses continues to expand, but not aggressively.

The Alternative/Clean Coal scenario demonstrates the production of the same (or very nearly the same) goods and services as in the BAU scenario, but does so in a different way, with different environmental consequences. As such, the Alternative scenario uses the same rates of growth of key variables such as population, households, urban migration, and the use of energy services, and industrial production. The major differences between the Alternative/Clean Coal and BAU scenarios lie in the degree to which modifications—including use of "end-of-pipe" pollution control equipment, washed coal, and advanced power generation cycles such as Integrated Gasification Combined-cycle (IGCC) and supercritical (SCPF) coal-fired power plants—are employed to reduce emissions of air pollutants (notably sulfur oxides) from electricity generation. The Alternative scenario is intended as one example of one of many possible outcomes, and it focuses on clean coal technologies primarily to illustrate the potential role of clean coal technologies—as well as the limitations of those technologies—in addressing environmental problems in China.

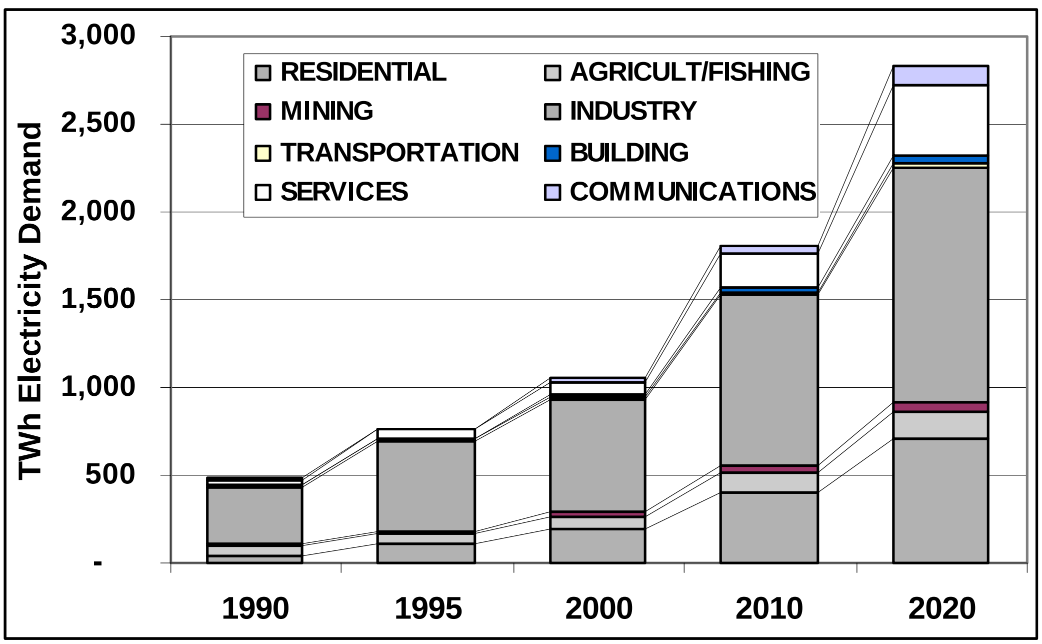
Figure ES-1 shows the changing sectoral pattern of energy demand under the BAU scenario. Although the industrial sector remains the largest consumer of energy through 2020, the fraction of energy used in the transportation and services sectors increase markedly. Residential energy demand increases less rapidly, primarily as a result of decreasing population growth and a trend toward more efficient use of fuels, including movement toward electric and gas home appliances.

***Figure ES-1: Estimated Energy Demand by Sector in China: BAU Scenario***




The pattern of increase of electricity use is somewhat different than that of overall energy use under the BAU scenario, as shown in Figure ES-2. Growth in electricity demand is greater (an average of 5.5 percent annually from 1995 to 2020) than growth in use of all energy forms, and the residential sector, as well as the service sector, is a major source of increasing demand.

***Figure ES-2: Electricity Demand by Sector in China: BAU Scenario***




Under both the BAU and Alternative/Clean Coal scenarios, coal remains by far the dominant fuel in terms of primary energy supply. Coal-fired power supplies over 80 percent of electricity demand throughout the projection period under both scenarios. In both scenarios, generating capacity increases from approximately 210 GW in 1995 to about 740 GW in 2020. In the BAU scenario, however, less than 15 percent of coal plants are fitted with scrubbers to remove sulfur oxides (or are advanced-cycle plants) by 2020, while in the Alternative/Clean Coal case only 20 percent of coal-fired generation—half of which burns washed coal—lacks equipment to control sulfur oxides by 2020. As a result of this difference, sulfur oxides emissions from power generation actually decreases after 2000 under the Alternative/Clean Coal scenario (returning to 1990 levels by 2020), while increasing at a rate of over 3 percent annually after 2000 in the BAU scenario. The decrease in sulfur oxide emissions from the electricity sector in the Alternative/Clean Coal scenario is insufficient, however, to prevent overall emissions of sulfur oxides from energy use to increase by roughly 50 percent between 1995 and 2020. Though emissions of particulate matter are substantially decreased under the Alternative/Clean Coal scenario (relative to the BAU scenario), emissions of carbon dioxide increase slightly.

The overall cost difference between the two scenarios totals approximately $11 billion in 1995 US dollars. This total includes payments (including interest and principal) on incremental capital costs of more expensive clean-coal capacity, the differential costs of O&M, other net fuel supply costs, and net resource costs associated with additional coal use. Of the approximately $11 billion total difference, about $2.5 billion is associated with net resource costs. The estimated additional capital costs, in real 1995 dollars, for electricity generation equipment under the Clean Coal scenario vary from about $1.5 to about $6 billion per year between 2000 and 2020. The total estimated difference in investment costs for electricity generation equipment between the two scenarios during 2000 to 2020 (when the major differences between the scenarios occur) is $66 Billion in real, undiscounted 1995 dollars. Discounted back to 2000 at a real discount rate of 10 percent, this is equivalent to about $21 billion in NPV terms. The estimated capital cost of all additions to electricity generation capacity between 2000 and 2020 is approximately $345 billion in undiscounted 1995 dollars, or $128 billion in NPV terms.

Major conclusions from the work described in this report are:

- The additional investment required to implement clean coal technologies to significantly reduce future sulfur oxide emissions from the electricity sector in China will be on the order of billions of dollars per year, an added investment of approximately 15 to 20 percent over the next 20 years.
- Finding funding sources for this type of investment in a better environment will require creative and innovative financial mechanisms, perhaps involving multilateral as well as private lenders and/or donors.
- Reductions in sulfur oxide (and particulate matter) emissions through use of clean coal technologies alone may come at the expense of an increase in greenhouse gas emissions.
- Although the application of a set of specific clean coal technologies to the electricity generation sector accomplishes a significant reduction in sulfur oxide emissions from electricity generation, overall $SO_x$ emissions under the scenario still approximately double between 1990 and 2020, a level of emissions reduction likely to be insufficient to prevent severe problems in the future. As a consequence, demand-side sources of emissions must be

addressed as well through a combination of fuel-switching, pollution control, and energy efficiency measures.

The expected "next steps" following from the work described in this report include:

- Working with experts in China and elsewhere, review model results and inputs for accuracy/reasonableness and cross-check with other sources of energy and environmental data.
- Refine and add to base of information on clean coal and standard coal technologies.
- Obtain additional information—preferably China-specific—on energy-efficiency options, technologies for using renewable fuels, natural gas-using equipment and supply infrastructure.
- In collaboration with selected colleagues in China, prepare and evaluate renewables/gas supply scenario, and/or mixed renewables/gas/clean coal scenario.
- Prepare and evaluate demand-side emissions reduction scenario.
- Prepare full report on China scenarios, disseminate to reviewers, both inside and outside of China, modify based on the reviews obtained, and distribute to those responsible for making or influencing energy development policies.
- In collaboration with groups from the other countries of the region, extend analysis to other countries in Northeast Asia, and to region as a whole.

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# 1. INTRODUCTION AND PROJECT BACKGROUND

## 1.1 Energy and Environmental Concerns in China

As China, and the rest of the word, enters the 21$^{st}$ century, energy supply and demand in China, and the local, regional, and global environmental concerns related to fuels production and use in China, are of increasing interest. The rate of growth of the Chinese economy over much of the last two decades has been considerable, and the energy needs of the country have expanded at a similar rate. The major fuel used in China, coal from domestic sources, has for the most part been burned in stoves and boilers that lack emission controls, resulting in air pollution that is certainly local and national, and likely also regional in its impacts, as well as contributing to global greenhouse gas (GHG) emissions. Although China is certainly not alone as a major energy consumer and emitter of GHGs, the recent period of sustained expansion in the Chinese economy, coupled with the sheer size of the nation, makes the way in which China will meet its needs for energy services a topic of global concern

Continued development in China will require a significant share of the world's resources—physical, financial, environmental. Different paths of development, and particularly energy-sector development, in China will have different global, regional, and local environmental ramifications, and different local and regional security implications as well. Different energy paths will also have different implications for how energy sector investments in China are financed.

In this paper, we begin a study of alternative energy futures in China by elaborating an energy demand scenario for China, then present two different visions of how supplies for energy—and specifically electricity—might be developed to meet future energy demand over the next 20 years. The focus here is on two cases; a Business-as-Usual Case, and an Alternative case the focuses on "Clean Coal" and other electricity generation technologies. We compare the relative environmental and cost impacts of the two scenarios, and very briefly suggest what implications the results might have for how Chinese energy sector development, and the global community's support for that development, proceeds.

Given the magnitude of the resources that will be required (under almost any scenario) in Chinese development, and notwithstanding the uncertainty with which we analysts, peering into the future without the benefit of a time machine, understand these coming needs, it is important to try and do just that. A concrete, though illustrative, look at possible alternative "futures" for the Chinese energy sector helps to focus debate on the problems and opportunities of most import. The goal of this paper is to describe and evaluate two scenarios for the development of the Chinese energy sector between now and the year 2020, and to evaluate those scenarios based on the relative "internal" direct costs of fuel and equipment, the relative "external" (primarily environmental) costs of energy sector activities, and, more briefly, the relative "security" costs associated with the energy scenarios. In so doing, we hope to illuminate to some extent both the magnitude and types of financing that will be required for different paths of energy development in China.

### 1.2 Project Background

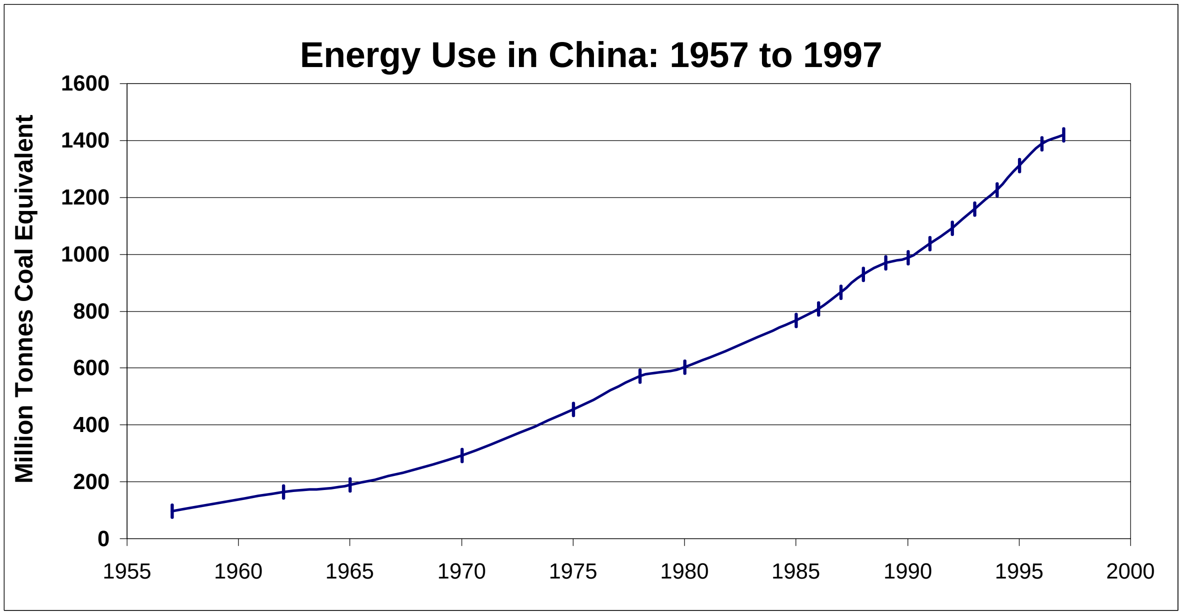
The scenarios analysis presented in this report is a part of a series of Nautilus initiatives, all, in different ways, focussed on the environmental and security (broadly defined) implications of different paths for the evolution of the energy systems of the countries of Northeast Asia. Some of the Nautilus projects that contributed to the work presented here, and vice versa, are:

- The **East Asia Energy Futures (EAEF) Project**. The EAEF project has as its goal the elaboration and comparison of Business as Usual and Alternative energy scenarios for each of the countries of Northeast Asia. The scenarios are then compared on the basis of relative internal costs (for example, capital, operating, and fuel costs), external costs (including the costs of environmental emissions) and security costs. Preliminary energy scenarios for most of the countries of the region have been prepared, and additional work is underway[1].
- The **Pacific Asian Regional Energy Security (PARES) Project**. Under the PARES project, a team of researchers from Nautilus and from counterpart organizations in Japan have prepared an analytical framework for evaluating the relative implications for energy security (broadly defined) of different energy paths. The PARES team prepared a case study of Japan as a test application of the energy security analytical framework[2].
- Building on the methodologies developed in the EAEF project, a Nautilus team prepared a study of the future of **nuclear power and nuclear waste disposal** in the region. This study focused on "Business-as-Usual" and "Maximum Nuclear" scenarios of nuclear electricity generation expansion in Northeast Asia, and evaluated the consequences of the two scenarios with regard to a number of parameters, including nuclear waste generation and the potential for storage and/or disposal of such wastes[3].
- A series of several Nautilus studies of the energy system in the **Democratic Peoples' Republic of Korea (DPRK)** have quantitatively estimated the energy balance in the DPRK in both 1990 and 1996, and have elaborated and evaluated scenarios for the evolution of the DPRK energy economy through 2005[4].
- The three-year **Energy Security and the Environment in Northeast Asia (ESENA) Project**. The ESENA project has brought together officials—acting in non-official capacities—and other experts from the United States and Japan in informal conversations on a series of specific topics. In the first year of ESENA, the two workshops focused on acid rain and its relation to the growth in energy use in the region. The topics of the second year of ESENA were marine pollution and marine governance issues, particularly as those issues relate to the Sea of Japan (the East Sea of Korea). Financing of implementation of clean coal technologies, particularly for China, has been the topic of the third year of the ESENA project. The analysis presented in this report was prepared as an input to the financing-related discussions at the first workshop of the third year of the ESENA project.

### 1.3 Summary of Current and Recent Energy/Environmental Situation in China

The growth in fuel demand in China, in particular over the past two decades, has been remarkable both in its absolute magnitude and in the relatively steady rate at which expansion has occurred. Figure 1-1 shows the trend in energy demand in China over the past 40 years[a]. Between 1980 and 1997, average annual growth in fuels consumption averaged slightly over five percent per year, implying a doubling of energy demand on the order of every 14 years. The combination of this strong growth in fuels demand, the main resource—coal—that China has at its disposal to supply its energy needs, China's geographical position, and the size of the Chinese population all make China's choice of an energy path a matter of profound interest with respect to the environment both within and outside of China.

***Figure 1-1:***




### 1.3.1 Current fuel supply mix

Figure 1-2 presents the overall fuel supply mix in China as of 1997. Coal provided nearly three-quarters of domestic energy supply, with crude oil, natural gas, and hydropower (counted at the level of the equivalent coal input to generate electricity) accounting for nearly all of the rest of the country's production of commercial (non-biomass) fuels[b].

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[a] Original data for Figures 1-1 and 1-2 from China Statistical Publishing House (1998), China Statistical Yearbook. Electricity generated in hydroelectric plants is counted in these statistics at the average heat rate of fossil-fueled power plants in China.

[b] The small amount of nuclear power generation as of 1997 is not shown separately on this graph. The use of biomass fuels in China is uncertain in quantity but certainly significant in terms of overall fuels use. Estimates of rural household biomass fuel use (Department of Communications and Energy and State Planning Commission of P.R. China (1995), '95 Energy Report of China; September, 1995) totaled approximately 240 million tonnes of coal equivalent as of 1994, or about 20 percent of the commercial fuels use reported in Figure 1.

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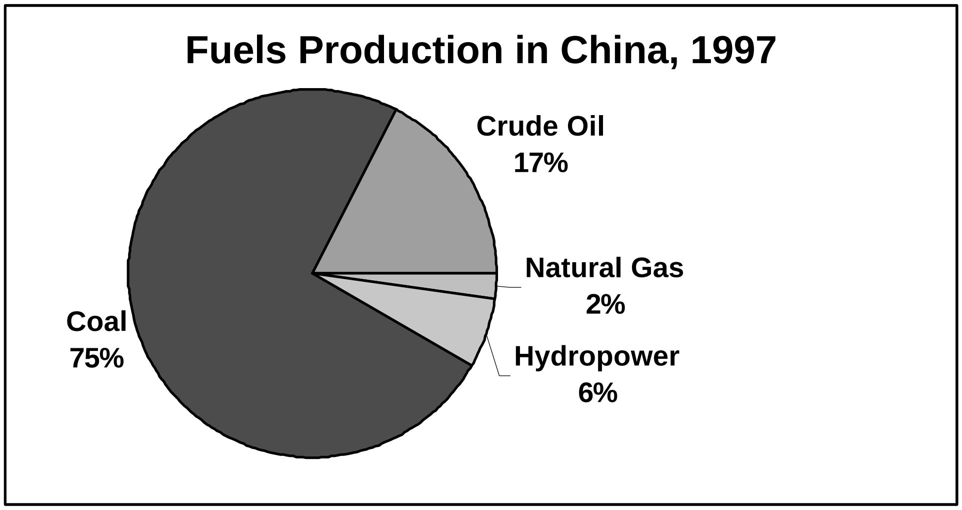
*Figure 1-2:*

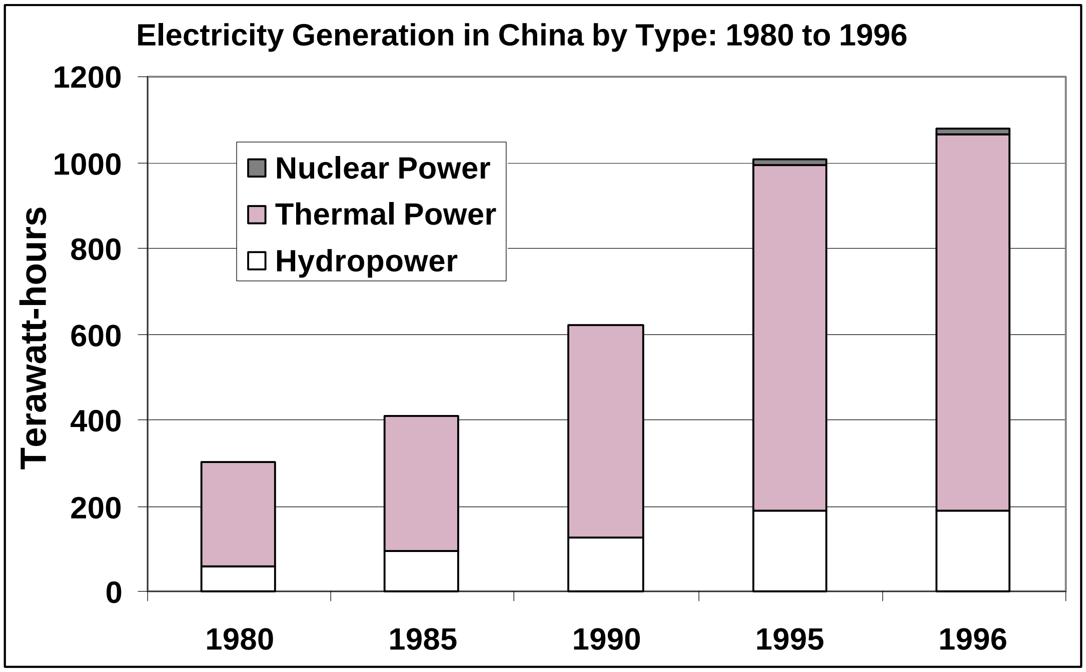



1.3.2 Current and recent patterns of growth in electricity output

As shown in Figure 1-3[c], thermal power—of which the overwhelming proportion is coal-fired, has for some time provided the bulk of generation in China, accounting for over 80 percent of generation in 1996. Moreover, growth in power generation has been very strong in recent years. The growth in electricity output between 1985 and 1996—years in which expansion in the Chinese economy was particularly robust—averaged 9.2 percent annually.

[c] Original data for Figures 1-3 and 1-4 from Table 7-5 of China Statistical Publishing House (1998), China Statistical Yearbook.

***Figure 1-3:***

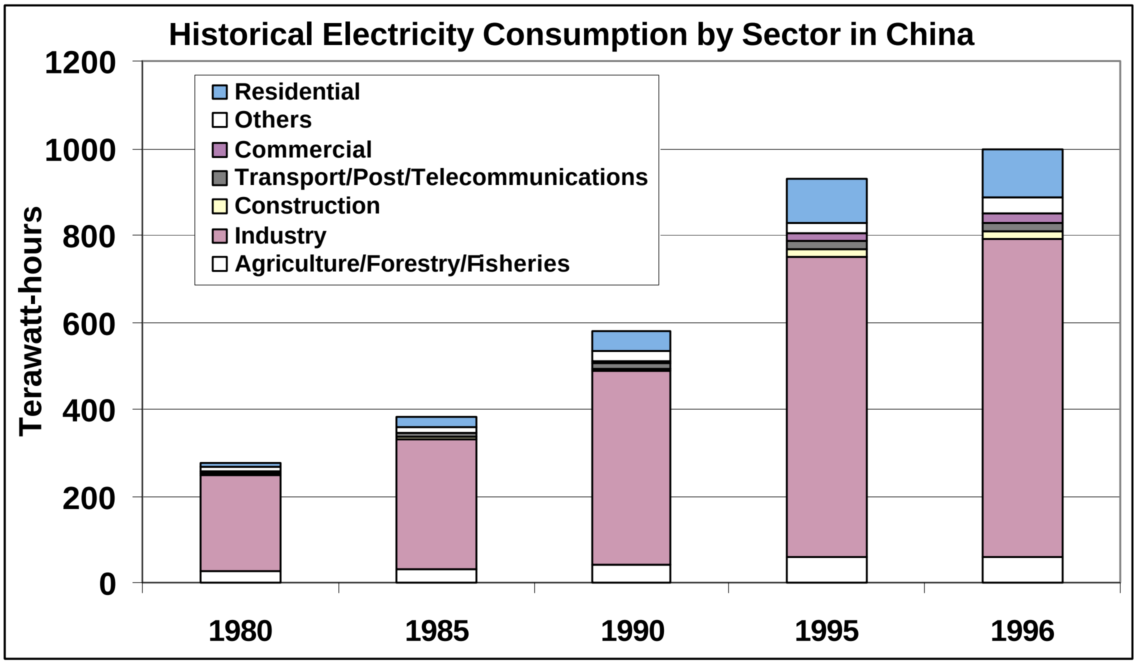



### 1.3.3 Current and recent electricity demand patterns

As shown in Figure 1-4, electricity consumption in China has historically been dominated by the industrial sector. The early and mid-1990s, however, have seen marked growth in the fraction of demand accounted for by the residential, commercial, and other sectors. Note that Figure 1-4 does not include transmission and distribution losses of electricity. Not surprisingly, overall electricity consumption between 1985 and 1996 grew at an annual average rate similar to overall generation: 9.2 percent annually. Of the major sectors during the same period, growth in electricity use in industry averaged 8.5 percent annually, residential sector consumption grew at an annual average rate of 15.9 percent, and commercial sector electricity use increased at 17.5 percent/yr[d].

[d] Note that the sectoral definitions in Figures 1-4 and 1-5, which are taken from the definitions used in the China Statistical Yearbook, do not necessarily correspond exactly to the definitions used in compiling base year (1990 and 1995) sectoral energy use data for the China Energy model presented later in this report.

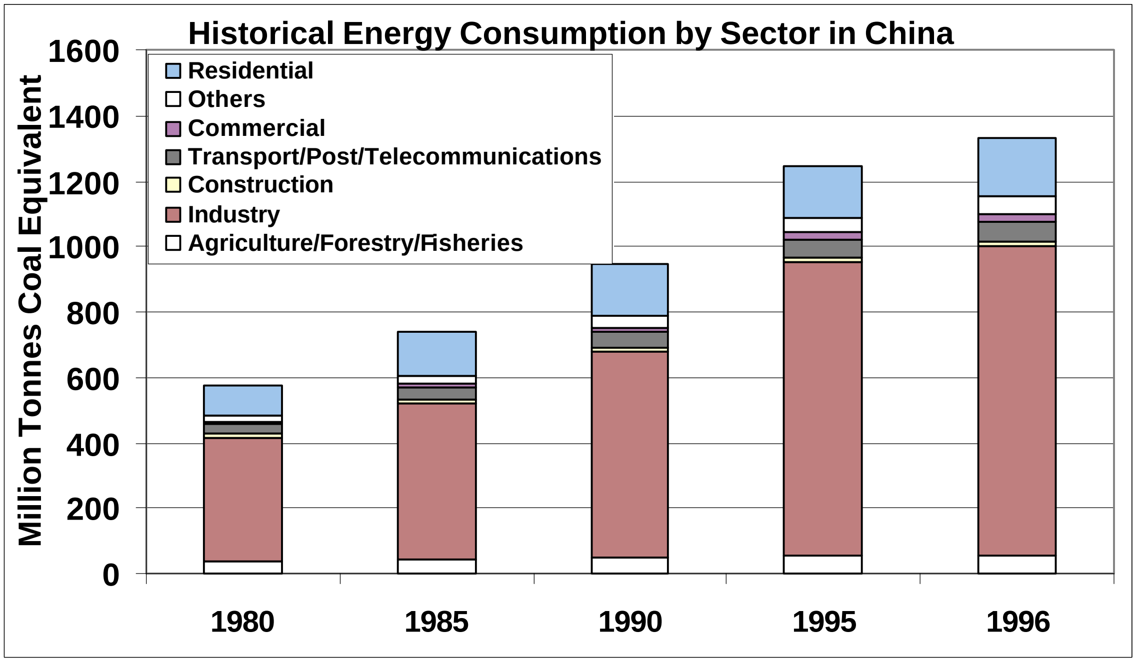
***Figure 1-4:***




1.3.4 Recent energy demand patterns by sector

Overall Chinese consumption of all commercial fuels (mostly fossil fuels and electricity) by sector from 1980 to 1996 is shown in Figure 1-5. Growth in overall fuel use has been less (an average of 5.5 percent annually from 1985 to 1996) than growth in electricity use. In addition, industrial sector energy demand rises at a rate higher than overall demand (6.3 percent/yr), while residential sector demand for all commercial fuels grows considerably more slowly (2.6 percent annually) than either overall energy demand or residential sector electricity demand. The slower growth of residential demand for all commercial fuels is probably largely the result of a shift toward using more efficient devices plus a shift in the composition of energy use in the residential sector away from coal to electricity, as well as to gaseous and liquid fuels.

*Figure 1-5:*



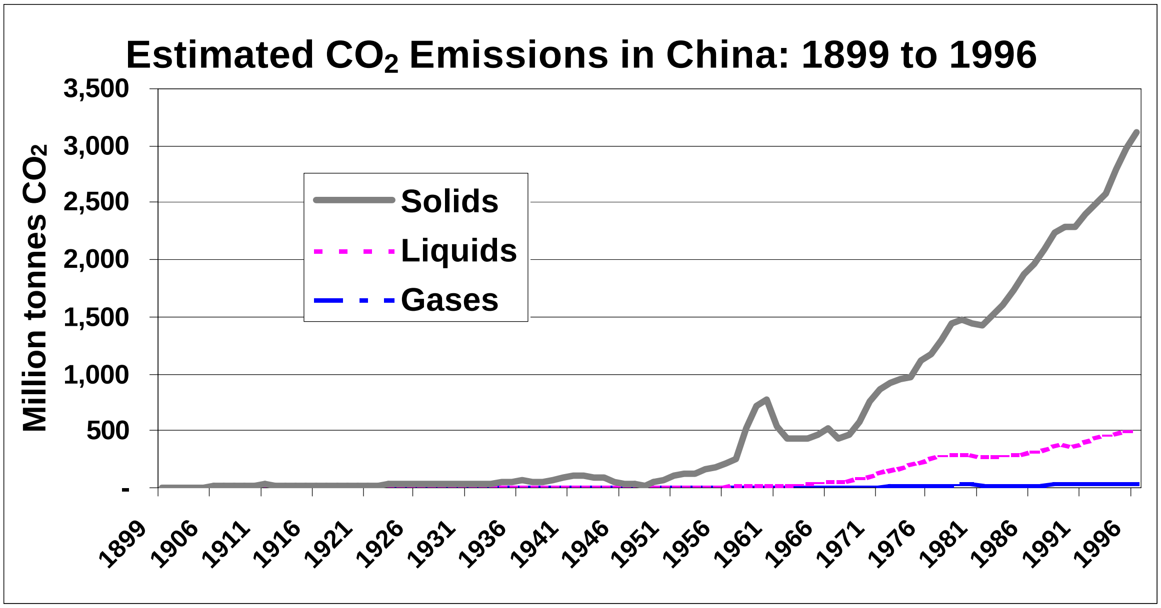

1.3.5 Summary of key environmental emissions as estimated by others

A summary of estimated historical carbon dioxide emissions as estimated by a team led by researchers at the Carbon Dioxide Information Analysis Center (CDIAC) of Oak Ridge National Laboratory (USA) is presented in Figure 1-6[5, e]. The overwhelming majority of Chinese emissions from fuel combustion are from use of solid fuels—namely coal. Overall estimated $CO_2$ emissions from fuels use rose at an average rate of 4.7 percent annually between 1985 and 1996. As of 1996 (based on CDIAC estimates), China had the world's second highest total $CO_2$ emissions (from fuels use and from cement manufacture), with emissions of 3.37 billion tonnes (versus 5.30 billion tonnes for the United States). On a per capita, basis, however, Chinese emissions ranked 104th, and were about one-seventh of 1996 per-capita US emissions.

Emissions of sulfur oxides have been estimated at 13.24 million tonnes as of 1985, rising to 17.95 million tonnes by 1993 (for an annual average growth rate of 3.9 percent)[6].

[e] Note that this figure only reflects CDAIC estimates for emissions from fuels use, and thus excludes emissions from cement production, bunker fuels use, and gas flaring. With the exception of cement production, which accounted for roughly 7 percent of $CO_2$ emissions in 1996, the contributions of other sources to overall emissions are small. In the original source document, carbon dioxide emissions estimates were expressed in thousand metric tonnes of carbon. Estimates have been converted to a carbon dioxide basis for consistency with conventions used later in this report.

***Figure 1-6:***




## 1.3.6 Key ongoing energy/environment-related changes in China

As economic, political, and social change continues in China, the formulation and evaluation of energy scenarios must be considered against a backdrop of ongoing processes in the nation. Among the changes and/or policy debates that promise to continue to affect the energy and environmental situation in China are:

- How generally to manage continued economic growth and development without degradation of environmental quality;
- Changes in the way that major energy infrastructure projects are financed, including a move away from State-financed projects to projects financed in part by loans from abroad, and even privately-owned power generation;
- How to influence choices of fuels and fuel cycles in a market that is increasingly controlled by the private sector;
- To what extent reliance on imported fuels will be acceptable, including the role of imported liquid fuels and gaseous fuels in addressing environmental concerns associated with domestic coal use;
- Transport-sector issues associated with fuel supply, including the movement of coal between provinces in China;
- Issues associated with rapid growth in personal transportation, including private automobile use;
- China's role in regional plans for extensive gas, oil, and electricity supply projects;
- How, in particular, to finance alternatives to standard energy infrastructure and investments in environmental quality; and

- What role energy efficiency and renewable power can play in the national energy system.

**[REVIEWERS—OTHER KEY ISSUES THAT DESERVE MENTION HERE?]**

The above is hardly an exhaustive list, but it serves to indicate the complexity of the context in which energy scenarios for China must be considered.

#### 1.3.7 Role of scenario work described in this report

The work described in this report—the initial elaboration and evaluation of energy scenarios for China—is designed as a first step toward informing choices faced by China and others regarding the energy and environmental future of Northeast Asia. The goal is to provide an analytical framework whereby the impacts (costs and benefits) of different technologies and/or policies can be estimated in a quantitative manner, at the same time organizing assumptions and other information in a manner that is transparent to the reviewer. The scenario evaluation tool and its results are thus designed to provide a means of testing different policies, and of informing policy formulation and debate.

### 1.4 Contents of Remainder of Report

The remainder of this report is organized as follows

- **Section 2** presents a description of the modeling approach and data sources used to prepare estimates of future energy demand and supply in China under different scenarios.
- **Section 3** provides descriptions of the energy scenarios themselves, including descriptions of the key assumptions that drive energy demand and supply in the Business-as-Usual and Alternative scenarios.
- **Section 4** presents the energy demand results of the Business-as-Usual scenario, including demand for electricity and other fuels by fuel and by economic sector.
- **Section 5** provides scenario results relating to fuel supply for the Business-as-Usual and Alternative scenario, including primary energy use, shares of electricity generation by technology, and descriptions of expansion of other types of fuel transformation infrastructure.
- **Section 6** shows the environmental and cost results of the scenarios, including estimates of current and future emissions of key environmental pollutants and presentations of cost-benefit comparisons between the two scenarios.
- **Section 7** provides our initial conclusions in this ongoing study of energy futures for China, and describes potential "Next Steps" in the analytical work of elaborating and evaluating energy scenarios for China and for other countries in the region.

- **Annexes** to this report provide background details on data sources, preparation of data for the China energy sector model, and detailed scenario results.

# 2. MODELING APPROACH AND DATA SOURCES

## 2.1 Overall Approach

In creating and evaluating alternative energy scenarios for China, we chose to use a demand-driven model with substantial sector, subsector, end-use and fuel detail. We used the LEAP (Long-range Energy Alternatives Planning) software tool, which provides a simple, transparent, and convenient framework for assembly and testing of alternative energy futures. Using base year (1990 and 1995) data from a variety of sources (as described below), a data set that described the flows and end-uses of fuels in the Chinese energy sector was compiled. Using a combination of analysis of recent trends and conjectures about changes in the consumption of energy services in China over the period through 2020, a Business-as-Usual scenario for energy demand was developed. The supply of resources, and the capacity to transform primary resources into fuels (including the stock of power generation facilities), was built up to meet final fuel demand.

Once Business-as-Usual (BAU) cases for fuel demand and fuel supply were assembled, a second scenario for fuel supply, called the "Alternative" scenario, was created. The Alternative scenario modifies the BAU case by incorporating electricity generation equipment that is designed to lower emissions of sulfur oxides in particular, as well as other pollutants.

The LEAP software provides the means to associate environmental pollutant emissions factors with the use of fuel-consuming (for example, coal-fired boilers) and fuel-transforming (for example, oil refineries) devices and facilities. With these "links" between fuel consumption and emission factors set up, LEAP can calculate the stream of any of a number of emissions over time. Costs can also be associated with demand- or supply-side equipment—or with environmental emissions—and LEAP provides a facility for comparing the benefits and costs of alternative scenarios. A brief description of LEAP is provided in Annex D to this paper.

## 2.2 Sources and Treatment of Base Year and Other Historical Data

For energy demand, the LEAP data set uses a Base Year of 1990, with 1995 used as a second year of historical fuels demand. Base and historical year data were obtained from a variety of sources, notably the <u>China Energy Databook</u>[7], the <u>China Statistical Yearbook</u>[8], and the <u>China Energy Statistical Yearbook, 1991 – 1996</u>[9]. Specific sources used to compile particular portions of the data set are referenced in the workpapers included in Annex A. We were also fortunate to acquire an initial LEAP data set from the Stockholm Environment Institute—Boston Center. This data set was prepared by a team of Chinese researchers during a UNEP (United Nations Environment Programme)-funded project in approximately 1994 – 1995. The original China data set was, however, modified and updated substantially during the course of the work described here. For the most part, base year results from the data set as modified track fairly closely energy data as compiled in the China Energy Databook and the China Statistical Yearbook, but there are a number of instances where changes were made in ascribing energy use to one subsector or another in order to make the data set internally consistent, or to make the data consistent with specific sources. These changes and data treatments are described in Annex A, which is a printout of the Microsoft Excel workbook used to compile and pre-process data used in the modeling effort. The LEAP data set thus prepared is quite detailed, and provides a valuable starting point for generating scenarios of energy use in China.

## 2.3 Overview of Energy Demand Data Set

### 2.3.1 Time period covered

As noted above, 1990 was used as the base year for the energy demand data set (as well as for the supply-side data set), with 1995 used as a data year as well. Using two historical years in the model helps to show how future projections of energy demand either follow or depart from recent trends. The end year for the energy scenarios modeled is 2020, with 2000 and 2010 also used as data years (years in which activities that drive energy demand are specified).

### 2.3.2 Sectoral/subsectoral structure

The LEAP energy demand data set prepared for this study has the sectoral and subsectoral structure shown in Table 2-1. The data set has a branched structure, with one or more subsectors per sector, one or more end-uses per subsector, and one or more energy-using devices per end-use. Each device uses a single fuel. In some sectors, substantial end-use detail was used (for example, in the residential sector), while in other cases only limited end-use information was available, and end-uses and devices were distinguished mainly by fuel type.

*Table 2-1: Sectoral/Subsectoral Structure of Demand Data Set*

| Sectors | Subsectors |
|---|---|
| Residential | Urban |
| | Rural |
| Agriculture/Fishing | Agriculture |
| | Fishing |
| | Sideline Production (Generally, processing of agricultural goods) |
| Mining (and Forestry)[f] | Ferrous Metals Mining |
| | Non-Ferrous Metals Mining |
| | Non-Metallic Minerals |
| | Other Minerals |
| | Logging/Wood Products/Bamboo Production |
| Industry | Ferrous Metals Production |
| | Cement Production |
| | Building Materials (Brick and Tile, Glass, and Other) |
| | Chemicals Production (Fertilizers and Other Chemicals) |
| | Non-Ferrous Metals Production |
| | Light Industry |
| | Machinery |
| | Other Industry |
| Transportation | Public Passenger Transport |
| | Freight Transport |
| | Motorcycles |
| | Private Cars |
| | Other Road Vehicles |
| Building | All Subsectors |
| Services | Commercial |
| | Other Services |
| | Tap Water Provision |
| Communications | All Subsectors |

### 2.3.3 Fuels

LEAP version 95.0 allows the modeling of the production, transformation, and use of up to 65 fuels (including end-use fuels, intermediate fuels, and resources). For the China data set, a full range of fuels and resources were modeled as separate fuel/resource categories, including:

- Electricity
- Heat

[f] Includes electricity consumption data only. Consumption of other fuels in the Mining sector is included in industrial sector energy use.

- Coal and coal briquettes
- Coke and other coking products
- Crude oil
- Petroleum fuels, including diesel, gasoline, liquefied petroleum gas (LPG), residual/heavy fuel oil, kerosene, jet fuel, petroleum coke, and other petroleum products
- Gaseous fuels, including natural gas, producer gas, coking gas, liquefied natural gas (LNG), refinery gas, biogas, and coal-bed methane
- Biomass fuels, including firewood, crop wastes, and animal wastes (dung)
- Other energy forms, including solar energy, hydraulic energy (hydro), nuclear energy, geothermal energy, wind energy, and tidal energy

#### 2.3.4 Changes in demand over time

Future fuels demand by each sector, subsector, end-use, and device in the data set are modeled a function of changes in "activities", which are physical, economic, demographic, or other parameters that are assumed to "drive" changes in energy demand at each level in the branch structure. At the device level, an energy intensity and a fuel type is ascribed to each branch. For example, the future use of coal for cooking in the urban household sector is a function of the number of households in China, the proportion of households that are in cities, the fraction of urban households that use coal stoves, and the energy intensity (coal use per household/stove per year) of the coal stoves (on average). Each of these parameters can and do (in this example case) change over time. Changes in activities or energy intensities can be expressed directly (by specifying, for example, steel output targets in future years), by ascribing a future growth rate, or by modeling changes in the activity or intensity as a function of changes in one or more driving variables (for example, population or gross domestic product) and one or more elasticities that express the relationship between the driving variables and the activity or energy intensity. The specific assumptions that underlie growth in fuels use in the BAU demand scenario are described in section 3 of this paper.

### 2.4 Overview of Energy Supply Data Set

As with the demand data set for the China energy model, the base/historical year information used for the fuel supply (or the "Transformation" program of LEAP) data set was gleaned from a variety of sources, as described and referenced in Annex A. The supply model describes the extraction of resources, the importation and export of fuels, and the conversion of fuels to intermediate products and, ultimately, to end-use fuels. The energy supply data set also uses 1990 as a base year, but in many cases includes more recent historical data for capacity of power generation and other equipment.

### 2.4.1 Structure of supply model

The supply model is structured as a series of modules, as shown in Table 2-2. Resources, either domestic or imported, can be thought of as flowing in at the bottom of the list of "transformation modules", and delivered fuels to meet final demand are produced at the top of the list. Losses and inefficiencies in fuel transformation are accounted for within the transformation modules, and modules can produce intermediate fuels that are used by another module.

***Table 2-2: Fuel Transformation Modules in the Energy Supply Model***

| **Transformation Modules** |
| --- |
| Distribution (of fuels) |
| Electricity Generation |
| Heat Generation |
| Coke Production |
| Gasification |
| Biogas Production |
| Oil Refining |
| Coal Briquette Production |
| Natural Gas Production |
| LNG Imports |
| Coal Washing |
| Crude Oil Production |
| Coal Production |
| |
| **RESOURCES** (Crude Oil, Coal, Solar, Wind, Hydro, Geothermal, Nuclear, Natural Gas, LNG, Animal Wastes, Tidal Energy…) |

### 2.4.2 Changes in fuels supply over time

In LEAP 95.0, fuel supply does not necessarily automatically expand to meet demand. In fuel transformation where production capacities are specified, such as oil refining, electricity generation, and coal production (among others), capacity additions must be specified by the modeler so as to meet demand over the forecast period. This is done iteratively, by running the demand and supply programs, then adjusting the assumed capacity of transformation processes until the capacity factors, reserve margins, and other measures of capacity sufficiency (or surplus) are within acceptable ranges throughout the period modeled.

## 2.5 Creation of Base Case and Alternative (Clean Coal) Scenarios

The Base Case (BAU) scenario for demand is defined by the modelers' best estimate of how energy demand—and the activities that drive it—are most likely, based on current and foreseeable trends, to change over time. The BAU scenario for supply is likewise a projection of recent patterns and policies in such a way that demand for all fuels is met. Alternatives to the BAU demand- and supply-side scenarios are perturbations of base scenarios in that one or more future values—for example, the growth rate of automobile stocks on the demand side, or the relative proportion of power plants fired with washed coal on the supply side—are different than in the BAU case. Generally, but not always, alternative scenarios are designed to deliver the same energy services to society that the BAU case does. In creating the Alternative supply scenario described below, we have attempted to keep the level of energy services consistent between the BAU and Alternative scenarios, meaning, for example, that the fuel supply systems under the two scenarios run to the same level of reliability.

In this paper, an Alternative scenario is described and evaluated only on the supply side. We will develop and evaluate alternative demand-side scenarios (and additional supply-side scenarios) in future research. The assumptions as to future circumstances that will drive energy demand under the BAU scenario, and as to the supply-side infrastructure that will be built to meet demand under the BAU and Alternative scenarios, are discussed in Section 3, below.

### 2.6 Estimation of Air Pollutant Emissions

A central goal in assembling and assessing alternative scenarios for energy sector development is to determine options for reducing the environmental impacts of energy sector activities, with air pollutant emissions being a primary concern.

An international database of coefficients for estimating pollutant emissions and other direct impacts (for example, coal mining injuries and deaths) of energy-using or fuels-transforming devices is part of the LEAP software system. This database is called the Environmental Database or EDB. Emissions or impacts coefficients in EDB can be linked to LEAP demand and supply scenarios, allowing the calculation of emissions in both the base year and in future years. For the China scenarios, the emission coefficients selected to and “linked” to the demand and supply databases in LEAP were drawn largely from international emissions compendia, as specific emission factors for Chinese technologies are not yet, to our knowledge, widely available.

### 2.7 Inclusion of Cost Data

In the LEAP modeling system, costs can be specified for changes in equipment on the demand side, the supply side, or both. Domestic and imported fuels and resources can also be ascribed costs, which can change over time. “Externality” costs can also be applied to air pollutant emissions, although this approach was not used in the modeling described here.

In the energy demand model, costs can be associated with changes in activity—such as changes in the number of a particular type of refrigerator—or can be associated changes in use of fuel by a particular device. Costs of changing activity are described by assigning capital costs—in monetary units per unit of activity—together with estimates of the rate at which those costs will increase relative to the general inflation rate, the foreign exchange fraction of the costs, and the lifetime of the device to which the cost applies. Alternatively, modifications that result in changes in fuel use by a device can be evaluate in terms of cost of conserved energy; for example, dollars per GJ of coal saved in commercial boilers. Costs of conserved energy can also be associated with escalation rates and foreign exchange fractions. In demand models within LEAP, costs are most typically developed and applied for those demand-side devices whose number, usage, or energy intensity changes between scenarios. As alternative demand-side scenarios were not prepared as part of the work described in this paper, no costs were applied in the demand-side analysis, although as noted above, we expect that demand-side scenarios will be developed—with costs—as part of upcoming scenario work at Nautilus.

In the energy supply or transformation portion of the energy model, costs are typically expressed in terms of capital and fixed and variable operating and maintenance (O&M) costs. Capital costs can be assigned an interest rate and recovery period, and all costs can be associated with a foreign exchange fraction. As two supply-side scenarios were prepared (the BAU and "Alternative" scenarios), costs were applied to those supply-side elements—notably those associated with electricity generation—that were different between scenarios. Cost data were assembled from a variety of sources, including China-specific studies and experts in the "Clean Coal" field. A summary of the cost data used, and the sources of those data, is provided in Section 3.

### 2.8 Estimation of Relative Costs and Emissions of Different Scenarios

Having calculated the relative energy demand under each scenario, and the fuel use or fuel transformation by each element of the energy supply system, the next step is to compare the relative costs and benefits of alternative scenarios. LEAP provides a mechanism for comparing the costs, on a whole energy system basis as well as on the different components of the energy system, of combinations of alternative scenarios. Comparison of the BAU and Alternative scenarios described below, for example, includes an evaluation of the tradeoffs between the capital costs (higher in the Alternative scenario) and pollutant emissions (higher in the BAU) scenario of the two energy paths, as well as an evaluation of the relative resource costs of the scenarios.

## 3. PRESENTATION OF ENERGY SCENARIOS

### 3.1 Introduction

The two energy scenarios described in this paper were built up so as to illustrate two significantly different energy futures, but futures that include the provision of very similar energy services to the people of China. Maintaining the same set of energy services in both scenarios allows the results of the scenarios to be compared on a consistent basis[g]. With the scenarios thus elaborated—quantitatively and in considerable detail—it is possible to estimate the relative costs of the two scenarios. Costs in this case include internal costs (such as the

[g] Note that it is certainly possible to generate scenarios in which energy services are qualitatively and/or quantitatively different, including, for example, scenarios that have significantly different rates of economic growth, that assume less (or more) opportunity for private-vehicle travel, or offer electrical service that is more (or less) likely to be disrupted. While it may be valid to compare scenarios that offer significantly different energy services, it renders the comparison significantly less clear, as the connection between overall costs and overall benefits is muddied by the fact that different services are provided.

capital and operating costs of power plants and pollution control equipment, as well as fuel costs), external costs (including the estimated costs of environmental impacts), and security costs. In this section, many of the specific assumptions included in the two scenarios are discussed. Sections 4 and 5 of this paper provide summaries of the demand- and supply-side scenario results, and Section 6 summarizes the work to date on comparing the costs and benefits of the scenarios, including the difference in environmental performance and cost between the two options. The workpapers provided in Annex A show the assumptions underlying and derivation of the base year and future year parameters that were used in the scenarios. Annex B provides a printout of the LEAP data sets themselves.

## 3.2 Business as Usual Scenario

### 3.2.1 Key demand-side assumptions

The only demand-side scenario elaborated thus far is the Business-as-Usual, or BAU scenario. In general, the BAU scenario is an extrapolation of the performance of the Chinese economy over the last 15 years or so, tempered somewhat by consideration of the recent crisis in the Asian financial markets and its impacts on economies in the region. As such, the BAU scenario postulates continued strong economic growth through the end of the 1990s and into 2000, with growth gradually slowing as the Chinese economy begins to mature. The commercial sector and lighter industries are assumed to show the strongest growth of the different sectors of the Chinese economy, with the growth in the output of heavy industries slowing, as recent trends already seem to show. Residential energy consumption is assumed to increase markedly, even though household size declines and population growth slows. The level of personal travel is also assumed to expand markedly, with particularly rapid (continued) expansion in the stock and use of private vehicles. Energy intensities for demand-side devices continue to improve, but not at a rapid rate, as a combination of the desire to keep most production in-country and a lack of capital for high-efficiency investments tend to keep energy intensities higher than in the United States, Europe, and Japan. The type of economic evolution outlines here is consistent with a continued, but controlled and not abrupt, opening to the market economy model by China, with a reduction in materials use (cement and iron and steel, in particular) as domestic materials-use efficiency improves.

Assumptions as to trends in driving activities (those economic, social, demographic, or technical trends and activities that act to “drive” end-use demand for fuels within the LEAP model) and energy intensities are given briefly below for each end-use sector.

## RESIDENTIAL SECTOR

Changes in Driving Activities:

**Population**: The population of China is assumed to increase to 1.45 billion by 2020 (1.39 billion in 2010).

**Households**: The number of households is assumed to increase to 437 million by 2020 from 273 million in 1990, representing a decrease in the average number of persons per household from 4.19 to 3.37. We assume that the number of households in the heating and "transition" zones declines slightly until 2000, then remains relatively constant, meaning that net North-to-South migration is assumed to be minimal[h].

**Urban/Rural Split**: The fraction of the population living in cities is assumed to increase from 32 percent in 1990 to 41 percent in 2020. The size of urban households is assumed to decrease from 3.51 persons per household in 1990 to 2.90 persons per household in 2020. Rural households are also expected to decline in size, decreasing from 4.35 to 3.50 persons per household by 2020.

**Urban Cooking/Water Heating**: The fraction of urban homes using raw coal for cooking and water heating in is assumed to be phased down to 10 percent by 2010 (from over 35 percent in 1990), and to 3 percent by 2020. Coal briquettes (15 percent), electricity (10 percent) and gaseous fuels (LPG, natural gas, and producer/coking gases) are thus assumed to supply virtually all cooking and water heating needs by 2020.

**Urban Space Heating**: The fraction of urban households living in heated homes is assumed to decrease from 59 percent in 1990 to 57 percent in 2000 (as a result of demographic shifts), remaining the same thereafter. The fraction of households using raw coal-fired heaters is assumed to be phased down to 10 percent by 2020, with the use of coal briquettes initially rising to meeting some of the heating demand, then falling to 15 percent of households by 2020. District heat is assumed to supply 25 percent of households by 2020, with the remainder of the stock of heated urban households supplied from coal boilers (35 percent in 2020) and natural gas-fired boilers (5 percent in 2010, and 10 percent in 2020).

**Urban Lighting**: All urban households have electric lighting throughout the period modeled.

**Urban Residential Appliances**: The trend toward increased appliance ownership is assumed to continue, and as a consequence most urban homes will have major appliances (refrigerator, washer, TV) by 2020. Ownership of air conditioners and "other" appliances (for example, stereo and computer equipment) is also assumed to increase substantially. Table 3-3 shows the assumed "penetration", or average numbers of appliances per urban household, as they change over time. Note that values over 100 percent (for fans) mean that many households have more than one unit of a particular type of appliance.

[h] An alternative, though less attractive, interpretation might be that the direction of net migration actually switches to South to North, but that the impacts of global warming increase the average temperatures in China sufficiently to move the heating and transition zones Northward as well.

***Table 3-3: Assumptions as to Changes in Appliance Ownership in Urban Households in China***

| Appliance Type | Penetration 1990 | 2000 | 2010 | 2020 |
|---|---|---|---|---|
| Refrigerators | 42% | 80% | 98% | 100% |
| TV | 61% | 94% | 98% | 100% |
| Fan | 136% | 170% | 180% | 180% |
| Washing Machine | 78% | 95% | 98% | 100% |
| Air Conditioning | 0% | 12% | 25% | 40% |
| Other Appliances | 100% | 100% | 100% | 100% |

**Rural Electrification**: Rural electrification is assumed to proceed slowly, with most of the non-grid-connected households (9 of the 13 percent not connected as of 1990) connected to the grid by 2020, and about half of the rest served by solar PV lighting systems.

**Rural Cooking/Water Heating (Commercial Fuels)**: Coal stoves are assumed to be used by 30 percent of households in 2000, decreasing to 20 percent by 2020. The fraction of households with coal briquette stoves increases to 30 percent by 2020 from about 6 percent in 1990, and the fraction of households with LPG stoves increases to 57 percent by 2020 (from just 2 percent in 1990). In addition, the fraction of households using biogas stoves is assumed to rise from about 11 percent in 1990 to 24.5 percent in 2010, remaining at that level through 2020. The assumption is that many rural households will have use than one means of cooking and water heating at their disposal. In addition, rural households are assumed to continue using biomass fuels, although the fraction of households using fuels is not a parameter in the demand model (see below, however, for a discussion of the overall reduction of biomass fuel usage per household over time).

**Rural Space Heating**: The fraction of rural households using non-traditional fuels for heating is assumed to increase from 42 percent in 1990 to 50 percent in 2020. The use of raw coal-fired heaters is assumed to be phased out by 2020. Coal briquette stoves and coal-fired boilers are each assumed to supply heat to half of the heated rural homes by 2020.

**Rural Lighting**: The fraction of rual households with electric lighting powered by grid electricity is assumed to rise from about 87 percent in 1990 to 96 percent by 2020. The use of kerosene lamps for lighting is assumed to fall from about 12 percent in 1990 to 5.5 percent in 2010 and 2 percent in 2020. The use of solar photovoltaic-powered, stand-along rural lighting systems in remote areas is assumed to start in 1995, and to be applied to 2 percent of households by 2020.

**Rural Residential Appliances**: The trend toward increased appliance ownership that was assumed in the urban sector is assumed to hold in the rural sector as well, but the increase in appliance owrnership is assumed to occur at a slower pace. Still, the adoption of major appliances in rural households is assumed to reach 80 to 95 percent by 2020, though penetration of air conditioners is assumed to lag substantially behind that in the urban sector. Table 3-4 shows the assumed penetration of appliances per urban household as they change over time.

***Table 3-4: Assumptions as to Changes in Appliance Ownership in Urban Households in China***

| | Penetration | | | |
|---|---|---|---|---|
| **Appliance Type** | 1990 | 2000 | 2010 | 2020 |
| Refrigerators | 1% | 15% | 50% | 80% |
| TV | 41% | 70% | 80% | 90% |
| Fan | 40% | 100% | 120% | 150% |
| Washing Machine | 9% | 35% | 70% | 100% |
| Air Conditioning | 0% | 2% | 5% | 10% |
| Other Appliances | 100% | 100% | 100% | 100% |

Changes in Energy Intensities:

**Urban Cooking/Water Heating Fuels**: Between 1990 and 2020, the energy intensities (use of fuel per household-yr) of solid fuel (coal and coal briquettes) use are assumed to decline fairly significantly (by about 29 percent), as stoves become more efficient. Over the same period, the energy intensities of cooking and water heating with electricity and gaseous fuels—especially natural gas and LPG—increase as the availability of those fuels (and household incomes to pay for them) increase.

**Urban Heating**: Coal and coal briquette use per household using coal stoves is assumed to increase by 24 percent between 1990 and 2020. Even though the intensity of coal and briquette use per unit area heated is assumed to decrease by 1 percent per year, the continuing increase in per capita residential floor area—from 6.7 square meters per person in 1990 to 12.3 square meters per person in 2020—results in the increasing overall use of fuel per household per year, even when factoring in decreasing household size. It is also assumed that the energy intensity of district heating increases over time per unit floor area served, but that with the increase in floor area per household overall intensity of heat use per household increases. The intensity of natural gas use per unit floor space is assumed to remain constant, so that the gas consumption for space heating per household rises with household floor space over time. This assumption could also be consistent with a situation where the efficiency of gas boiler (and their associated heating systems) is actually improving, but that the average winter indoor temperatures are also rising, as increasing affluence leads homeowners to want greater levels of comfort (warmer homes).

**Urban Lighting**: We assume that the per-household use of electricity for lighting in urban households increases at 3 percent per yr through 2020. As floor space per household is increasing by about 2 percent per year, the implication is that the offseting combination of increased lighting use and improved lighting efficiency results in a rate of increase of lighting electricity use per unit floor area of about 1 percent per year.

**Urban Appliances**: The trends in intensity of energy use per appliance vary. The annual per-household energy usage by refrigerators is assumed to rise between 1990 and 2000, remaining constant thereafter as increased appliance usage (and/or size) offsetts gains in energy efficiency. Electricity usage in televisions (and associated video equipment) increase as both hours spent watching TV and the size of TVs increase. Annual electricity usage per fan is assumed to remain constant, but the average electricity usage per household for air conditioning increases, largely as a result of an increased number of hours of air conditioner use per year. The household usage of electricity for other appliances, including other entertainment appliances, computers, and other electrical equipment, is assumed to increase significantly, rising at slightly under 9 percent per year over the projection period. Table 3-5 summarizes the assumptions used to compile energy intensitities for urban households.

***Table 3-5: Assumptions for Urban Household Appliance Use***

| | Wattage or kWh/yr | | | | Annual Hours Used* | | | | Energy Intensity (GJ/yr) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Appliance Type | 1990 | 2000 | 2010 | 2020 | 1990 | 2000 | 2010 | 2020 | 1990 | 2000 | 2010 | 2020 |
| Refrigerators (kWh/yr) | 350 | 441.65 | 441.65 | 441.65 | 1 | 1 | 1 | 1 | 1.260 | 1.590 | 1.590 | 1.590 |
| TV (kW) | 0.085 | 0.1 | 0.16 | 0.2 | 650 | 1000 | 1200 | 1200 | 0.1989 | 0.36 | 0.6912 | 0.864 |
| Fan (kW) | 0.035 | 0.04 | 0.04 | 0.04 | 540 | 600 | 600 | 600 | 0.0680 | 0.0864 | 0.0864 | 0.0864 |
| Washing Machine (kW) | 0.13 | 0.16 | 0.18 | 0.2 | 200 | 250 | 250 | 250 | 0.0936 | 0.1440 | 0.162 | 0.18 |
| Air Conditioning (kW) | 0.965 | 1.081 | 1.081 | 1.081 | 300 | 480 | 600 | 800 | 1.0425 | 1.8681 | 2.3351 | 3.114 |
| Other Appliances (kWh/yr) | 44 | 120 | 250 | 550 | 1 | 1 | 1 | 1 | 0.1584 | 0.432 | 0.9 | 1.98 |
| Implied total kWh/yr | 272.84 | 708.39 | 1,120.44 | 1,670.80 | | | | | | | | |
| Implied total GJ/HH-yr | 0.982 | 2.550 | 4.034 | 6.015 | | | | | | | | |
| Implied lighting GJ/HH-yr | 0.262 | | | | | | | | | | | |

* Note: A "1" is used in the "Annual Hours Used" section when kWh/yr instead of wattage figures are entered in the left-hand section of this table.

**Rural Cooking/Water Heating**: Coal and coal briquette stove intensity is assumed to decline by 2 percent per year as stove efficiency increases and other cooking and water heating fuels are increasingly used in rural households. The intensity of LPG use in households is assumed to rise from just under 1 GJ per household (HH)-year in 1990 and 1995 to about 5.3 GJ/HH-yr in 2020, or about the same per-household usage as in biogas-fired stoves as of about 1995[10]. The biogas use in those households that use biogas stoves is assumed to remain constant. The usage of electricity for cooking is assumed to rise from about 0.5 GJ per household in 1990 and 1995 to 4 GJ per household in 2020.

**Rural Household Biomass Fuel Use**: We assume that per-household use of firewood and crop stalks decrease at about 0.70 percent/yr from 1990 to 1995, at 1 percent per year from 1995 to 2005, and 2 percent per year thereafter. It is also assumed that per-household use of dung continues to decrease at about 8 percent/yr through 2000, and decreases at an average of 5 percent/yr thereafter.

**Rural Space Heating**: The energy intensity of raw coal stoves is assumed to increase somewhat (as increasing dwelling size and increasing affluence counter efficiency gains) through 2010, remaining constant thereafter. The intensity of briquette stove use is assumed to increase slightly through 2010, and more rapidly thereafter as the amount of heating used by rural households expands. The per household intensity of coal use in coal boilers is assumed to remain constant, with any efficiency gains balanced by the combination of increased dwelling size and increased comfort levels.

**Rural Lighting**: Electricity use for lighting per household increases substantially in rural areas due to a combination of increasing availability of high-quality power, increasing dwelling size, and increasing affluence, tempered somewhat by improved efficiency. Overall, the rate of increase is assumed to average about 5.4 percent/yr, rising from about 50 to just under 240 kWh per household year. The intensity of kerosene lighting in rural households is assumed to stay roughly the same through 2020. For solar PV system energy intensity (computed on a solar energy basis), it is assumed that solar systems provide about 200 W-hr of energy per day, or about 73.0 kWh/HH-yr, and thus, assuming an overall system efficiency of 10 percent, use solar energy totalling 2.628 GJ/HH-yr.

**Rural Appliances**: Electricity use per household for appliances is assumed to roughly 14-fold to about 870 kWh per household (an average increase of more than 9%/yr) by 2020, relative to 1990 usage. The pattern of change of individual appliance usage, as described in Table 3-6, is similar to that in the urban sector, although overall usage per appliance is often less in rural areas.

***Table 3-6: Assumptions for Rural Household Appliance Use***

| | Wattage or kWh/yr | | | | Annual Hours Used* | | | | Energy Intensity (GJ/yr) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Appliance Type | 1990 | 2000 | 2010 | 2020 | 1990 | 2000 | 2010 | 2020 | 1990 | 2000 | 2010 | 2020 |
| Refrigerators | 350 | 441.65 | 441.65 | 441.65 | 1 | 1 | 1 | 1 | 1.260 | 1.590 | 1.590 | 1.590 |
| TV | 0.070 | 0.080 | 0.12 | 0.15 | 650 | 800 | 1000 | 1200 | 0.1638 | 0.2304 | 0.432 | 0.648 |
| Fan | 0.035 | 0.04 | 0.04 | 0.04 | 540 | 600 | 600 | 600 | 0.0680 | 0.0864 | 0.0864 | 0.0864 |
| Washing Machine | 0.13 | 0.16 | 0.18 | 0.2 | 200 | 275 | 275 | 275 | 0.0936 | 0.1584 | 0.1782 | 0.198 |
| Air Conditioning | 0.965 | 1.081 | 1.081 | 1.081 | 300 | 420 | 480 | 600 | 1.042 | 1.635 | 1.868 | 2.335 |
| Other Appliances | 27 | 50 | 120 | 200 | 1 | 1 | 1 | 1 | 0.0972 | 0.18 | 0.432 | 0.72 |
| Implied total kWh/yr | 58.71 | 207.26 | 526.22 | 871.18 | | | | | | | | |
| Implied total GJ/HH-yr | 0.211 | 0.746 | 1.894 | 3.136 | | | | | | | | |
| Implied lighting GJ/HH-yr | 0.17 | | | | | | | | | | | |

## AGRICULTURAL/FISHERIES SECTOR

Changes in Driving Activities:

**Agriculture Subsector**: Land area cropped is assumed to decrease from 95.7 million hectares in 1990 just under 91.5 million hectares by 2020. The fraction of the land area cultivated with tractors is assumed to increase from 50.5% in 1990 to 68 percent in 2020. Mechanical irrigation and drainage of fields is assumed to increase from 49.5% of agricultural area in 1990 to 60 percent in 2020, and the use of electric pumps is assumed to increase to 35% of all irrigated/drained area by 2020, with diesel pumping used on 15 percent of lands from 1995 on (additional irrigation is assumed to be gravity-fed via canals).

**Fisheries Subsector**: Fisheries output is assumed to increase by a factor of 3.7 between 1995 and 2020 (about 5.3 percent per year), with continued strong growth in the 1990s (Chinese output of aquatic products, in tonnes, increased by more than a factor of two between 1990 and 1995) followed by much lower growth between 2000 and 2020 (as physical limits to fish stocks and aquaculture areas begin to be factors). As more fisheries production shifts to larger fishing boats and to on-shore “aquaculture”, the boat engine power per unit output (in kW per tonne) is assumed to continue to decline, with the most rapid reduction in the near-term.

**“Sideline” Agricultural Production**: The output, in Yuan, of “Sideline Production”—assumed to mean (primarily) agricultural product processing—is assumed to increase at an average rate of 2.7 percent/yr through 2020, with higher growth earlier in the period.

Changes in Energy Intensities:

**Agricultural Subsector**: Energy intensities (fuel use in tractors and pumps per hectare cultivated) are assumed to remain at 1990 levels through 2020. This situation could also be interpreted as an offsetting combination of increased efficiency and increased intensity of cultivation per hectare (in an effort to achieve higher yields).

**Fisheries Subsector**: Diesel ships are assumed to require more fuel per unit motor power as time goes on, with fuel use per kW engine power increasing at 0.5 percent per year. This increase could reflect, in part, the longer hours at sea (or on the river) needed to harvest an increasingly scarce stock of fish.

**Sideline Production**: The intensity of coal use in "Sideline Production" (coal use per unit economic output) is assumed to decrease substantially through 2010, remaining stable thereafter. Diesel use declines somewhat from 1995 to 2000, remaining stable thereafter. The intensity of electricity use increases by 2.50 percent per year through 2010, then at 1 percent per year from 2010 to 2020. Crude oil use is phased out by 2010, but the intensities of use of all other fuels are assumed to remain at 1995 levels through 2020.

## MINING AND FORESTRY SECTOR

Only electricity use was modeled separately for the mining and forestry sector. Driving activities have not yet been applied for the subsectors modeled, so mining electricity use in mining was modeled as a series of growth rates in each subsector, as shown in Table 3-7.

***Table 3-7: Assumptions for Future Electricity Consumption in Mining and Forestry***

| | | | Annual Growth From | | |
|---|---|---|---|---|---|
| TOTAL ELECTRICITY USE IN: | 1990 | 1995 | 95-2000 | 2000-10 | 2010-20 |
| Ferrous Metals Mining and Dressing | 17.947 | 12.344 | 0.95% | 3.00% | 2.00% |
| Non-ferrous Metals Mining and Dressing | 20.213 | 29.915 | 7.0% | 5.0% | 2.5% |
| Non-metal Minerals Mining and Dressing | 14.051 | 18.998 | 2.19% | 3.00% | 2.00% |
| Other Minerals Mining and Dressing | 0.288 | 1.216 | 7.0% | 6.0% | 4.0% |
| Logging and Transport of Wood/Bamboo | 3.735 | 4.685 | 7.0% | 6.0% | 4.0% |
| **TOTAL** | 56.233 | 67.159 | | | |

## INDUSTRIAL SECTOR

### Changes in Driving Activities

Changes in output vary by subsector, with three to ten-fold increases in output. Heavier industries, including iron and steel, non-ferrous metals, and (especially) cement and other building material show reduced growth rates in the later years of the projection period, as the economy matures. Light industry, machinery and chemicals are the fastest-growing subsectors. Table 3-8 summarizes the assumed changes in activities in the industrial subsectors.

***Table 3-8: Assumptions as to Driving Activities in Industrial Subsectors***

| Subsector/product | Units | 1990 | 1995 | Annual Growth From 95-2000 | 2000-10 | 2010-20 |
|---|---|---|---|---|---|---|
| Steel | Mte | 66.35 | 95.3599 | 0.95% | 3.00% | 2.00% |
| Cement | Mte | 209.71 | 475.6059 | 2.19% | 3.00% | 2.00% |
| Brick and Tile | Bill Pcs | 458.5 | *600* | 1.50% | 1.00% | 0.00% |
| Glass | Mil Boxes | 80.67 | 157.3171 | 0.34% | 1.50% | 1.50% |
| Other Building Materials | Bil Y Output | 58.02 | *110* | 3.5% | 3.00% | 2.00% |
| Chemical Industry Output | Tril Y Output | 0.189 | 0.2907999 | 7% | 5.50% | 4.00% |
| --Fraction as Fertilizer | | 20% | 17.50% | | | |
| --Fraction as Other | | 80% | 82.50% | | | |
| Non-Ferrous Metals | Bil Y Output | 70.45 | 103.51416 | 7.0% | 5.00% | 2.50% |
| Light Industry | Tril Y Output | 1.118 | 1.8005502 | 8.0% | 6.00% | 5.00% |
| Machinery | Tril Y Output | 0.407 | 0.8186224 | 9.0% | 7.00% | 5.00% |
| Other Industry | Tril Y Output | 0.23801 | 0.3497148 | 7.0% | 6.00% | 4.00% |

The estimates of output shown above call for growth that is somewhat less, in most cases, than is reflected in the World Bank's estimates made as part of the "Issues and Options in Greenhouse Gas Control" series[11]. The reasons for these reduced growth estimates include the recent (and ongoing) Asian economic crisis, the maturing of the Chinese economy, and recent trends in output. In the iron and steel, cement, and some building materials sectors, in particular, there has recently been a marked reduction in State output targets for 2000 (as reflected in the figures above) due to oversupply of key products. The assumptions shown above assume that building materials-related sectors (and iron and steel) resume growing again after 2000, but do so at a more moderate rate, as the rate of building begins to decrease somewhat (with decreasing population growth) and as the efficiency with which building materials are used increases.

Changes in Energy Intensities:

Energy intensities in the industrial subsectors are assumed to decline nearly across the board, with substantial reductions (up to 75 percent) for some coal-fired devices, and more modest reductions in other applications. The exception is the intensity of electricity use, which is assumed to increase gradually in some subsectors, remain static in some, and decline gradually in others. The reader is urged to review the LEAP Demand Data Echo (in Annex B) and the workpapers used to derive industrial-sector inputs for the LEAP China model (in Annex A) for more details on intensity changes in Chinese industries.

## TRANSPORT SECTOR

Making sense of the existing transport data for China, and deriving a relatively disaggregated end-use model from those data, is a difficult problem at best. Given the data presently available, a number of assumptions (although not, in all probability, implausible assumptions), have been built into the disaggregation of historical transport statistics described in Annex A. Some of the central assumptions as to driving activities in the sector are described in Table 3-9, below. Passenger transportation in public conveyances (by plane, bus, rail, and ship) are treated separately from private motorized transport such as private cars and motorcycles.

*Table 3-9:*

| Freight and Passenger Transport Activities and Shares for Entry into LEAP | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Annual Average Growth from: | | | | | |
| | 1990 | 1995 | 1995 - 2000 | 2000 - 2010 | 2010 - 2020 | 2000 | 2010 | 2020 |
| **Freight tonne-km (Trillion)** | 2.62 | 3.57 | 3.5% | 3.5% | 3.00% | 4.24356 | 5.98596 | 8.04463 |
| Fraction of freight by: | | | | | | | | |
| Rail | 40.53% | 36.02% | | | | 33.0% | 30.00% | 30.00% |
| Road | 12.81% | 13.14% | | | | 14.2% | 17.00% | 19.00% |
| Waterway | 44.23% | 49.13% | | | | 51.20% | 51.65% | 49.80% |
| Pipeline | 2.39% | 1.65% | | | | 1.50% | 1.20% | 1.00% |
| Air | 0.03% | 0.06% | | | | 0.10% | 0.15% | 0.20% |
| **Total Pass-km (Trillion)** | 0.563 | 0.900 | 5.0% | 5.0% | 4.00% | 1.1489 | 1.87143 | 2.77017 |
| Fraction of travel by: | | | | | | | | |
| Rail | 46.40% | 39.39% | | | | 32.80% | 27.00% | 27.70% |
| Road | 46.58% | 51.13% | | | | 57.50% | 62.00% | 60.00% |
| Waterway | 2.93% | 1.91% | | | | 1.20% | 1.00% | 0.80% |
| Air | 4.10% | 7.57% | | | | 8.50% | 10.00% | 11.50% |

Changes in Driving Activities (by subsector)

**Freight Transport**: The total tonne-kilometers of goods transport are assumed to grow at 3.5 percent/yr through 2010, and at 3 percent annually thereafter. Freight traffic is assumed to continue to shift from rail transport to road, water, and (to a lesser extent) air transport through 2010, when the fraction of goods transported by rail plateaus, and the fraction transported by water starts to decline. The fraction of goods transported by pipeline declines slowly over time, corresponding to a decrease in the production of crude oil relative to other commodities. In a pattern similar to that for passenger rail transport, the use of steam locomotives continues to decline through 2020, the use of diesel locomotives increases until 2000, remains steady until 2010, then declines, and the use of electric locomotives increases throughout the period. Of the portion of freight carried by road, the fraction carried in large diesel trucks increases from 17 percent in 1990 to 25 percent in 2020, and the fraction carried by tractors (2 and 4-wheeled combined) declines by about half (from a 1990 value of somewhat over 5 percent). The share of freight carried in large gasoline-engine trucks declines somewhat (from 71.5 to 58 percent) between 1990 and 2020, but the fraction of freight carried by small gasoline trucks more than doubles over the same period, increasing from 6 to 14 percent of road freight.

**Public Passenger Transport**: The total passenger kilometers of public passenger transport are assumed to grow at 5 percent/yr through 2010, and at 4 percent per year thereafter. Passenger traffic is assumed to continue to shift from railroad and water transport to road and air transport through 2010, with the share of traffic handled by rail increasing again (slightly) after 2010. The use of steam locomotives continues to decline, with steam locomotives carrying only one percent of traffic in 2020. The fraction of rail passenger traffic hauled by electric locomotives increases to 39 percent by 2020, with the fraction of passengers carried on diesel trains increasing slightly until 2010, then decreasing. Diesel buses carry 28 percent of public road passenger traffic by 2020, up from somewhat under 20 percent in 1990. The share of passenger traffic in gasoline-powered buses declines somewhat, but the share of passenger traffic in gasoline "mini-buses" increases relative to traffic in larger gasoline buses.

**Motorcycles**: The number of motorcycles is assumed to increase to almost 46 million in 2020, up from 4.2 million in 1990. The growth rate of the motorcycle fleet decreases over the period modeled, particularly after 2010.

**Private Cars**: The number of private cars is assumed to increase to over 72 million by 2020, including annual rates of increase of 12 percent from 2000 to 2010 and 10 percent from 2010 to 2020. Fleets of specialty vehicles and "other vehicles" increase much more slowly, at rates ranging from 2 to 4 percent annually, with lower rates of increase in future years.

<u>Changes in Energy Intensities</u>:

**Freight Transport**: Steam and electric locomotive energy intensities (for example, kWh per tonne-km) are assumed to remain at 1995 levels through 2000, while the energy intensity of diesel-fueled rail freight increases at 0.5 percent per year. Diesel and gasoline truck energy intensities decrease at approximately 0.5 percent/yr through 2020. The energy intensities for the decreasing portion of freight transported by tractor, as well as water- and air-borne freight transport energy intensities, are assumed to remain at 1990 levels. Pipeline transport is fueled by electricity, coal, and crude oil, but, lacking statistics on what fraction of pipeline loads have been carried by pipelines using the three different fuels, it was assumed that the intensity of electric-driven pipeline transport (in GJ per tonne-km of all pipeline freight) does not change over the period, while the intensities of coal- and crude-oil-fueled pipeline transport decline at 5 and 1 percent per year, respectively, from 1990 to 2020.

**Public Passenger Transport**: Diesel passenger train energy intensities are assumed to increase at 0.5 percent per year (presumably as passengers demand more elbow room), while the kWh per passenger-km in electric trains remains the same (as efficiency increases balance a reduction in passengers carried per locomotive). The energy intensity of coal steam trains is assumed to remain the same as this type of passenger train is phased out. Both diesel and gasoline bus energy intensities decrease at 0.5 percent/yr through 2020, while water-borne and air transport energy intensities remain at 1995 levels through 2020.

**Motorcycles**: The average energy intensity of motorcycle use (GJ of gasoline per vehicle/yr) is assume to remain at its 1990 level through 2020, as motor efficiency increases are balanced by a trend toward the use of more powerful engines in motorcycles.

**Private Cars**: The average energy intensity of private car use (GJ of gasoline per vehicle/yr) is assume to decline at an average rate of 0.5 percent per year from 1995 to 2020, with the decline being the result of an improvement in fuel economy (from 12 liters per 100 km in 1995 to 10.6 liters/100 km in 2020); vehicle kilometers traveled per vehicle are assumed to remain the same, on average, through the period modeled. The energy intensities of “specialty vehicles” and “other vehicles” (on a GJ per vehicle-yr basis) are assumed to remain constant through 2020.

## BUILDING SECTOR

Changes in Driving Activities

**Building Sector Output**: Gross output, measured in billion Yuan, in the Building (construction) sector is assumed to increase by an average of 6.8 percent/yr through 2020, with growth at a higher rate earlier in the period (10 percent annually from 1995 to 2000), decreasing in later years (5 percent per year from 2010 to 2020). Real output growth in the building sector from 1990 to 1997 averaged about 12 percent annually, but the 1995 to 1997 growth rate was considerably lower.

Changes in Energy Intensities:

Energy intensities (GJ per unit output) are assumed to decline for all fuels, at rates generally varying from 1 to 3 percent per year, and with steeper declines generally occurring early in the period modeled. The intensity of electricity use in the building sector is assumed to decline by 2 percent annually from 1995 to 2000, moderating to a decline of 0.5 percent annually from 2000 to 2010, and remaining stable thereafter.

## SERVICES SECTOR

The services sector is modeled as three different subsectors: “Commercial”, “Other Services”, and “Tap Water Provision”.

Changes in Driving Activities:

**Commercial and Other Services Output**: Economic output (on a real basis) in these subsectors is assumed to at 10 to 11 percent annually through 2010, declining modestly (to 7.5 and 8 percent/yr, respectively) thereafter. These rates of increase are somewhat lower than, but similar to growth rates assumed in a 1995 World Bank study of greenhouse gas emissions in China[12].

**Tap Water Provision**: The level of tap water provision is assumed to scale with population.

Changes in Energy Intensities:

**Commercial and Other Services**: In both the commercial and other services subsectors, energy intensities decrease markedly for coal and coke, with the rate of decline particularly rapid through 2000. The intensity (in GJ of fuel use per unit output), is assumed to increase for most other petroleum-based fuels through 2000, either remaining at the year 2000 level or decreasing at 2 percent per year thereafter. The intensity of electricity use per unit output in the commercial subsector is assumed to grow slowly (at 0.5 percent/yr through 2000, then remain the same until 2010, when it decreases at 0.5 percent annually. Electricity use intensity in the other services subsector is assumed to rise until 2000, remaining the same thereafter. decreasing or increasing modestly for other fuels and electricity.

**Tap Water Provision**: The use of electricity in providing tap water in China, on a per-capita basis, is at about 1 percent per year from 1995 on as water becomes increasingly scarce and (possibly) contaminated, and water purification thus becomes increasingly energy-intensive.

## COMMUNICATIONS SECTOR

Changes in Driving Activities:

**A**ssumptions as to the growth in communications output are derived primarily from a portion of the World Bank study Issues and Options in Greenhouse Gas Control[13]. It is assumed that communications will be one of the fastest-growing sectors of the Chinese economy, with economic output in the sector increasing at over 9 percent per year through 2000, and at between 7 and 8 percent per year thereafter

Changes in Energy Intensities:

It is assumed that the intensity of coal use in the communications sector will decrease markedly over time, falling from about 0.5 GJ per thousand Yuan of output in 1995 to about 0.25 GJ per thousand Yuan in 2020. The intensities of oil products use is assumed to generally remain steady after increasing slowly through 2000, but the intensity of electricity use in the communications sector is assumed to increase at rates ranging from 1.2 to 2.8 percent per year (with higher rates of increase in later years). Natural gas use in the sector, which is modest to begin with, is assumed to decrease at rates ranging from 1.4 to 2.6 percent per year.

### 3.2.2 Assumptions as to changes in electricity generation infrastructure

On the energy supply/transformation side in the BAU scenario, lack of capital means that coal-fired generation facilities continue to provide the great bulk of power supplies, with most of the expansion of coal-fired capacity being domestically-produced units. Progressively larger fractions of coal fired power plants have domestically-produced scrubbers to remove sulfur oxides, however, though the scrubbing efficiencies are not as high as for new coal-fired power plants in North America, Europe, or Japan. Nuclear power continues to expand, but modestly. Natural gas use expands as well, but only such that its share of overall demand increases relatively modestly. The increase in natural gas use is fed through a combination of several LNG (liquefied natural gas) and pipeline projects, plus some increased domestic production. The use of renewable energy sources for electricity and other uses continues to expand, but not aggressively. Specific assumptions for electricity generation infrastructure are described below.

**Electricity Generation Efficiencies**: We assume gross energy efficiencies of 31.2 percent for existing coal-fired plants from 1996 on, with similar figures for existing oil-fired plants, 36 percent (rising to 38.5 percent in 2010) for new raw-coal plants, 37 percent (rising to 39 percent in 2010) for new washed-coal plants. 35.5 percent (rising to 38 percent in 2010) for plants with FGD (flue gas desulfurization), and 41 percent (rising to 45 percent in 2010 and 46 percent in 2020) for integrated gasification/combined-cycle (IGCC) and supercritical coal-fired plants. For new oil-fired plants, gross generation efficiencies are assumed to be 33 percent, rising to 37 percent in 2010. The efficiency of gas-fired steam-cycle plants is assumed to start at 35 percent in 1996, rising to 42 and 44 percent in 2010 and 2020, respectively. The efficiency of existing cogeneration is assumed to be 22 percent as of 1996 (with an additional 60 percent of fuel energy recovered as heat), and new cogeneration systems are assumed to have an average efficiency of 25 percent (again with 60 percent of fuel energy content recovered as heat. Geothermal plant generation efficiency is assumed to be 10 percent.

**Electricity Generation Capacity Additions**: Coal (standard, washed coal, and FGD-equipped, with limited use of IGCC and supercritical plants), oil, gas, hydro, and nuclear plants are added to maintain capacity factors at reasonable levels. Some wind, solar, and tidal power is also included in the BAU scenario. See section 5 of this report for a presentation of the changes in plant capacities over time.

**Electricity Generation Auxiliary Power Use**: In-plant or auxiliary use of electricity in thermal power plants is assumed to range from about 3 percent of gross generation (for new natural gas-fired plants) to about 8 percent of gross generation (for existing coal-fired plants).

**Electricity Transmission and Distribution**: Electricity transmission and distribution (T&D) losses are assumed to decline modestly between 1990 and 2010—from a nominal 8.79 percent in 1993 to about 7.5 percent in 2010. Note that in Chinese electricity data, it has usually been the case that electricity distribution losses are to some extent "lumped" with sectoral electricity use, so the figures given here probably represent only T&D losses from transmission and high-voltage distribution lines, and thus do not reflect what are likely to be considerable losses from lower-voltage distribution lines.

### 3.2.3 Other supply-side changes

**Distribution**: Gas distribution losses are assumed to increase from 1 percent in 1990 to 2 percent by 2000 and beyond, as gas distribution networks become more widespread and reach more consumers. Oilfield losses of crude oil are assumed to decline from 1.8 percent in 1990 and 1992 to 1.0 percent by 2000. Distribution loss figures for petroleum-based fuels (gasoline, diesel, and residual fuel oil) from the original LEAP data set ranged from 3.5 percent to 5 percent of production, which seems a bit high, but may include some losses due to theft. No changes were made in these petroleum product loss figures from 1990 on.

**District Heat**: Heat production capacity is assumed to more than triple by 2010 relative to 1990, and capacity continues to increase through 2020. Coal remains the dominant fuel for plants providing steam for district heating and other uses, although plants using oil (residual), manufactured gas (coking gas), and natural gas are also assumed to be added. The efficiency of new coal-fired heating plants is assumed to be 80 percent, new oil- and manufactured gas-fired plants are assumed to be 84 percent efficient, and natural gas-fired plants are assumed to be 86 percent efficient. All plants use electricity as an auxiliary fuel at a rate of 12.2 kWh per GJ of heat produced[i].

**Coking**: Coking capacity was estimated from historical data by assuming a capacity factor of 90 percent, and calculating capacity based on coke output. Coking capacity is assumed to rise to meet coke demand, thereby increasing about 30 percent between 1995 and 2020. The average efficiency of coke plants is assumed to increase slowly, going from 84 percent in 1995 to 87 percent in 2020. Coking gas recovery averages 8 percent of total energy input in 1995, rising to 9.5 percent in 2020.

**Gasworks**: Gasworks capacity is assumed to rise as demand for gasworks products (about 63 percent producer gas, 24 percent coke, 11 percent coking gas, and 1.4 percent other coke products) increases. Assuming a capacity factor of 100 percent (again, figures for actual capacity have not been available, so capacity estimates are based on historical figures for annual production), gasworks capacity rises from about 24 billion cubic meters per year in 1995 to 105 billion cubic meters per year in 2020. Gasworks efficiency is assumed to rise from just under 86 percent in 2000 to 88 percent in 2020.

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[i] Estimated based on data in China Statistical Publishing House (1998), China Energy Statistical Yearbook, 1991 - 1996.

**Biogas Production**: No specific capacity estimates for biogas production were used, rather biogas production was implicitly assumed to expand to meet demand. Biogas is produced from animal wastes, and a conversion efficiency of 60 percent was assumed throughout the period modeled.

**Oil Refining**: Oil refinery capacity is assumed to expand approximately two-fold between 1990 and 2020, with a maximum refinery capacity factor of 98 percent[j]. This level of expansion maintains the ratio of total oil products imports to oil products requirements at roughly 1990 levels. Refinery efficiency is assumed to be 96.5 percent from 2000 on, and auxiliary fuel use by refineries was assumed to be 67 kWh of electricity and 0.41 GJ of heat per tonne of product output. The output of refined products (gasoline, diesel, residual fuel oil, LPG, other oil products, kerosene/jet fuel, and refinery gas) was assumed to be proportional to requirements for these fuels[k].

**Coal Briquette Production**: Coal briquette production, including both "honeycomb briquettes" and "industrial briquettes" is assumed to have an efficiency of 98 percent (that is, 98 percent of the energy content of the raw coal input is contained in the briquettes produced. Production is assumed to expand to meet demand.

**Natural Gas Production**: Production of natural gas is assumed to expand from somewhat under 16 billion cubic meters per year in 1990 to 57 billion cubic meters per year in 2020.

**Liquefied Natural Gas Imports**: The first terminal for LNG imports is assumed to come on line in 2005, with a capacity of 3 billion cubic meters per year. An additional 3 billion cubic meters of annual capacity is assumed added every five years, for a total capacity of 12 billion cubic meters/yr by 2020.

**Coal Washing**: Capacity to "wash" coal is assumed to increase from a rough estimate of 150 million tonnes per year (1.5 times the level of actual washed coal production) in 1990 to 550 million tonnes annually in 2020. The efficiency of coal washing (defined as GH of washed coal out of the process divided by GJ of raw coal in) is assumed to be 91.6 percent (as derived from energy statistics for 1996) from 2000 on.

**Crude Oil Production**: Crude oil production capacity (and output, since crude oil production is assumed to run to maximum capacity) is assumed to rise modestly, from just under 140 million tonnes of crude in 1990 to 220 million tonnes in 2020. The efficiency of crude oil production from 2000 on is assumed to be 98.9 percent. From 2000 on, auxiliary use of fuels in oil extraction are assumed to be 165 kWh

[j] That is, the maximum possible refinery output is equal to capacity times 0.98. Note that this figure is significantly higher than the implied actual average 1990 capacity factor for Chinese refineries (about 74 percent).
[k] This assumption for oil refining is probably less than realistic. Modeling of the oil refining sector is one area in which there is likely room for improvement in the current LEAP model for China.

of electricity per tonne of crude oil extracted, plus 3.4 kg of gasoline, 12 kg of diesel, and 7 kg of residual oil per tonne of crude oil produced.

**Coal Mining**: Coal production capacity is assumed to increase from an aggregate of just under 1.1 billion tonnes annually in 1990 to about 2.9 billion tonnes annually in 2020. The proportion of coal produced by rural collectives increases from 1990 to 2000, but decreases thereafter, as more efficient state- and ministry-owned mines are emphasized. Auxiliary use of electricity in coal mining is assumed to remain at the calculated 1990 value of approximately 28 kWh per tonne of coal produced. Auxiliary use of coal in coal production throughout the period modeled (based on statistics for 1996), is assumed to be approximately 20 kg per tonne, of which about 90 percent (18 kg per tonne) is raw coal.

**Resources**: No new reserves of crude oil reserves are assumed to be added from 1990 through 2020, meaning that the total crude oil available is the 79 billion tonnes estimated to be extant as of 1990. Wind and solar resources are assumed to be 3.8 and 22 billion GJ annually, respectively. Reserves of uranium for producing nuclear fuel are adequate for virtually any level of nuclear power development. Coal reserves are about 970 billion tonnes as of 1990, and no assumptions as to additions to coal reserves were made (or needed). Recoverable hydroelectric resources are assumed to be just over 7 billion GJ annually[14]. Tidal energy reserves were taken to be 170 million GJ annually, and the availability of animal wastes was assumed to increase from 192 million tonnes in 1990 to 560 million tonnes in 2020 (as the average Chinese diet becomes richer in meat and other animal products). Domestic natural gas reserves start at 1380 billion cubic meters in 1990, and an additional 500 billion cubic meters of reserves is assumed to be added every ten years starting in 2000.

### 3.3 Alternative/Clean Coal Scenario

In general, the goal in preparing an Alternative scenario is to demonstrate that the same (or very nearly the same) goods and services can be produced for an economy in a different way, and specifically, in a way that has different environmental consequences. As such, the Alternative scenario presented in this paper uses the same rates of growth of key variables such as population, households, urban migration, and the use of energy services, and industrial production.

#### 3.3.1 The Demand side of the Alternative/Clean Coal Scenario

For the purposes of the analysis presented here, the Alternative case uses the same demand-side assumptions as the BAU Case. In near-term future work, however, Nautilus will be elaborating and evaluating an Alternative scenario that includes a combination of fuel substitution and energy efficiency measures that markedly decrease energy consumption and environmental emissions.

### 3.3.2 Changes in electricity generation infrastructure relative to Base Case

The major differences between the Alternative/Clean Coal and BAU scenarios, as they are presently configured, lie in the degree to which modifications are employed to reduce emissions of air pollutants (notably sulfur oxides) from electricity generation. The Alternative scenario is not intended to be either an "optimal" application of control technologies, nor is it designed to represent the most possible or probably lower-emissions scenario for the sector. Rather, the Alternative scenario is intended only as an example of one of many possible outcomes, and it focuses on clean coal technologies primarily to illustrate the potential role of clean coal technologies—as well as the limitations of those technologies—in addressing environmental problems in China. Some of the key assumptions in the Alternative/Clean Coal scenario are as follows:

- All new standard coal plants (except cogeneration facilities and plants using washed coal) plants have flue gas desulfurization (FGD) systems by 2010.
- All existing coal-fired plants that did not originally have FGD (except cogeneration facilities and plants using washed coal) have been retrofitted with FGD by 2020.
- The rate of introduction of high-efficiency coal-fired generation—here assumed to be a combination of integrated gasification/combined cycle (IGCC) and super critical boiler technology (SCPF) plants is increased after the year 2000 relative to the BAU scenario, resulting in a combined total IGCC/SCPF capacity of 60 GW by 2020.

There are no significant changes in other generation types or fuel supply systems in the Alternative/Clean Coal scenario relative to the BAU scenario.

# 4. FUTURE ENERGY DEMAND IN CHINA

## 4.1 Introduction: Presentation of results for BAU Case Demand Scenario

The assumptions that have gone into our "bottom-up" (sector and subsector activity-driven) Business as Usual energy demand scenario for China were described in Section 3, above. The aggregate results of these individual assumptions—that is, our BAU projections for fuel use in China through 2020, are presented below. This section focuses on overall energy demand by fuel, the distribution of overall fuel demand by sector and subsector, and demand for electricity in particular by sector and subsector. We also describe what we see as some of the major determinants of growth in energy demand in China over the coming years, and reflect on some of the major uncertainties in the analysis presented.

Additional detailed results of the BAU demand scenario are presented in Annex C of this paper.

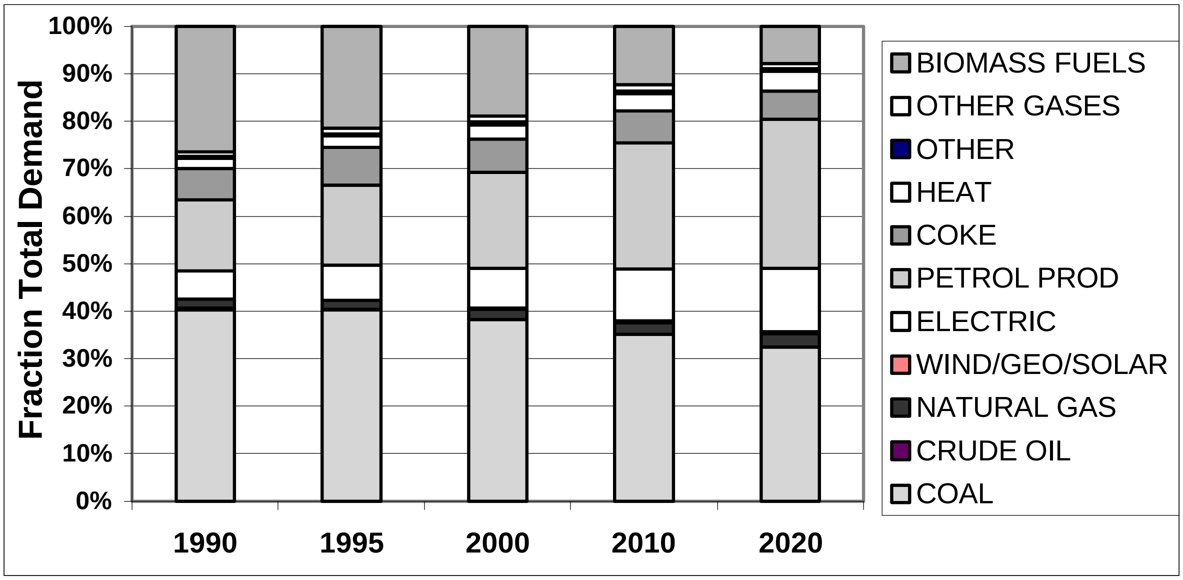
### 4.2 Energy demand by fuel

Table 4-1 presents a summary of the evolution of fuel use over time for each of the end-use fuels included in the LEAP China model. Overall fuel use grows at an average rate of 2.8 percent annually from 1995 through 2020. Although coal remains the dominant fuel in the economy, coal use grows at a slower rate than overall fuels demand—averaging 1.9 percent growth annually. Growth of demand for heat, producer gas, and electricity is considerably stronger, averaging between 5 and 6 percent annually, with growth in natural gas use only somewhat lower, and growth in LPG use somewhat higher. Growth in refined motor fuels (diesel, gasoline, jet fuel) averages between 4 and 7 percent per year. Biomass fuels use declines over time, with use of both firewood and crop wastes (crop stalks) decreasing at an average rate of 1.2 percent/yr. This pattern of replacement of solid fuels with electricity, heat, and liquid and gaseous fuels is seen more clearly in Figure 4-1, which presents the fraction of total end-use demand provided by fuels in different fuel categories.

***Table 4-1:***

| ENERGY DEMAND: FUEL BY YEAR, ALL SECTORS (MILLION TONNES COAL EQ) | | | | | | Ave. Annual Growth Rate: 1995 to 2020 |
|---|---|---|---|---|---|---|
| **FUEL** | 1990 | 1995 | 2000 | 2010 | 2020 | |
| COAL | 363.3 | 470.8 | 514.0 | 628.3 | 760.7 | 1.9% |
| WASHED COAL | 14.8 | 18.0 | 19.6 | 22.8 | 22.0 | 0.8% |
| HEAT | 21.4 | 31.8 | 43.6 | 75.9 | 112.8 | 5.2% |
| HONEYCOMB BRIQUT | 25.4 | 34.0 | 39.9 | 53.5 | 57.9 | 2.2% |
| COKE | 67.5 | 103.0 | 107.9 | 135.6 | 153.4 | 1.6% |
| PRODUCER GAS | 1.4 | 3.2 | 5.7 | 9.4 | 13.4 | 5.9% |
| COKING GAS | 8.9 | 12.7 | 13.1 | 16.1 | 17.6 | 1.3% |
| OTH COKE PRODUCT | 1.6 | 2.1 | 2.7 | 3.9 | 4.7 | 3.3% |
| CRUDE OIL | 3.8 | 2.9 | 0.7 | 0.6 | 0.6 | -6.0% |
| GASOLINE | 39.4 | 62.0 | 91.0 | 179.7 | 305.8 | 6.6% |
| DIESEL/GAS OIL | 36.3 | 49.0 | 62.5 | 98.3 | 143.3 | 4.4% |
| RESIDUAL/FUELOIL | 34.6 | 49.1 | 59.4 | 90.7 | 126.8 | 3.9% |
| OTHER OIL PROD. | 26.0 | 39.7 | 57.1 | 105.6 | 160.4 | 5.7% |
| LPG/BOTTLED GAS | 4.4 | 9.9 | 16.0 | 34.4 | 48.6 | 6.6% |
| NATURAL GAS | 20.0 | 23.5 | 30.4 | 50.3 | 73.8 | 4.7% |
| REFINERY GAS | 3.9 | 5.0 | 6.0 | 6.4 | - | N/A |
| ELECTRICITY | 59.0 | 94.4 | 129.0 | 222.0 | 348.6 | 5.4% |
| SOLAR | 0.1 | 0.8 | 2.2 | 6.8 | 11.4 | 11.2% |
| KEROSENE/JETFUEL | 4.2 | 7.0 | 9.8 | 19.9 | 34.4 | 6.6% |
| BIOGAS | 4.0 | 5.7 | 7.7 | 10.3 | 10.2 | 2.3% |
| FIREWOOD | 131.4 | 138.2 | 141.8 | 124.5 | 101.3 | -1.2% |
| ANIMAL WASTES | 2.5 | 1.8 | 1.3 | 0.8 | 0.5 | -5.3% |
| CROP STALKS | 131.7 | 138.4 | 142.0 | 124.6 | 101.5 | -1.2% |
| **TOTAL** | 1,006 | 1,303 | 1,503 | 2,020 | 2,610 | 2.8% |

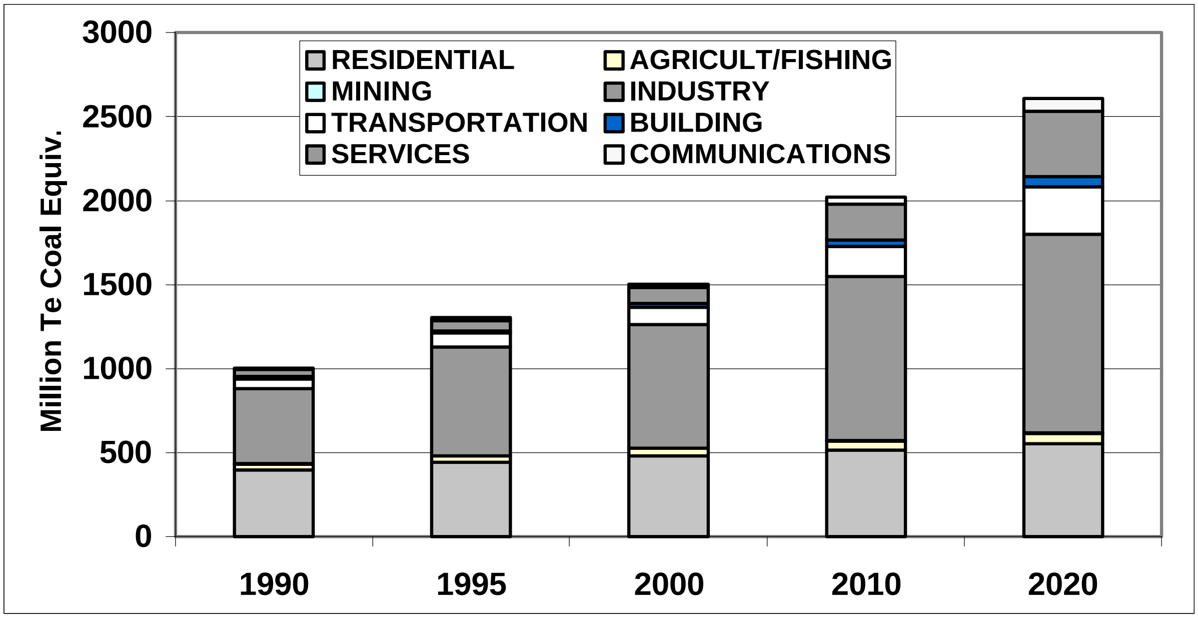
***Fig**ure **4-1: Energy Demand by Fuel Category***




## 4.3 Energy Demand by Sector

Figure 4-2 shows the changes in energy demand by sector in our BAU scenario for China. Here the industrial sector continues to account for the major share of fuels demand through 2020, but the importance of the residential, transportation, and services sectors rises considerably compared to 1990, especially between 2010 and 2020. Growth in overall industrial sector energy use averages 2.4 per cent per year between 1995 and 2020, while growth in energy use in the services and communications sectors rise at more than 7 percent per year, and transport sector fuel consumption increases at more than 5 percent per year. Despite the increase in GDP per capita, residential energy consumption rises at only 0.9 percent annually, on average, between 1995 and 2020. This slow rate of increase is likely due largely to the ongoing shift toward consumption of gaseous fuels, heat, and electricity, which are used more efficiently than solid fuels.

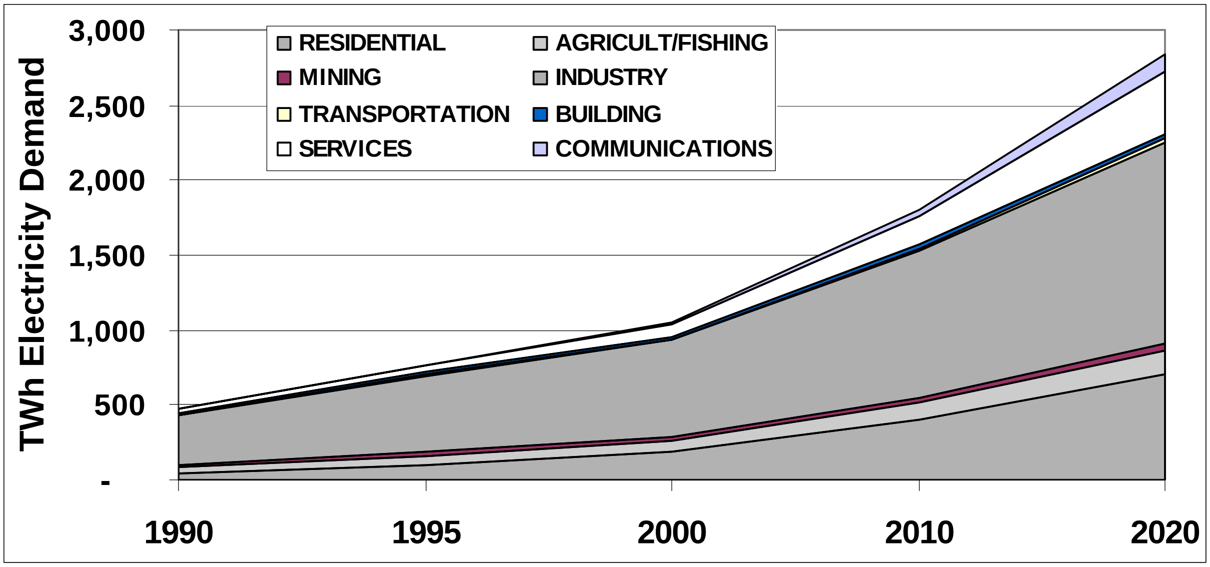
*Figure 4-2: Energy Demand by Sector, All Fuels*




## 4.4 Electricity Energy Demand by Sector and Sub-sector

Figure 4-3 and Table 4-2 present BAU scenario results for the trajectory of electricity demand by sector and subsector. Overall electricity demand grows at an average rate of 5.4 percent annually between 1995 and 2020. The residential, services, and communication sectors show the strongest growth in electricity demand (at almost 8 to over 9 percent annually), while growth in electricity demand in the agriculture, industrial, mining, and transport sectors are all near 4 percent annually.

*Figure 4-3: Estimated Electricity Demand by Sector, 1990 to 2020*




Among the industrial subsectors, electricity demand increases most in the light industrial and machinery subsectors, while heavy industries such as iron and steel making and cement manufacturing show slower growth in electricity use.

*Table 4-2:*

| ENERGY DEMAND: SECTOR BY YEAR, ELECTRICITY (THOUSAND GIGAWATT-HOURS) | | | | | | Ave. Annual Growth Rate: |
|---|---|---|---|---|---|---|
| **SECTOR**/SUBSECTOR | 1990 | 1995 | 2000 | 2010 | 2020 | 1995 to 2020 |
| **RESIDENTIAL** | **48.2** | **107.2** | **189.4** | **401.6** | **713.4** | **7.9%** |
| URBAN | 28.4 | 63.4 | 106.2 | 226.8 | 434.6 | 8.0% |
| RURAL | 19.8 | 43.8 | 83.2 | 174.8 | 278.9 | 7.7% |
| | | | | | | |
| **AGRICULT/FISHING** | **42.7** | **58.3** | **75.9** | **113.4** | **151.5** | **3.9%** |
| AGRICULTURE | 17.1 | 23.7 | 31.2 | 39.1 | 46.3 | 2.7% |
| FISHING | - | - | - | - | - | |
| SIDELINE PRODUCE | 25.6 | 34.6 | 44.7 | 74.3 | 105.1 | 4.5% |
| | | | | | | |
| **MINING** | **15.6** | **18.7** | **23.4** | **35.8** | **45.9** | **3.7%** |
| Ferr Metals Min. | 5.0 | 3.4 | 3.6 | 4.8 | 5.9 | 2.2% |
| Non-ferr Metals | 5.6 | 8.3 | 11.7 | 19.0 | 24.3 | 4.4% |
| Non-Metal Miner. | 3.9 | 5.3 | 5.9 | 7.9 | 9.6 | 2.4% |
| Other Minerals | 0.1 | 0.3 | 0.5 | 0.9 | 1.3 | 5.4% |
| Logging Wood/Bam | 1.0 | 1.3 | 1.8 | 3.3 | 4.8 | 5.4% |
| | | | | | | |
| **INDUSTRY** | **328.3** | **513.8** | **647.2** | **979.7** | **1,341.9** | **3.9%** |
| FERROUS | 62.5 | 90.4 | 100.7 | 142.2 | 182.2 | 2.8% |
| CEMENT | 22.1 | 50.4 | 53.3 | 67.7 | 81.5 | 1.9% |
| BUILDING MATER. | 6.5 | 9.9 | 10.9 | 12.3 | 12.5 | 1.0% |
| CHEMICAL | 79.0 | 107.4 | 132.7 | 195.5 | 230.1 | 3.1% |
| NON-FERROUS | 25.2 | 42.6 | 56.8 | 85.3 | 101.8 | 3.5% |
| LIGHT INDUSTRY | 88.5 | 132.1 | 180.1 | 276.4 | 428.7 | 4.8% |
| MACHINERY | 44.5 | 81.0 | 112.7 | 200.3 | 304.9 | 5.4% |
| OTHER INDUSTRY | - | - | - | - | - | |
| | | | | | | |
| **TRANSPORTATION** | **5.0** | **7.2** | **8.2** | **11.4** | **19.9** | **4.2%** |
| PUBLIC PASSENGER | 2.1 | 3.4 | 3.9 | 5.1 | 9.6 | 4.2% |
| FREIGHT | 2.9 | 3.8 | 4.3 | 6.3 | 10.3 | 4.1% |
| MOTORCYCLES | - | - | - | - | - | |
| PRIVATE CARS | - | - | - | - | - | |
| OTHER ROAD VEH. | - | - | - | - | - | |
| | | | | | | |
| **BUILDING** | **6.5** | **9.5** | **13.8** | **25.8** | **42.0** | **6.1%** |
| | | | | | | |
| **SERVICES** | **28.0** | **43.4** | **76.7** | **196.9** | **412.6** | **9.4%** |
| COMMERCIAL | 7.6 | 19.9 | 32.9 | 83.4 | 167.6 | 8.9% |
| OTHER SERVICES | 20.3 | 23.5 | 43.8 | 113.5 | 245.0 | 9.8% |
| Tap Water Provision | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 2.8% |
| | | | | | | |
| **COMMUNICATIONS** | **5.7** | **10.4** | **15.7** | **42.4** | **110.5** | **9.9%** |
| **TOTAL** | **480.0** | **768.4** | **1,050.2** | **1,806.9** | **2,837.6** | **5.4%** |

### 4.5 Major Determinants of Growing Demand

As the above figures and tables indicate, industrial energy use becomes a less dominant portion of total energy demand, as well as electricity demand, in China. Changes in the way that fuels are provided to and used in the residential sector, including increasing electricity use in residences, will also be an important factor in specifying which fuels will be needed. Services and Communication sector demand for electricity (in particular) and other fuels is the fastest growing part of the Chinese energy economy. The increase in private transportation use, and particularly the vastly increased use of private cars, is largely responsible for an almost four-fold increase in demand for petroleum products between 1995 and 2020.

### 4.6 Implications of Results, and Major Uncertainties in Estimates

Some of the major conclusions that can be drawn from the above results are as follows:

- Growth in fuels demand in China will continue to be robust. Even though coal demand grows more slowly than demand for other fuels, end-use demand for coal and coke is projected to nearly double between 1995 and 2020, which by itself suggests has serious implications for coal production infrastructure and for local, regional, and global environmental problems.
- The rapid increase in the use of refined products may have ramifications for oil and oil products demand and supply throughout Asia, and possibly the world.
- The increase in electricity consumption in most sectors implies that growth in electricity infrastructure will be a major consumer of capital in the coming two decades.
- The increase in electricity consumption, particularly in homes and the service sector, also implies that attention should be focused on improving the efficiency of electricity-using appliances and equipment during the critical period where many households, businesses, and institutions are making first-time purchases of such devices.

The scenario formulation process is, of course, subject to considerable uncertainties. Some of the most uncertain of the assumptions included in the BAU demand scenario include:

- The rate of growth in the use of private autos. The BAU scenario includes robust growth in personal automobile use, but even so the level of per capita private vehicle ownership in China in 2020 will be less than a tenth of the level of vehicle ownership per person that prevails in the United States today. A two-fold lower or higher level of growth in private vehicle use will make a huge difference in petroleum products use (and associated pollutant emissions) in China.
- The extent of growth in energy use in the services and communications sectors is uncertain. While growth is probably likely to be strong over the next decade, after 2010 it is possible that the combination of the effects of a maturing economy and an increasing focus on improvements in energy efficiency will constrain growth in these sectors to a greater degree than is reflected in the BAU results shown here.

- Similarly, industrial energy demand could be somewhat overstated if a higher priority is given to energy efficiency, if the Chinese economy further de-emphasizes heavy industry, or a combination of the two.
- Capital constraints, on the other hand, may make it harder to expand the use of gaseous fuels and district heating. If the penetration of these fuel types is less than has been estimated in the BAU scenario, coal demand would be even higher than shown.

# 5. PRESENTATION OF FUEL SUPPLY RESULTS, INCLUDING ELECTRICITY GENERATION, BY SCENARIO

## 5.1 Introduction: Presentation of Results for BAU and Alternative/Clean Coal Scenarios

The section that follows presents the results of the fuel supply BAU and Alternative/Clean Coal scenarios described in Section 3 of this paper. The overall energy balance and primary energy use resulting from each scenario are presented, with a focus on the electricity supply mix implied by each of the two scenarios. Additional detailed results of the two scenarios can be found in Annex C to this paper.

## 5.2 Energy Supply Results of the BAU Scenario

### 5.2.1 Overall energy balance and primary energy use

Tables 5-1a and b present overall energy balances for the years 1995 and 2020 under the BAU energy supply scenario. In comparing the two tables, the degree to which coal continues to dominate the energy supply picture between 1995 and 2020 is clear. In 2020, however, the proportion of coal used in fuel transformation—principally in electricity generation, heat production, and coking—is an even greater fraction of overall coal supplies than in 1995. Another major qualitative difference between the 1995 and 2020 is that crude oil and oil products imports, which are at a relatively low level in 1995 relative to domestic crude oil production, expand such that imports of oil and oil products are considerably greater than domestic oil production by 2020.

Figure 5-1 shows the changes in primary energy supplies over the period from 1990 to 2020 under the BAU supply scenario. Here the expansion of requirements for crude oil and, in particular, refined oil products imports in the next 20 years is evident. Primary use of biomass fuels decreases in absolute terms, and supplies a decreasing portion of primary fuel needs. Primary requirements for coal approximately double, to over 2 billion tonnes of coal equivalent, between 1995 and 2020.

## *Table 5-1a:*

**ENERGY BALANCE: 1995**
**(MILLION TONNES COAL EQ)**

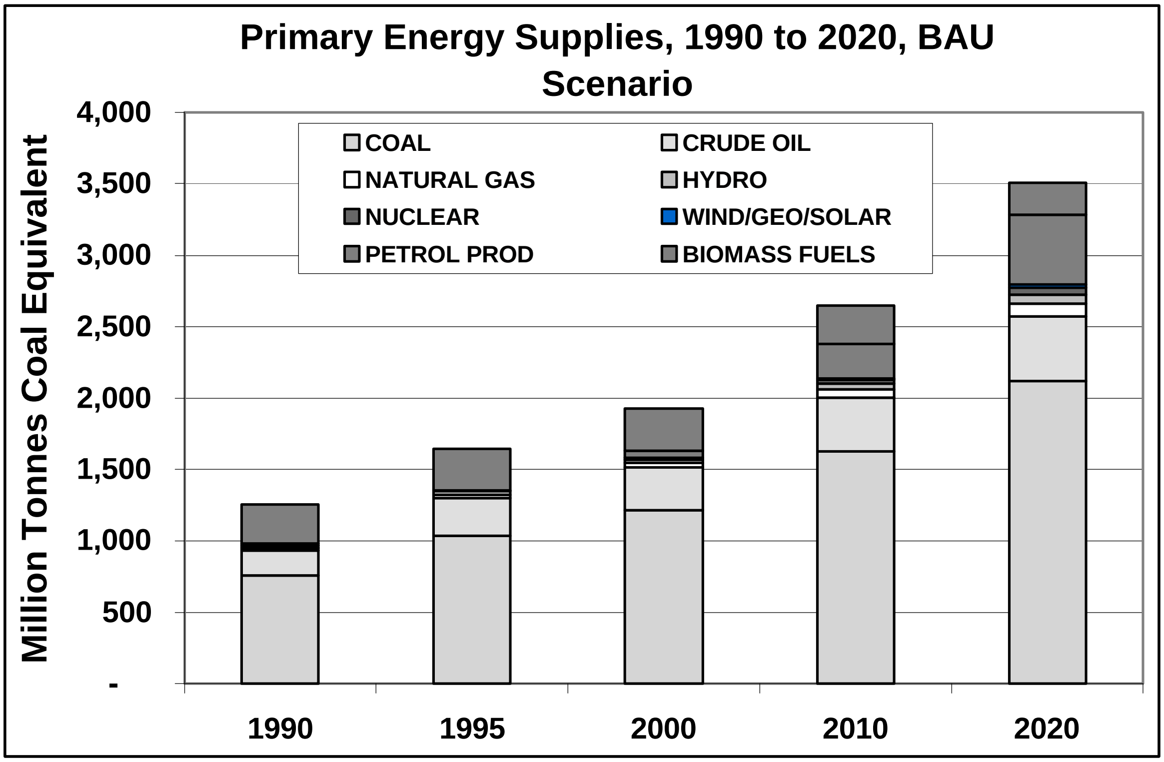
| | COAL | CRUDE OIL | NATURAL GAS | HYDRO | NUCLEAR | WIND/GEO /SOLAR | ELECTRIC | PETROL PROD | COKE | HEAT | OTHER | OTHER GASES | BIOMASS FUELS | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| INDIGENOUS PRODN. | 1039.32 | 216.96 | 24.43 | 23.08 | 4.99 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 287.93 | 1597.72 |
| EXPORTS | -5.86 | -17.15 | 0 | 0 | 0 | 0 | -3.35 | -2.93 | -10.28 | 0 | 0 | 0 | 0 | -39.59 |
| IMPORTS | 1.58 | 64.44 | 0 | 0 | 0 | 0 | 0 | 5.36 | 0 | 2.37 | 0 | 1.52 | 0 | 75.26 |
| PRIMARY SUPPLIES | 1035.03 | 264.25 | 24.43 | 23.08 | 4.99 | 1 | -3.35 | 2.43 | -10.28 | 2.37 | 0 | 1.52 | 287.93 | 1633.39 |
| COAL PRODUCTION | -21.53 | 0 | 0 | 0 | 0 | 0 | -4.84 | 0 | 0 | 0 | 0 | 0 | 0 | -26.37 |
| CRUDE PRODUCTION | 0 | -2.6 | 0 | 0 | 0 | 0 | -3.18 | -4.1 | 0 | 0 | 0 | 0 | 0 | -9.88 |
| COAL WASHING | -14.31 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -14.31 |
| LNG IMPORTS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| GAS PRODUCTION | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BRIQUET PRODUCT. | -0.71 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -0.71 |
| OIL REFINING | 0 | -258.07 | 0 | 0 | 0 | 0 | -1.39 | 248.65 | 0 | -2.37 | 0 | 0 | 0 | -13.18 |
| BIOGAS PRODUCTIO | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5.74 | 0 | -9.57 | -3.83 |
| GASIFICATION | -6.04 | 0 | 0 | 0 | 0 | 0 | 0 | -0.73 | 0.91 | 0 | 0 | 5.07 | 0 | -0.78 |
| COKING | -134.33 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 112.38 | 0 | 0 | 10.98 | 0 | -10.98 |
| HEAT GENERATION | -8.45 | -0.01 | -0.01 | 0 | 0 | 0 | -0.36 | -1.28 | 0 | 8.21 | 0 | -0.15 | 0 | -2.05 |
| ELECTRICITY | -324.07 | -0.65 | -1.08 | -23.08 | -4.99 | -0.19 | 117.99 | -13.82 | 0 | 24.24 | 0 | -1.52 | 0 | -227.17 |
| DISTRIBUTION | -0.69 | -0.04 | -0.37 | 0 | 0 | 0 | -10.58 | -9.45 | 0 | -0.65 | 0 | 0 | 0 | -21.79 |
| FINAL CONSUMPTION | 524.91 | 2.87 | 22.97 | 0 | 0 | 0.81 | 94.29 | 221.69 | 102.99 | 31.8 | 5.74 | 15.89 | 278.37 | 1302.33 |
| RESIDENTIAL | 125.13 | 0 | 2.69 | 0 | 0 | 0.81 | 13.17 | 9.3 | 0 | 2.39 | 5.74 | 4.48 | 278.37 | 442.07 |
| AGRICULT/FISHING | 13.26 | 0.15 | 0.03 | 0 | 0 | 0 | 7.16 | 17.5 | 1.13 | 0 | 0 | 0 | 0 | 39.23 |
| MINING | 0 | 0 | 0 | 0 | 0 | 0 | 2.29 | 0 | 0 | 0 | 0 | 0 | 0 | 2.29 |
| INDUSTRY | 348.18 | 2.19 | 20.01 | 0 | 0 | 0 | 63.11 | 79.97 | 101.34 | 20.63 | 0 | 11.41 | 0 | 646.83 |
| TRANSPORTATION | 8.49 | 0.52 | 0 | 0 | 0 | 0 | 0.88 | 71.59 | 0 | 0 | 0 | 0 | 0 | 81.48 |
| BUILDING | 4.09 | 0 | 0.63 | 0 | 0 | 0 | 1.16 | 9.86 | 0.17 | 0 | 0 | 0 | 0 | 15.91 |
| SERVICES | 21.24 | 0.01 | 0.03 | 0 | 0 | 0 | 5.34 | 24.86 | 0.35 | 8.79 | 0 | 0 | 0 | 60.61 |
| COMMUNICATIONS | 4.53 | 0 | 0.15 | 0 | 0 | 0 | 1.28 | 8.62 | 0 | 0 | 0 | 0 | 0 | 14.58 |
| TOTAL DEMANDS | 524.91 | 2.87 | 23.54 | 0 | 0 | 0.81 | 94.38 | 221.69 | 102.99 | 31.8 | 5.74 | 15.89 | 278.37 | 1303 |

## *Table 5-1b:*

**ENERGY BALANCE FOR BAU SCENARIO: 2020**
**(MILLION TONNES COAL EQ)**

| | COAL | CRUDE OIL | NATURAL GAS | HYDRO | NUCLEAR | WIND/GEO /SOLAR | ELECTRIC | PETROL PROD | COKE | HEAT | OTHER | OTHER GASES | BIOMASS FUELS | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| INDIGENOUS PRODN. | 2120.42 | 317.88 | 75.7 | 59.04 | 48.99 | 26.97 | 0 | 0 | 0 | 0 | 0.01 | 0 | 220.33 | 2869.34 |
| EXPORTS | -0.32 | 0 | 0 | 0 | 0 | 0 | -3.35 | 0 | -13.14 | 0 | 0 | -2.56 | 0 | -19.38 |
| IMPORTS | 0 | 134.68 | 13.46 | 0 | 0 | 0 | 0 | 490.42 | 0 | 4.11 | 0 | 0 | 0 | 642.67 |
| PRIMARY SUPPLIES | 2120.11 | 452.56 | 89.15 | 59.04 | 48.99 | 26.97 | -3.35 | 490.42 | -13.14 | 4.11 | 0.01 | -2.56 | 220.33 | 3492.63 |
| COAL PRODUCTION | -44.16 | 0 | 0 | 0 | 0 | 0 | -9.93 | 0 | 0 | 0 | 0 | 0 | 0 | -54.09 |
| CRUDE PRODUCTION | 0 | -3.48 | 0 | 0 | 0 | 0 | -4.45 | -7.15 | 0 | 0 | 0 | 0 | 0 | -15.08 |
| COAL WASHING | -27.41 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -27.41 |
| LNG IMPORTS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| GAS PRODUCTION | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BRIQUET PRODUCT. | -1.21 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -1.21 |
| OIL REFINING | 0 | -447.85 | 0 | 0 | 0 | 0 | -2.42 | 432.18 | 0 | -4.11 | 0 | 0 | 0 | -22.21 |
| BIOGAS PRODUCTIO | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10.24 | 0 | -17.07 | -6.83 |
| GASIFICATION | -20.82 | 0 | 0 | 0 | 0 | 0 | 0 | -3.43 | 3.04 | 0 | 0 | 17.92 | 0 | -3.29 |
| COKING | -188.66 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 163.52 | 0 | 0 | 18.37 | 0 | -6.77 |
| HEAT GENERATION | -60.24 | 0 | -2.61 | 0 | 0 | 0 | -2.47 | -6.56 | 0 | 56.26 | 0 | -0.37 | 0 | -15.98 |
| ELECTRICITY | -931.07 | -0.58 | -11.22 | -59.04 | -48.99 | -15.58 | 402.95 | -50.84 | 0 | 58.84 | -0.01 | -2.37 | 0 | -657.92 |
| DISTRIBUTION | -1.18 | -0.01 | -1.51 | 0 | 0 | 0 | -31.97 | -35.26 | 0 | -2.3 | 0 | 0 | 0 | -72.23 |
| FINAL CONSUMPTION | 845.36 | 0.61 | 73.82 | 0 | 0 | 11.4 | 348.35 | 819.35 | 153.42 | 112.8 | 10.24 | 30.98 | 203.26 | 2609.59 |
| RESIDENTIAL | 136.68 | 0 | 29.03 | 0 | 0 | 11.4 | 87.63 | 44.19 | 0 | 13.21 | 10.24 | 15.46 | 203.26 | 551.1 |
| AGRICULT/FISHING | 12.58 | 0 | 0.06 | 0 | 0 | 0 | 18.6 | 28 | 2.14 | 0 | 0 | 0 | 0 | 61.38 |
| MINING | 0 | 0 | 0 | 0 | 0 | 0 | 5.64 | 0 | 0 | 0 | 0 | 0 | 0 | 5.64 |
| INDUSTRY | 572.1 | 0 | 43.16 | 0 | 0 | 0 | 164.83 | 182.62 | 149.34 | 52.27 | 0 | 15.52 | 0 | 1179.83 |
| TRANSPORTATION | 1.34 | 0.56 | 0 | 0 | 0 | 0 | 2.45 | 281.93 | 0 | 0 | 0 | 0 | 0 | 286.27 |
| BUILDING | 13.4 | 0 | 0.85 | 0 | 0 | 0 | 5.16 | 38.82 | 0.56 | 0 | 0 | 0 | 0 | 58.8 |
| SERVICES | 96.02 | 0.05 | 0.18 | 0 | 0 | 0 | 50.68 | 190.49 | 1.38 | 47.33 | 0 | 0 | 0 | 386.12 |
| COMMUNICATIONS | 13.25 | 0 | 0.54 | 0 | 0 | 0 | 13.57 | 53.3 | 0 | 0 | 0 | 0 | 0 | 80.66 |
| TOTAL DEMANDS | 845.37 | 0.61 | 73.82 | 0 | 0 | 11.4 | 348.56 | 819.35 | 153.42 | 112.8 | 10.24 | 30.98 | 203.26 | 2609.81 |

*Figure 5-1:*




5.2.2 BAU case electricity supply mix—capacities and fuels used

Table 5-2 presents the evolution of electricity generation capacity in China between 1999 and 2020 for the BAU case. Coal-fired power plants continue to dominate the generation mix, with approximately 12 percent of standard coal plants equipped with flue-gas desulfurization (FGD) equipment by 2020. Advanced coal-fired power plants, including IGCC (integrated gasification/combined-cycle) and supercritical (SCPF) configurations are introduced slowly, totaling 14 GW (about 5 percent of total capacity) by 2020. Hydroelectric power generation is also assumed to grow rapidly, nearly tripling in capacity between 1995 and 2020, while power generation with other renewable resources (solar, wind, and geothermal) begins to grow substantially after 2000. Figure 5-2 shows the evolution of capacity under the BAU scenario in a graphical format.

The share of energy input to electricity generation over time, in the BAU scenario, is shown in Figure 5-3. The combined share of coal and washed coal in fuel for electricity generation declines somewhat over time, but is still well over 80 percent of fuel input by 2020.

***Table 5-2: Electric Generation Capacity (GW)--BAU Case***

| | 1990 | 1995 | 2000 | 2010 | 2020 |
|---|---|---|---|---|---|
| Existing Coal | 88 | 141 | 154 | 154 | 154 |
| New Coal | 0 | 0 | 49 | 156 | 283 |
| New Coal with FGD | 0 | 2 | 7 | 30 | 60 |
| IGCC/SCPF | 0 | 0 | 1 | 7 | 14 |
| Oil-fired | 10 | 14 | 15 | 30 | 45 |
| Gas-fired | 2 | 4 | 4 | 8 | 12 |
| Hydro | 36 | 50 | 55 | 90 | 140 |
| Nuclear | 0 | 2 | 3 | 12 | 23 |
| Wind/Solar/Others | 0 | 1 | 2 | 5 | 11 |
| TOTAL | 136 | 214 | 289 | 490 | 741 |

***Figure 5-2: BAU Estimates of Installed Electric Generation Capacity—China***

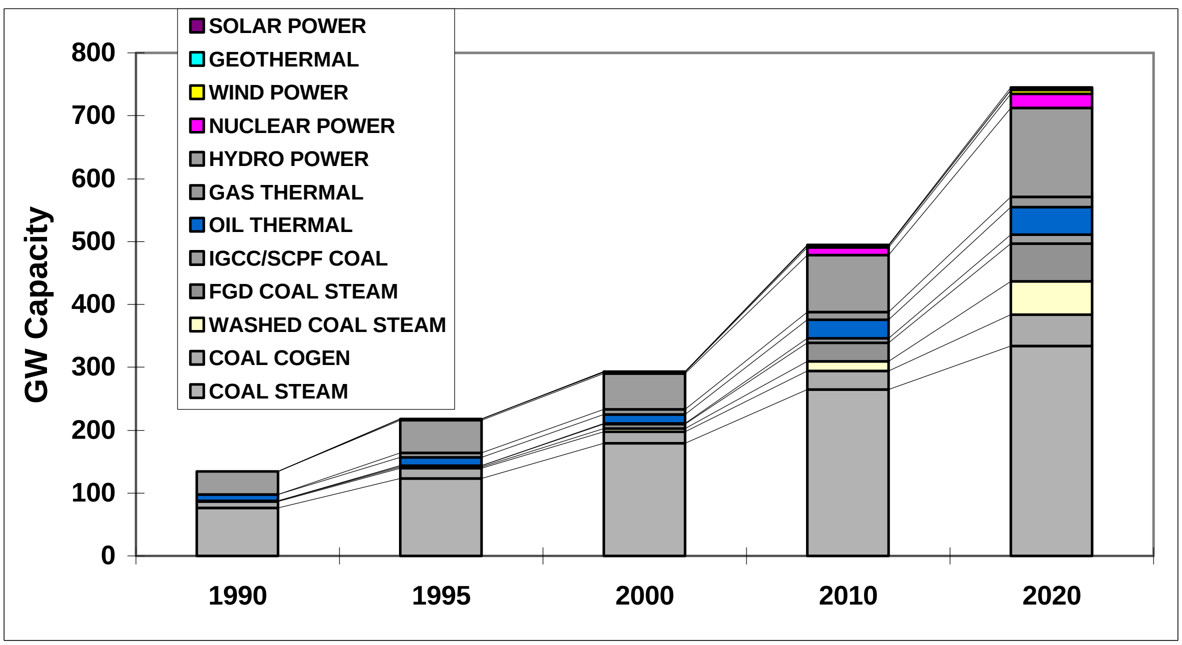
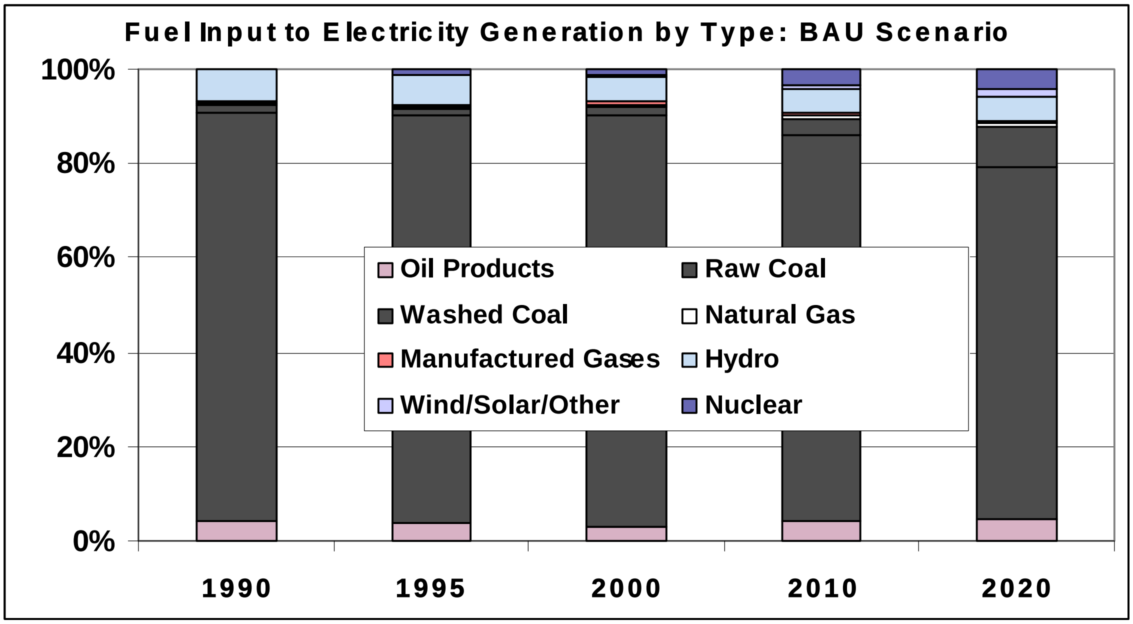


*Figure 5-3:*




5.2.3 Other BAU case fuel supply results

Other BAU case fuel supply results are primarily a direct function of the assumptions listed in Section 3 of this paper. Some of the attributes of the fuel supply system as of 2020 include:

- The fraction of fuel input to district heat generation provided by coal rises from somewhat over 76 percent in 1995 to 83 percent in 2020.
- Coke output grows at a progressively slower pace between 2000 and 2020, and the proportion of washed coal in the fuel input to coking increases over time, reaching 85 percent by 2020 (as opposed to 71 percent in 1995).
- Oil refinery products become progressively "lighter", with more gasoline, kerosene/jet fuel, and diesel fuel produced and imported, and less residual oil produced. The fraction of domestic oil products consumption supplied from domestic refineries declines from almost 98 percent in 1995 to under 47 percent by 2020, despite a 75 percent increase in domestic refining capacity (from 173 to 300 million tonnes per year) from 1995 to 2020.
- Natural gas production capacity and output increases approximately three-fold between 1995 and 2020, with the most rapid absolute expansion in capacity occurring between 2010 and 2015.
- LNG imports (and the terminal capacity to handle them) rise from zero in 2000 to nearly 400 million GJ by 2020.
- The output of washed coal rises from about 126 million tonnes coal equivalent in 1995 to nearly 300 million tonnes coal equivalent by 2020.

- Domestic crude oil production rises by approximately 50 percent between 1995 and 2020, reaching 216 million tonnes oil equivalent (from 147 million tonnes oil equivalent in 1995) by the end of the projection period.
- Annual coal production essentially doubles between 1995 and 2020, from over 1 billion tonnes coal equivalent in 1995 to over 2 billion tonnes coal equivalent by 2020.

Additional details of LEAP results for the BAU and Clean Coal scenarios can be found in Annex C to this paper.

## 5.3 Presentation of energy supply results of Alternative/Clean Coal scenario

The principal difference between the Business-as-Usual scenario and the Alternative/Clean Coal scenario is in the latter’s use of clean coal technologies for electricity generation. The supply-side results of the Alternative/Clean Coal scenario are provided below.

### 5.3.1 Overall energy balance and primary energy use

As shown in Table 5-3, the overall energy balance in the Alternative/Clean Coal scenario for the year 2020 is nearly the same as that in the BAU scenario. A minor increase in coal supplies (from 2.120 billion tonnes in the BAU case to 2.155 billion tonnes in the Alternative/Clean Coal case) caused (almost entirely) by increased consumption of coal in electricity generation is essentially the only difference between the energy balances in the two scenarios. Primary energy supplies over the period modeled are likewise quite similar in the two scenarios. The reason for the similarity in these results between the scenarios is that the Alternative/Clean Coal scenario focuses more on using coal in a manner that produces less sulfur oxides. Thus, though the Alternative/Clean Coal scenario includes electricity generation resources that use coal more efficiently, the efficiency gains from phasing in these plants are offset by the efficiency penalty (and additional coal usage) required by the use of pollution control equipment (flue gas desulfurization) on existing and new standard-type coal-fired power plants.

## *Table 5-3:*

**ENERGY BALANCE FOR ALTERNATIVE/CLEAN COAL SCENARIO: 2020**
**(MILLION TONNES COAL EQ)**

| | COAL | CRUDE OIL | NATURAL GAS | HYDRO | NUCLEAR | WIND/GEO /SOLAR | ELECTRIC | PETROL PROD | COKE | HEAT | OTHER | OTHER GASES | BIOMASS FUELS | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| INDIGENOUS PRODN. | 2155.46 | 317.88 | 75.7 | 56.88 | 47.2 | 26.4 | 0 | 0 | 0 | 0 | 0.01 | 0 | 220.33 | 2899.85 |
| EXPORTS | -0.31 | 0 | 0 | 0 | 0 | 0 | -3.35 | 0 | -13.13 | 0 | 0 | -2.58 | 0 | -19.37 |
| IMPORTS | 0 | 134.65 | 13.14 | 0 | 0 | 0 | 0 | 488.8 | 0 | 4.11 | 0 | 0 | 0 | 640.71 |
| PRIMARY SUPPLIES | 2155.14 | 452.53 | 88.84 | 56.88 | 47.2 | 26.4 | -3.35 | 488.8 | -13.13 | 4.11 | 0.01 | -2.58 | 220.33 | 3521.19 |
| COAL PRODUCTION | -44.16 | 0 | 0 | 0 | 0 | 0 | -9.93 | 0 | 0 | 0 | 0 | 0 | 0 | -54.09 |
| CRUDE PRODUCTION | 0 | -3.48 | 0 | 0 | 0 | 0 | -4.45 | -7.15 | 0 | 0 | 0 | 0 | 0 | -15.08 |
| COAL WASHING | -27.09 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -27.09 |
| LNG IMPORTS | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| GAS PRODUCTION | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| BRIQUET PRODUCT. | -1.21 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | -1.21 |
| OIL REFINING | 0 | -447.85 | 0 | 0 | 0 | 0 | -2.42 | 432.18 | 0 | -4.11 | 0 | 0 | 0 | -22.21 |
| BIOGAS PRODUCTIO | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10.24 | 0 | -17.07 | -6.83 |
| GASIFICATION | -20.76 | 0 | 0 | 0 | 0 | 0 | 0 | -3.42 | 3.03 | 0 | 0 | 17.86 | 0 | -3.28 |
| COKING | -188.65 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 163.51 | 0 | 0 | 18.37 | 0 | -6.77 |
| HEAT GENERATION | -62.54 | 0 | -2.71 | 0 | 0 | 0 | -2.57 | -6.82 | 0 | 58.41 | 0 | -0.39 | 0 | -16.61 |
| ELECTRICITY | -964.19 | -0.57 | -10.81 | -56.88 | -47.18 | -15.01 | 403.16 | -48.98 | 0 | 56.69 | -0.01 | -2.28 | 0 | -686.08 |
| DISTRIBUTION | -1.18 | -0.01 | -1.51 | 0 | 0 | 0 | -32.08 | -35.26 | 0 | -2.3 | 0 | 0 | 0 | -72.33 |
| FINAL CONSUMPTION | 845.37 | 0.61 | 73.82 | 0 | 0 | 11.4 | 348.36 | 819.35 | 153.42 | 112.8 | 10.24 | 30.98 | 203.26 | 2609.6 |
| RESIDENTIAL | 136.68 | 0 | 29.03 | 0 | 0 | 11.4 | 87.63 | 44.19 | 0 | 13.21 | 10.24 | 15.46 | 203.26 | 551.1 |
| AGRICULT/FISHING | 12.58 | 0 | 0.06 | 0 | 0 | 0 | 18.6 | 28 | 2.14 | 0 | 0 | 0 | 0 | 61.38 |
| MINING | 0 | 0 | 0 | 0 | 0 | 0 | 5.64 | 0 | 0 | 0 | 0 | 0 | 0 | 5.64 |
| INDUSTRY | 572.1 | 0 | 43.16 | 0 | 0 | 0 | 164.83 | 182.62 | 149.34 | 52.27 | 0 | 15.52 | 0 | 1179.83 |
| TRANSPORTATION | 1.34 | 0.56 | 0 | 0 | 0 | 0 | 2.45 | 281.93 | 0 | 0 | 0 | 0 | 0 | 286.27 |
| BUILDING | 13.4 | 0 | 0.85 | 0 | 0 | 0 | 5.16 | 38.82 | 0.56 | 0 | 0 | 0 | 0 | 58.8 |
| SERVICES | 96.02 | 0.05 | 0.18 | 0 | 0 | 0 | 50.68 | 190.49 | 1.38 | 47.33 | 0 | 0 | 0 | 386.12 |
| COMMUNICATIONS | 13.25 | 0 | 0.54 | 0 | 0 | 0 | 13.57 | 53.3 | 0 | 0 | 0 | 0 | 0 | 80.66 |
| TOTAL DEMANDS | 845.37 | 0.61 | 73.82 | 0 | 0 | 11.4 | 348.56 | 819.35 | 153.42 | 112.8 | 10.24 | 30.98 | 203.26 | 2609.81 |

### 5.3.2 Electricity supply mix under Alternative/Clean Coal scenario

Table 5-4 presents the evolution of electricity generation capacity under the Alternative/Clean Coal scenario. In contrast to the BAU scenario, plants with pollution control equipment dominate, and penetration of advanced technologies (IGCC and SCPF) is much more extensive. Capacity figures in the "existing coal" and "new coal" categories in Table 5-4 by 2020 include only plants burning washed coal and coal-fired cogeneration facilities. A side-by-side comparison of the types of coal-fired capacity included in the two scenarios is presented in Table 5-5. Annual consumption of coal in electricity generation is about 3 percent higher in the Alternative/Clean Coal scenario than in the BAU case by 2020, but it should be noted that this 3 percent represents a significant mass (30 million tonnes coal equivalent) of fuel, when considered on an absolute basis.

***Table 5-4: Electric Generation Capacity (GW)—Clean Coal Case***

| | 1990 | 1995 | 2000 | 2010 | 2020 |
|---|---|---|---|---|---|
| Existing Coal | 88 | 141 | 154 | 86 | 19 |
| Retrofit FGD | 0 | 0 | 0 | 84 | 184 |
| New Coal | 0 | 0 | 34 | 76 | 83 |
| New Coal with FGD | 0 | 2 | 22 | 76 | 164 |
| IGCC/SCPF | 0 | 0 | 1 | 24 | 60 |
| Oil-fired | 10 | 14 | 15 | 30 | 45 |
| Gas-fired | 2 | 4 | 4 | 8 | 12 |
| Hydro | 36 | 50 | 55 | 90 | 140 |
| Nuclear | 0 | 2 | 3 | 12 | 23 |
| Wind/Solar/Others | 0 | 1 | 2 | 5 | 11 |
| TOTAL | 136 | 214 | 289 | 490 | 741 |

***Table 5-5:***

**COMPARISON OF COAL-FIRED CAPACITY IN 2020: BAU Versus Clean Coal Scenario (GW)**

| **PLANT TYPE** | BAU | Clean Coal |
|---|---|---|
| Existing Standard Coal | 134 | - |
| FGD Retrofit | - | 184 |
| Washed Coal | 2 | 2 |
| New Std Raw Coal | 200 | - |
| New Washed Coal | 50 | 50 |
| Existing Coal Cogen. | 17 | 17 |
| New Coal Cogen. | 33 | 33 |
| New Standard Coal+FGD | 60 | 164 |
| IGCC | 7 | 30 |
| SCPF Coal-fired | 7 | 30 |
| **TOTAL COAL-FIRED** | **511** | **511** |

### 5.4 Implications of results and major uncertainties

Probably the key supply-side scenario result presented above is that, while it is possible, through a concerted program of electricity sector investment, to achieve an electricity generation infrastructure that is substantially "cleaner" in terms of emissions of SO2 and other pollutants (see section 6), these improvements come at a price. The price is paid in terms of additional consumption (and production) of coal, as well as in equipment costs (see below). Additional coal consumption occurs in the Clean Coal scenario (relative to the BAU scenario) even though the use of advanced, high-efficiency technologies (IGCC and SCPF) in the Clean Coal scenario is much more extensive. The major lesson here is that reducing coal use (and the associated greenhouse gas emissions) while accomplishing the important task of reducing emissions of sulfur oxides and other local air pollutants will require more than just the technologies included in the clean coal scenario. Some combination of meaningful energy efficiency improvements, increased fuel switching to gas or oil-based fuels, and increased use of renewable and other energy sources will be required as well.

Preparing an energy model for China is a strenuous and uncertain exercise at best. In addition to the unavoidable uncertainties about what will happen in the future, uncertainties and inaccuracies in even recent historical data from China means that all information must be subjected to careful scrutiny and cross-checking for accuracy. The data set compiled so far—which is based on the work of many different groups—provides an excellent basis upon which to continue, expand, and refine the modeling effort.

Particular areas in which the existing LEAP data set for China could be improved are:

- <u>Data for more recent years</u>: Obtaining and using historical data from the mid- to late-1990s will help to better define trends in both energy supply infrastructure and energy demand.
- <u>Electricity generation</u>: Specifically, incorporating better data on generation capacities by plant type, including expected retirement dates of older capacity, peak load data, and similar information will help to refine the way that electricity generation is modeled.
- <u>Oil refining</u>: Experts with special knowledge in this field may be able to help improve the understanding of what changes can be expected in the refined product slates of existing and new Chinese refineries.
- <u>District heat production and cogeneration</u>: The treatment of heat production in the transformation data set needs to be revisited. Additional data on the status of district heat systems, and of future plans for operation of existing systems and building of new systems, would be helpful.
- <u>Other transformation processes</u>: Operation of other transformation modules needs to be reviewed to ensure proper operation, including reflection of the use of auxiliary fuels and "own use" of module output fuels.

# 6. ENVIRONMENTAL AND COST RESULTS: EMISSIONS AND COST-BENEFIT COMPARISONS BETWEEN SCENARIOS

## 6.1 Introduction

The principal difference between the BAU and Alternative/Clean Coal scenarios, as noted above, is in the environmental performance benefits of the clean coal technologies used in the electricity generation sector, and in the additional costs associated with those technologies. This section presents an overview of the relative environmental benefits and costs of the two scenarios.

## 6.2 Air Pollutant Emissions by Scenario

Key emissions results from the two scenario are presented and compared below. Additional detailed results can be found in Annex C to this paper.

### 6.2.1 Emissions in BAU scenario, by pollutant

Table 6-1 presents an overview of the emissions of three key pollutants—carbon dioxide ($CO_2$), nitrogen oxides ($NO_x$), and sulfur oxides ($SO_x$) over time under the BAU scenario[l]. $CO_2$ emissions grow at an average rate of 3.3 percent annually between 1995 and 2020, and carbon dioxide emissions from the power generation sector constitute an increasing fraction of total emissions (from 27 percent in 1995 to nearly 36 percent by 2020). Emissions of nitrogen oxides grow at an even more rapid pace (over 4 percent annually from 1995 to 2020), as transport sector emissions, in particular, expand. Emissions of sulfur oxides grow at a somewhat lower average rate (about 3 percent annually, on average), as the importance of lower-sulfur fuels such as natural gas and oil products in the Chinese economy increase. The fraction of overall $NO_x$ emissions accounted for by the electricity generation sector remains relatively stable over time, while the fraction of total SOx emissions accounted for by electricity generation increases from 39 to nearly 45 percent by the year 2020.

[l] Note that emissions of all three gas species are expressed on a whole-molecule (for example, tonnes $CO_2$ rather than tonnes carbon) basis. To convert the $CO_2$ emission figures expressed here to millions of tonnes of carbon, multiply by the fraction 12/44. Note that the $CO_2$ emissions reported here include only "non-biogenic" or fossil-fuel-derived carbon.

***Table 6-1: Air Pollutant Emissions (million tonnes): Business as Usual Case***

| | 1990 | 1995 | 2000 | 2010 | 2020 |
|---|---|---|---|---|---|
| Carbon Dioxide | 2,485 | 3,402 | 4,045 | 5,701 | 7,665 |
| --From Demand | 67.5% | 67.0% | 64.3% | 62.1% | 59.5% |
| --From Electricity | 24.3% | 27.2% | 30.0% | 32.5% | 35.9% |
| Nitrogen Oxides | 10.8 | 15.2 | 19.2 | 29.0 | 41.2 |
| --From Demand | 62.8% | 62.5% | 61.2% | 63.0% | 62.9% |
| --From Electricity | 25.5% | 28.2% | 29.0% | 28.8% | 29.5% |
| Sulfur Oxides | 16.4 | 22.6 | 27.3 | 36.8 | 47.7 |
| --From Demand | 57.7% | 52.6% | 47.9% | 44.0% | 41.1% |
| --From Electricity | 34.6% | 39.2% | 41.2% | 42.6% | 44.8% |

### 6.2.2 Emissions in Alternative scenario, by pollutant

Table 6-2 summarizes emissions of $CO_2$, $NO_x$, and $SO_x$ for the Alternative/Clean Coal scenario. Here annual emissions of sulfur oxides increase roughly 50 percent between 1995 and 2020, growing at an average rate of approximately 1.5 percent annually. The contribution of electricity-sector $SO_x$ emissions to total emission, however, is nearly halved between 1995 and 2020, decreasing from over 39 percent to 20.4 percent of total $SO_x$ emissions from energy sector activities.

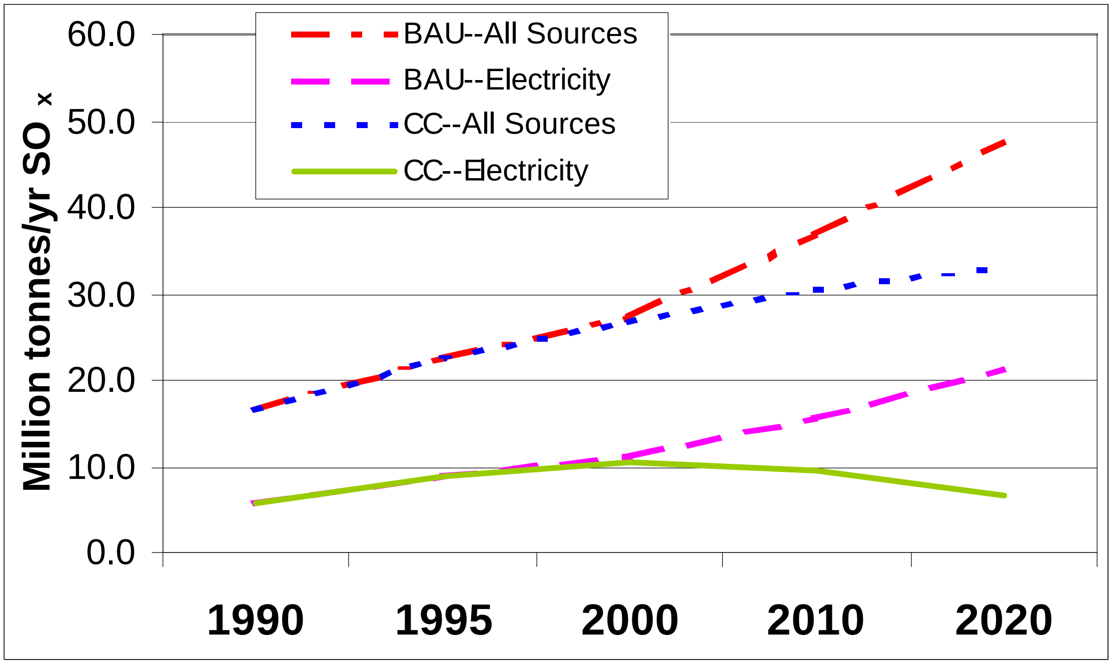
***Table 6-2: Air Pollutant Emissions (million tonnes): Alternative/Clean Coal Case***

| | 1990 | 1995 | 2000 | 2010 | 2020 |
|---|---|---|---|---|---|
| Carbon Dioxide | 2,485 | 3,403 | 4,063 | 5,785 | 7,763 |
| --From Demand | 67.5% | 67.0% | 64.0% | 61.2% | 58.8% |
| --From Electricity | 24.3% | 27.2% | 30.3% | 33.4% | 36.6% |
| Nitrogen Oxides | 10.8 | 15.2 | 19.3 | 29.3 | 41.3 |
| --From Demand | 62.8% | 62.5% | 60.9% | 62.4% | 62.8% |
| --From Electricity | 25.5% | 28.2% | 29.4% | 29.5% | 29.5% |
| Sulfur Oxides | 16.4 | 22.6 | 26.6 | 30.5 | 33.2 |
| --From Demand | 57.7% | 52.6% | 49.1% | 53.0% | 59.1% |
| --From Electricity | 34.6% | 39.1% | 39.7% | 30.7% | 20.4% |

### 6.2.3 Comparison of emission results for key pollutants

Annual carbon dioxide emissions under the Alternative/Clean Coal scenario are slightly (about 100 million tonnes $CO_2$, or 1.3 percent) higher, by 2020, than in the BAU scenario, with the difference in emissions coming because of higher electricity sector emissions. Emissions of $CO_2$ in the electricity sector are higher in the Clean Coal case largely because of the effect of emissions controls on the efficiency of coal-fired power plants. Annual emissions of sulfur oxides in the Clean Coal case begin to diverge significantly from those in the BAU case after 2000. By 2020, annual emissions of $SO_x$ in the Alternative/Clean Coal case are some 14.5 million tonnes less than in the BAU case, a decrease of approximately 30 percent. A proportionately greater decrease in emissions occurs in the electricity generation sector; 2020 emissions of $SO_x$ from electricity generation in the Alternative/Clean Coal case are less than 32 percent of 2020 electricity sector emissions in the BAU case. Absolute emissions of $SO_x$ from electricity generation, in fact, decrease after 2000 in the Alternative/Clean Coal case. The trajectories of $SO_x$ emissions in the economy as a whole and for electricity generation under both scenarios are shown Figure 6-1.

***Figure 6-1: Comparison of $SO_x$ Emissions by Scenario***




### 6.3 Comparison of Costs, BAU and Alternative Scenarios

The Clean Coal scenario emissions reduction described above comes at a cost—namely the cost of cleaner and higher-efficiency coal-fired generation technologies. The cost assumptions used to compare the relative economics of the two scenarios, and the results of the cost comparison, are presented below.

#### 6.3.1 Capital, O&M costs for electricity generation

Key capital and operating and maintenance (O&M) cost estimates for coal-fired electricity generation equipment used in the BAU and Alternative/Clean Coal scenarios are presented in Table 6-3. Costs shown are in 1995 US dollars. Flue gas desulfurization, for example, is assumed to cost $220 per kW of electricity generation capacity to which it is applied on a retrofit basis, and to cost an incremental $150 per kW of new coal-fired capacity to which it is applied. Most types of coal-fired power plants are assumed to increase in cost over the study period (at 0.5 percent per year on a real basis), as a combination of a maturing Chinese economy and more stringent quality, safety, and environmental standards combine to render the plants more expensive.  The exceptions to this pattern of escalation are the IGCC and SCPF units, which are assumed to decrease in cost at 1 percent annually (on a real basis) as the technologies mature and are adopted and adapted for production in China.

***Table 6-3: Cost and Efficiency Assumptions for Coal-fired Generation Options***

| Plant Type | Cap. Cost $/kW | O&M Cost $/kW-yr | Gross Plant Effic. (%) 1995 | 2010 | Ann. Cap. Cost Escal. | $SO_x$ Removal |
|---|---|---|---|---|---|---|
| FGD Retrofit of existing | $220 | $5 | 33.0% | 34.0% | 0.0% | 85% |
| New Std Raw Coal | $630 | $25 | 36.0% | 38.5% | 0.5% | N/A |
| New Washed Coal | $800 | $25 | 37.0% | 39.0% | 0.5% | N/A |
| New Coal Cogeneration | $800 | $25 | 25.0% | 25.0% | 0.5% | N/A |
| New Std Coal + FGD | $780 | $30 | 35.5% | 38.0% | 0.5% | 85% |
| IGCC/SCPF | $1,350 | $29 | 41.0% | 45.0% | -1.0% | 99.99% |

### 6.3.2 Other capital and O&M costs

Although costs other than electricity generation costs do not figure prominently into the comparison of the two scenarios (as they are presently configured), selected other costs for supply infrastructure are provided below for reference and for review by readers.  Additional data on (and references for) cost assumptions are included in Annex A to this paper.

- Electricity distribution is assumed to cost $10.40 per GWh of energy distributed.  These costs are assumed to escalate at 2 percent annually above inflation.
- Heat generation (district heating plants) are assumed to cost between $6750 and $7000 per tonne of coal equivalent (tce) per year of heat production capacity, with annual fixed O&M costs ranging from $93 to $145 per tce/year of output.  Capital costs are assumed to escalate at 3 percent annually, and fixed O&M costs are assumed to escalate at 2 percent per year.
- Coke production is assumed to cost $250 per tonne/yr of capacity, with annual fixed O&M costs of $25 per tonne/yr, and costs escalating at 2 percent annually above inflation.
- Oil refining capital costs are estimated at 233 dollars per tonne of annual capacity, with fixed O&M costs of $28 per tonne of annual capacity.  Both costs are assumed to escalate at 1 percent annually.
- Production of “industrial” and “honeycomb” coal briquettes are assumed to cost $28 and $36.50 per tonne, respectively, with costs escalating at 2 percent per year.
- Capital and fixed O&M costs for natural gas production are assumed to be $0.77 and $0.027 per cubic meter per year, respectively, with capital costs (only) escalating at1 percent annually.
- Capital costs for LNG import terminals are assumed to be $83 per thousand cubic meters of annual production capacity, with fixed O&M costs of $12.50 per thousand cubic meters of annual capacity.  No escalation of capital costs are assumed (international costs for LNG terminals seem to have been decreasing in recent years).

- Coal washing is assumed to cost $10.47 per tonne/yr of capacity, with a variable production cost of $3 per tonne of washed coal produced. Coal washing costs are assumed to escalate at 2 percent annually on a real cost basis.
- Crude oil production capital costs are assumed to be $300 per tonne/yr of capacity, escalating at 1 percent annually.
- Coal production is broken into three types of mines—rural collectives, local state-owned mines, and ministry-owned mines—each with different costs, as shown in Table 6-4. An annual escalation rate of 2 percent was assumed for these costs.

***Table 6-4: Coal Production Cost Estimates***

| | Capital Cost per Te/yr | Fixed O&M per te/yr |
|---|---|---|
| | 1995 $ | 1995 $ |
| Coal Production | | |
| --Rural Collective | $ 30.01 | $ 5.82 |
| --Local State-Owned | $ 46.53 | $ 8.14 |
| --Ministry-Owned | $ 69.80 | $ 14.93 |

### 6.3.3 Fuel Costs

The assumed costs for the main imported fuels and domestic resources used in China are provided in Table 6-5. Table 6-5. Some of these cost estimates are based on a combination of information from a study published by Pacific Northwest National Laboratory's Advanced International Studies Unit[15], others (for example, LNG costs) are based on costs in nearby countries, and others are rough estimates. With the exception of nuclear fuels and domestic coal, the assumed average annual escalation rate for fuel prices is based on the 2000 to 2020 escalation of oil prices from the 1998 reference forecast contained in the US Department of Energy's Energy Information Administration Annual Energy Outlook document[16]. Additional detail on the derivation of these costs can be found in Annex A.

***Table 6-5: Imported Fuel and Resource Cost Estimates Used***

| Fuel | Units | Cost in 1995 | Annual Escalation |
|---|---|---|---|
| Nuclear | $95/GJ | $ 0.73 | 1% |
| Imported LNG | $95/GJ | $ 3.50 | 0.80% |
| Imported Oil | $95/bbl | $ 17.00 | 0.80% |
| Imported Gasoline | $95/te | $ 158.00 | 0.80% |
| Imported Diesel | $95/te | $ 148.00 | 0.80% |
| Domestic Gas (resource) | $95/GJ | $ 1.00 | 0.80% |
| Domestic Oil | $95/bbl | $ 8.00 | 0.80% |
| Domestic Coal | $95/te | $ 20.00 | 1% |

### 6.3.4 Overall cost comparison between scenarios

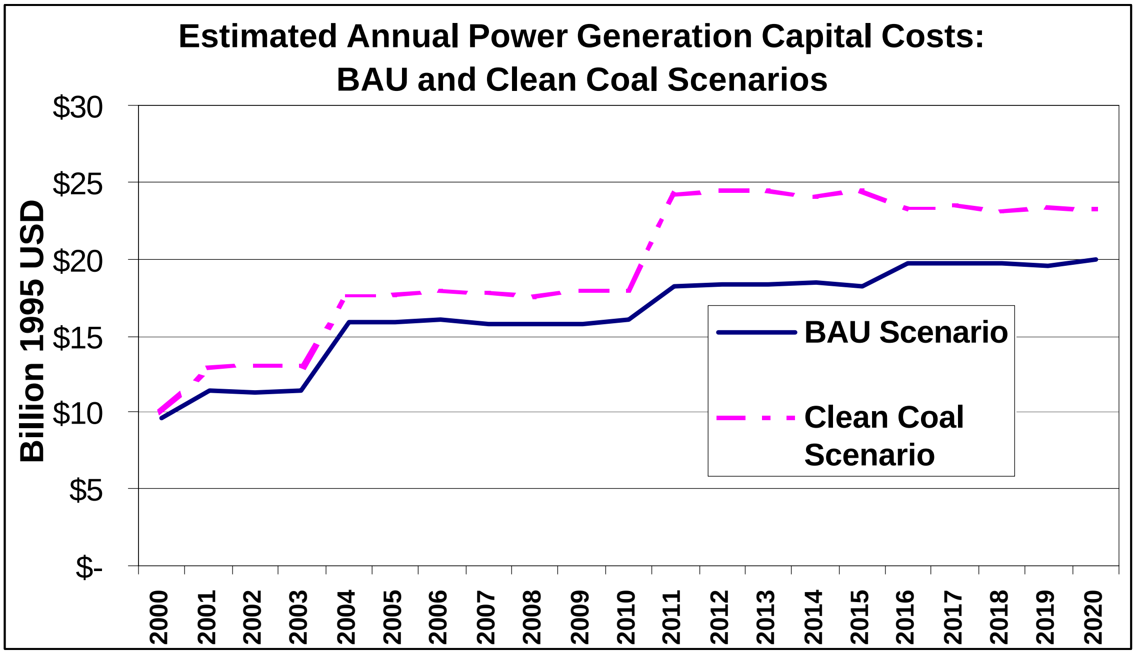
The Alternative/Clean Coal scenario trades higher costs for electricity generation equipment, and slightly higher costs for fuel resources (coal), against significantly reduced emissions of sulfur oxides and particulate matter. More detailed results of the comparison of the costs and benefits of the BAU and Alternative/Clean Coal scenarios can be found in Annex C to this paper. Some of the key results are as follows.

- The net present value difference (calculated using a real discount rate of 10 percent) between scenarios totals approximately $11 billion in 1995 US dollars. This total includes payments (including interest and principal) on incremental capital costs of more expensive clean-coal capacity, the differential costs of O&M, other net fuel supply costs, and net resource costs associated (mostly) with additional coal use. Of the approximately $11 billion total difference, about $2.5 billion is associated with net resource costs.
- The cost per saved tonne of $SO_x$, calculated as the net cost difference (in real, undiscounted dollars) between the scenarios divided by the difference in $SO_x$ emissions) is in the range from $500 to $700 between 2001 and 2020, varying year by year.
- The estimated additional capital costs, in real 1995 dollars, for electricity generation equipment under the Clean Coal scenario vary from about $1.5 to about $6 billion per year between 2000 and 2020[m].
- The total estimated difference in investment costs for electricity generation equipment between the two scenarios during 2000 to 2020 (when the major differences between the scenarios occur) is $66 Billion in real, undiscounted 1995 dollars. Discounted back to 2000 at a real discount rate of 10 percent, this is equivalent to about $21 billion in NPV terms. For the purpose of comparison, the estimated capital cost of all additions to electricity generation capacity between 2000 and 2020 is approximately $345 billion in undiscounted 1995 dollars, or $128 billion in NPV terms. Figure 6-2 shows the estimated annual capital costs for new electricity generation facilities under the two scenarios for the years 2000 through 2020.
- The total savings in $SO_x$ emissions from implementation of the Alternative/Clean Coal scenario over the period 2000 to 2020 is 146 million tonnes. This implies a discounted capital cost (for electricity generation equipment only) per tonne sulfur emissions avoided of just over $200 for the period from 2000 to 2020. It should be remembered, however, that the investments in "clean coal" equipment made during 2000 to 2020 will nominally continue to result in $SO_x$ emissions savings until 2030 to 2050, and possibly longer. If emissions savings taking place after 2020 were taken into account, the discounted cost of emissions reduction would be considerably lower. Interestingly, the average price of sulfur dioxide emissions

[m] Capital costs in this instance are calculated as "instantaneous" costs, that is, they are calculated as if the entire capital cost of a plant was paid in the year that the plant goes on line. The incremental annual capital cost of the Clean Coal scenario that are described here for the year 2000, for example, are thus estimated as the full capital cost of electricity generation equipment added during 2000 under the Clean Coal scenario, less the capital cost of power plants added in 2000 under the BAU scenario.

allowances in the United States has been in the range of $200 per tonne during mid-1998 through mid-1999[17].

***Figure 6-2:***




## 7. INITIAL CONCLUSIONS AND "NEXT STEPS" IN ANALYTICAL WORK

The scenario work presented in this report should be viewed as only the beginning of what should be a much more exhaustive evaluation of energy technology and energy policy alternatives for China. Some of the initial conclusions suggested by the work done to date, and a listing of some of the "next steps" that might be undertaken in the future, are provided below.

### 7.1 Significance of Clean Coal Scenario Among Other Alternatives: Conclusions

The Alternative/Clean Coal scenario presented here is just one of an infinite number of ways to deploy technologies designed to decrease air pollutant emissions. No attempt has been made to make the Alternative/Clean Coal scenario "optimal" with respect to costs, performance, greenhouse gas emissions, or other parameters. The scenario as specified has been designed primarily A) to be plausible, and B) to show the impact of a significant effort to decrease electricity sector emissions of sulfur oxides.

One of the key, if not unexpected, results of the scenario work to date has been that the additional investment required to implement clean coal technologies to significantly reduce future sulfur oxide emissions from the electricity sector in China will be on the order of billions of dollars ($1.5 to 6 billion for the scenarios presented in this paper) per year. This is an added investment of approximately 15 to 20 percent over the next 20 years. While the environmental and economic benefits of reducing $SO_x$ emissions are likely to be substantial, several billion dollars annually is still a substantial additional investment for the Chinese economy. Finding funding sources for this type of investment in a better environment will require creative and innovative financial mechanisms, perhaps involving multilateral as well as private lenders and/or donors[n].

In the particular variant of a clean coal scenario examined in this paper, reductions in sulfur oxide (and particulate matter) emissions come at the expense of an increase (though slight) in greenhouse gas emissions, as well as a small increase in emissions of nitrogen oxides. Also, though the application of a set of specific clean coal technologies to the electricity generation sector (in the Alternative/Clean Coal scenario) accomplishes a significant reduction in sulfur oxide emissions from electricity generation, overall $SO_x$ emissions under the scenario still approximately double between 1990 and 2020. Given the environmental problems that sulfur oxide emissions at current rates are causing in China today, it is safe to say that holding $SO_x$ emissions to a doubling will be insufficient to prevent severe problems in the future. What this means is that while it is necessary to address electricity supply sources of emissions, it is not sufficient. Demand-side sources of emissions must be addressed as well. These sources must be addressed, and are being addressed in parts of China today, through a combination of fuel-switching, pollution control, and energy efficiency measures. The evaluation (and, ultimately, application in China) of different combinations of demand and supply-side measures that can help to actually reduce emissions of sulfur oxides, as well as greenhouse gases and other pollutants, is thus an important goal.

### 7.2 Next Steps in Analytical Work

The authors see the next steps in the analytical work reported on here as including the following activities:

- **Review model results and inputs for accuracy/reasonableness and to cross-check with other sources of energy, environmental data**. A "bottom-up" (demand-based) study of future energy use in any country, let alone one as large and complex as China, requires a detailed compilation of energy sector data and more than a few assumptions. The authors intend to work with experts in China and elsewhere to examine the reasonableness of both the historical data and forward-looking assumptions used in the model. It is our hope that this collaboration will result in a more robust description of the Chinese energy system that can be used as a strong basis for future collaborative work.
- **Refine and obtain more information on clean coal and standard coal technologies**. The review of information on clean-coal technologies done for this paper has not been exhaustive, and new technologies are constantly under development. A more rigorous and expanded analysis of scenarios for China would include a deeper and more comprehensive review of

[n] For a discussion of a proposal of one such financial mechanism, see for example Razavi, H. (1997), Innovative Approaches to Financing Environmentally Sustainable Energy Development in Northeast Asia; and Razavi, H. (1998), Financing Clean Coal Technologies in China. Reports prepared for the Energy Security and Environment in Northeast Asia (ESENA) Project, Nautilus Institute.

cost, performance, and commercial availability information on clean coal technologies for electricity generation, district heating, and end-user applications.

- **Obtain additional information on energy-efficiency options, renewable fuels, natural gas**. As noted above, clean-coal technologies cannot by themselves be relied upon to solve energy-related environmental problems in China. An important "next step" in evaluating different energy/environmental futures for China is to develop information on a broader host of measures that can be used to address environmental problems, including information on energy efficiency options (as well as the "baseline" technologies that higher-efficiency options would supplant), applications for renewable fuels and energy systems on both the demand and supply sides, and switching to lower polluting fossil fuels, notably natural gas. The more that the information collected can be China-specific (that is, based specifically on costs and performance of technologies in China), the more plausible will be scenarios based on the information.

- **Prepare renewables/gas supply scenario, and/or mixed renewables/gas/clean coal scenario**. Given the findings of the clean coal scenario work presented above, it is clear that wider use of renewable fuels and expanded gas supplies will be needed in order to significantly address environmental problems in China. Including these options in the type of scenario work done here will allow the estimation of the costs and benefits of, as well as impediments to, different energy supply options for China. It is our intention that this and other scenario work be done in close collaboration between Nautilus Institute and selected colleagues in China.

- **Prepare and evaluate demand-side emissions reduction scenario**. An additional essential step in assessing different energy futures for China is to develop one or more scenarios that include aggressive application of energy efficiency technologies on both the demand and supply sides of the energy balance. "Alternative" scenarios that provide a mixture of energy efficiency, fuel-switching, renewable energy systems, and clean coal technologies may well turn out to provide the most attractive options for sustainable development in China.

- **Prepare full report on China scenarios**. Once the types of data described above have been assembled, and the scenarios of various types—both demand and supply-side—have been elaborated, run, and evaluated, the next step will be to prepare a report on the scenario work undertaken, and to disseminate the report. The report would be disseminated first to reviewers from academic, government and NGO circles both inside and outside of China, and modified based on the reviews obtained. The report thus modified will be distributed to those—again both within and outside of China—responsible for making or influencing energy development policies. Throughout the data assembly, scenario elaboration, and report preparation and review process, we would hope to continue actively exchanging views with other groups doing similar work.

- **Extend analysis to other countries in Northeast Asia, and to region as a whole**. The overall goal of the East Asia Energy Futures work is to promulgate the types of analysis presented in this report not only in China, but in the other nations of Northeast Asia as well. Some of the initial steps that Nautilus has taken toward such dissemination of methods have been noted in the introductory section of this report. Nautilus plans to work to establish collaborative work on energy futures, using the same general scenario methodology described in this report, with groups from the other countries of the region. The ultimate goal of this initiative is to establish a region-wide scenario working group—including members from each country in Northeast Asia—that can consider not only national-level solutions to energy/environment problems, but also solutions that involve regional cooperation on energy and environmental issues in Northeast Asia.

## 8. ENDNOTES

[1] D. F. Von Hippel, P. Hayes, and N. Kraft (1997), East Asia Energy Futures: Towards Least-Cost Energy Investment in Northeast Asia. Progress Report, March, 1997. Nautilus Institute report.
[2] T. Suzuki, D. F. Von Hippel, K. Wilkening, and J. Nickum (1998), Pacific Asian Regional Energy Security: Frameworks for Analysis and Japan Case Study. Synthesis Report for Pacific Asian Regional Energy Security (PARES) Project, Phase I..
[3] D.F. Von Hippel and P. Hayes (1998), "Two Scenarios of Nuclear Power and Nuclear Waste Production in Northeast Asia". Pacific and Asian Journal of Energy, Volume 8, No. 1, 1998, pp. 23 - 50.
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