Low-Carbon Development and Co-benefit in Shanghai:

Clean Fuel Substitution and Low-Carbon Development

（An Energy Foundation Project）

Shanghai Academy of Environmental Sciences
School of Public Health, Fudan University
Shanghai Energy Research Association
Shanghai Statistics Bureau

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Supporting foundation:	Energy Foundation
Project duration:	January 1 - December 31, 2003
Grant number:	G-0212-06632

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Chapter 1. Preface

1. Background

Shanghai's population density, energy consumption, and emissions production all rank among the highest of any city in China. Per capita energy consumption was 122 GJ in 2000, 4.1 times the national level. To improve ambient air quality, the government has implemented emissions control measures and worked to reduce coal use by final sectors since the 1980s. Such measures have met some success: current SO_2 and TSP concentrations in Shanghai's urban areas are 47% and 44% lower than their 1990 levels, respectively, and the average annual concentrations of index pollutants have satisfied China's Grade II National Standards.

However, local air pollution (LAP), pollutant concentrations, and CO_2 emission per unit GDP in Shanghai are all higher than in developed countries. As economic growth continues and more people buy private vehicles, energy demand in Shanghai continues to increase. If current energy environmental policies remain the same, pollution levels in Shanghai will continue to grow unabated.

At the *Summit on Sustainable Development* in Johannesburg, South Africa on September 4, 2003, China officially ratified the Kyoto Protocol. In so doing, China committed to reducing current carbon dioxide and other greenhouse gas emissions, and steering toward a more sustainable development path. Since countries and regions are so different from one another and the appropriate modes of sustainable development are likewise different, promoting global reduction of greenhouse gas emissions is perhaps best realized through local action; the Kyoto Protocol is a global commitment for such local action. Furthermore, as host of the 2010 World Expo, Shanghai has an even greater interest in emission reduction, environmental improvement, and sustainable development.

Now is the time to build a framework for the medium and long-term economic and social development of Shanghai that reduces LAP emissions, improves ambient air quality, and lowers CO_2 emissions, all while ensuring Shanghai's continued economic competitiveness.

2. Research Goals

Using scenario analysis, we analyzed the effects several medium- and long-term air quality management and low-carbon development measures—including energy switch, energy economy, and renewable energy utilization—would have on LAP and CO_2 emission levels. In specific, we assessed the impact of such policies on (1) LAP and CO_2 emission levels, (2) air pollutant exposure levels, and (3) public health.

All measures we considered adhere to the guidelines of the societal, economic, energy, and environmental goals set forth in Shanghai's Tenth Five-Year Plan for National Economic and Social Development and Atmospheric Environment Protection.

3. Research Methods

We adopted a Long-range Energy Alternatives Planning (LEAP) model and set up response relationships among (1) economic development, (2) energy demand, (3) air pollutant and CO_2 emissions, (4) public exposure to air pollution, (5) health outcomes, and (6) health benefits using geographical information systems (GIS) technology.

4. Background Investigations

Before starting our own analysis, we investigated the following:

(1) Economic development levels and energy demand in Shanghai;

(2) Clean energy switch and low-carbon emission policy analyses;

(3) Air quality impact estimates of clean energy switch;

(4) Health benefit estimates of clean energy switch;

(5) Suggestions for medium- and long-term low-carbon development strategies in Shanghai.

5. Project Duration

This project was started on January 1, 2003 and completed on December 31, 2003.

6. Scenario Design

The scenarios examined in this study include a business as usual (BAU) scenario; low-carbon scenarios, including energy efficiency advances (EE), clean energy switch (COAL+GAS), and wind generation (ELEC+WIND); and eight end-treatment scenarios, including air-pollution end control, sulfur-content control in fuels, etc.

7. Major Research Results

Our major results can be summarized as follows:

1. Shanghai's economy is growing rapidly, and energy consumption increases each year. Per capita energy consumption was 122 GJ in 2000, four times of the national level.

2. Coal is the primary dominant energy source, accounting for 66% of total energy produced.

3. In 2000, total SO_2 emission was 0.47 Mt; soot, 0.18 Mt; and CO_2, 136 Mt.

4. Due to air pollution control measures, coal-burning pollution has been reduced and SO_2 and coarse particle concentrations have recently been decreasing each year. Even with this progress, Shanghai's air quality is still worse than the air quality in European cities.

5. Shanghai's GDP will increase to 1,070 billion RMB by 2010, nearly 1.4 times its GDP in 2000. Per capita GDP will reach $10,000 by 2010.

6. In the business as usual scenario, total energy demand in Shanghai will reach 4150 PJ by 2010, 0.6 times more than in 2000.

7. In the business as usual scenario, by 2010 SO_2 emissions will reach 0.75 Mt, 1.6 times more than in 2000; PM_{10} emissions will reach 0.25 Mt, 1.7 times more than in 2000; and CO_2 emissions will reach 226 Mt, 1.7 times more than in 2000.

8. If certain low-carbon measures—clean energy switch, energy efficiency advances, and wind generation—are enacted, by 2010 Shanghai's total energy demand will be 6 percent lower than in the BAU scenario; total SO_2 emissions will be 0.5 Mt, 33 percent lower than BAU; PM_{10} emissions will be 0.154 Mt, 38 percent lower than BAU; and CO_2 emissions will be 199 Mt, 12 percent lower than BAU. SO_2 and PM_{10} emissions will still be 9 and 7 percent higher than in 2000, respectively. However, if end treatment control and fuel sulfur-content control measures are also enacted, SO_2 and PM_{10} emissions will decrease at an even greater rate, falling under 0.4 Mt and 0.1 Mt, respectively, by 2020.

9. If both low-carbon development and end-treatment measures are implemented, average SO_2 concentration in Shanghai will decrease from 0.044 mg/m^3 in 2000 to 0.035 mg/m^3 in 2010. Average PM_{10} concentration will decrease from 0.108 mg/m^3 to 0.097 mg/m^3.

10. If both low-carbon development and end-pipe treatment policies are enacted, the population-weighted average concentration of PM_{10} will decrease from 30.36 μg/m^3 in 2000 to 21.36 μg/m^3 in 2010 and 16.13 μg/m^3 in 2020. In the BAU scenario, however, population-weighted average concentration of PM_{10} will increase to 55.38μg/m^3 in 2010 and 88.98 μg/m^3 in 2020.

11. Implementation of the low-carbon development and end-pipe treatment policy scenarios considered would prevent 2,804-11,580 deaths in 2010 and 9,870-27,340 deaths in 2020. They would prevent even more diseases and injuries.

12. Preventing so many deaths and so much disease would also save a huge

amount of money. In 2010, 507.31-2097.30 million U.S. dollars (0.39-1.61 percent of Shanghai's projected GDP) and in 2020, 2642.45-7310.66 million U.S. dollars (1.03-2.84 percent of Shanghai's projected GDP) would be saved through the health benefits of low-carbon development and end-pipe treatment policies alone.

13. Our scenario analysis indicates that it is possible for Shanghai to steadily lower emissions while continuing to grow economically. To realize a low-carbon future, Shanghai should focus on medium- and long-term policies that do the following: (1) stimulate energy saving, (2) establish reasonable low-carbon energy prices, (3) speed up low carbon energy substitution, (4) actively develop new and renewable energy sources, and (5) introduce advanced energy technology by utilizing Clean Development Mechanisms (CDM).

8. Report Contents

This report consists of 12 chapters. Chapter 1 is a preface describing our research targets, tasks, and major results. Chapters 2, 3 and 4 introduce Shanghai's current social and economic status, energy supply, energy consumption patterns, and air pollutant emissions levels. Chapter 5 discusses projections of Shanghai's future economic development and energy demand. Chapter 6 discusses air pollutant and CO_2 emissions levels in BAU scenario. Chapters 7 and 8 analyze the effects of various low-carbon scenarios on energy demand, pollutant emissions levels, and overall air quality. Chapter 9 is a meta-analysis of exposure-response functions between air particulate matter and health; chapters 10 and 11 then evaluate the public health impact of various low-carbon and end-treatment measure scenarios. Finally, chapter 12 introduces our policy recommendations for Shanghai's low-carbon development.

Chapter 2. Shanghai's Economic Status

1. City Character and Population

Shanghai is the largest industrial, commercial, and trading center, as well as one of the most active economic areas, in China. Shanghai is composed of 16 districts and 3 counties, and has an administration area of 6340 km^2. In 2000, Shanghai's registered population was 13.21 million, 7 percent higher than in 1980. Its overall population density was 2,084 persons per square kilometer; the city center's population density was over 20,000 persons per square kilometer.

Table 2-1 Shanghai land area and population, 2000

	Unit	Central District	Other districts	County	Total
Land Area	km^2	289.44	3,176	2,416.26	6,340.5
Households	10,000	225.20	162	71.56	475.73
Population	10,000 people	628.24	443	184.81	1,321.63
Average Household Size	person	2.8	2.7	2.6	2.8
Population Density	person/km^2	21,705	1,395	765	2,084

2. Macroeconomic Development

Since the 1990s, Shanghai's economic development has been steady and rapid. Every year since 1992, the annual growth rate of Shanghai's GDP has exceeded 10 percent (see Table 2-2).

GDP in 2000 was 455.1 billion RMB; per capita GDP, more than $4,000. While high for China, Shanghai's per capita GDP was only 1/5 London's and Singapore's, and only 1/7 Paris's.

Over the last 20 years, Shanghai's economy has shifted from heavy reliance on industry to receiving roughly equal contributions from secondary and tertiary industries. In 2000, primary industry accounted for 2 percent of Shanghai's GDP; secondary industry, 47 percent; and tertiary industry, 51 percent.

Table 2-2 GDP growth rate of the three industrial sectors in Shanghai, 1980-2000

Years	Primary Industry	Secondary Industry	Tertiary Industry
1980-1990	2.7 %	6.6 %	10.1 %
1990-1995	1.4 %	13.9 %	12.5 %
1995-2000	3.4 %	9.7 %	15.1 %

Table 2-3 Composition of Shanghai's GDP, 1980-2000

Year	Primary Industry	Secondary Industry	Tertiary Industry
1980	3 %	76 %	21 %

1985	4 %	70 %	26 %
1990	4 %	64 %	32 %
1995	3 %	57 %	40 %
2000	1.8 %	47.5 %	50.6 %

3. Living Conditions

Per capita income is steadily increasing. The average annual income of residents in urban areas increased from 2,198 RMB in 1990 to 11,802 RMB in 2000; the average annual income of rural residents increased from 1,990 RMB in 1990 to 6,400 RMB in 2000. Expenditures on food, education, and housing account for 44, 14, and 10-20 percent of total household expenditures, respectively.

Over 50 household appliances—fans, TV sets, refrigerators, washing machines, air-conditioners, microwave ovens, hot water heaters, etc.—are used per every hundred families in Shanghai. This number significantly increases if personal computers are included.

4. Summary

Shanghai is developing extremely rapidly. Per capita GDP is higher than any other Chinese city, but still lags behind cities in developed countries.

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Chapter 3. Energy Supply and Consumption

1. Recent Energy Consumption Levels in Shanghai

Energy consumption is greater and increasing faster in Shanghai than in any other Chinese city. In 2000, total energy consumption in Shanghai was 54.83 Mtce (1607 PJ); per capita energy consumption was 4.15 tce (122 GJ), three times the national level.

From 1980 to 1990, the growth rate of energy consumption in Shanghai was 3.7 percent and energy elasticity was 0.51. From 1990 to 2000, the growth rate of energy consumption was 5.46 percent and energy elasticity was 0.45.

In 2000, energy consumption per 10,000 RMB GDP reached 35 GJ, which was 71% the amount in 1995, 54% the amount in 1990, and 70% the 2000 national average.

2. Energy Import and Export

In 2000, Shanghai imported 101.08 Mtce (2962 PJ) of energy and exported 46.23 Mtce (1355 PJ). Of the energy imported into Shanghai, 57 percent was primary energy; 43 percent was other forms of energy. Sixty-six percent of imported primary energy was coal; 34 percent was crude oil; and less than one percent was natural gas.

3. Energy Transformation

3.1. Power Generation

In 2000, Shanghai had a total of 19 power plants, with combined capacity of 9.36 GW. Coal combustion accounted for 87 percent (8.16 GW) of this total capacity; oil burning, 11 percent (0.925 GW); and blast furnace gas power generation, the final 2 percent (0.15 GW).

From 1995 to 2000, Shanghai's power generation grew 5-6 percent per year. Over the same time period, energy consumption per unit of power generation declined each year, falling to 332 gce per kWh in 2000 (*Annual Energy Report in Shanghai*). In 2000, power plants supplied 55.8 billion kWh, and had an energy efficiency of about 38 percent.

3.2. Heat Generation

In 2000, heat supply capacity in Shanghai was 1.9 GW, and heat supply was 45.1 PJ. The energy consumption of heat generation was about 38-40 kgce/GJ.

3.3. Coking and Gas Making

(1) *Coke Generation*. From 1995 to 2000, the consumption of coking coal in coke

generation increased each year. During that time, the proportion of output to input was kept between 0.94 and 0.97. In 2000, energy consumed by coke generation in Shanghai was 300 PJ, and the amount of coke produced was 283 PJ.

(2) *Coal Gas Generation*. In 2000, the generation of coal gas in Shanghai consumed 38 PJ of energy, 6.8PJ in the form of hard coal, 9.6 PJ in the form of coke oven gas, 6.1PJ in the form of fuel oil, 1.4 PJ in the form of heating power, and 38 PJ in the form of secondary energy. Although the energy efficiency of gas processing varies, it is always higher than 80 percent.

3.4. Petroleum Product Processing and Production

In Shanghai in 2000, 552 PJ of energy was consumed in the processing of crude oil to produce 545 PJ worth of petroleum products. Of these petroleum products, 21 percent was gasoline; 31 percent, diesel fuel; 4 percent, kerosene; 11 percent was fuel oil; 13 percent, liquefied petroleum gas (LPG) and dry gas; and 20 percent, other petrol products.

4. Structure of Final Energy Consumption

Final energy consumption grows every year in Shanghai. Total final energy consumption has recently been increasing on average 40 PJ (1.4 Mtce) annually, approaching 1230 PJ (42 Mtce) in 2000.

From 1995 to 2000, the industrial sector's final energy consumption remained fairly constant, staying basically around 790-820 PJ. During that period, primary industry's final energy consumption remained level at 2 percent of Shanghai's total final energy consumption; secondary industry's decreased from 79 to 67 percent; tertiary industry's increased from 12 to 23 percent; and residential consumption remained relatively stable at 8 percent (see Figure 3-1).

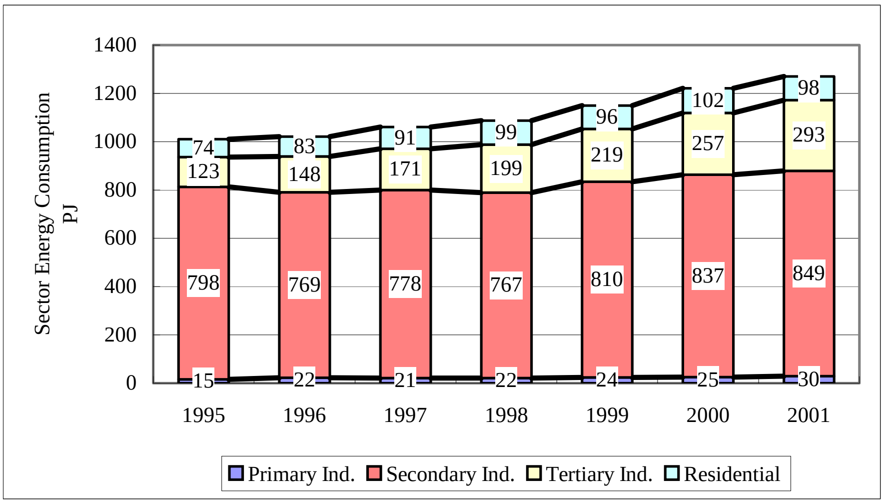

Figure 3-1 Final energy consumption in Shanghai by sector, 1995-2001

As Figure 3-2 shows, the amount of the final direct coal burning fluctuated only slightly, staying around 205 PJ during 1995-2000. The consumption of fuel oil increased greatly, to 171 PJ by 2000, due largely to an increase in tertiary industry's use of fuel oil. In 2000, power consumption was 190 PJ (52.9 billion kWh), a 40 percent increase from 1995.

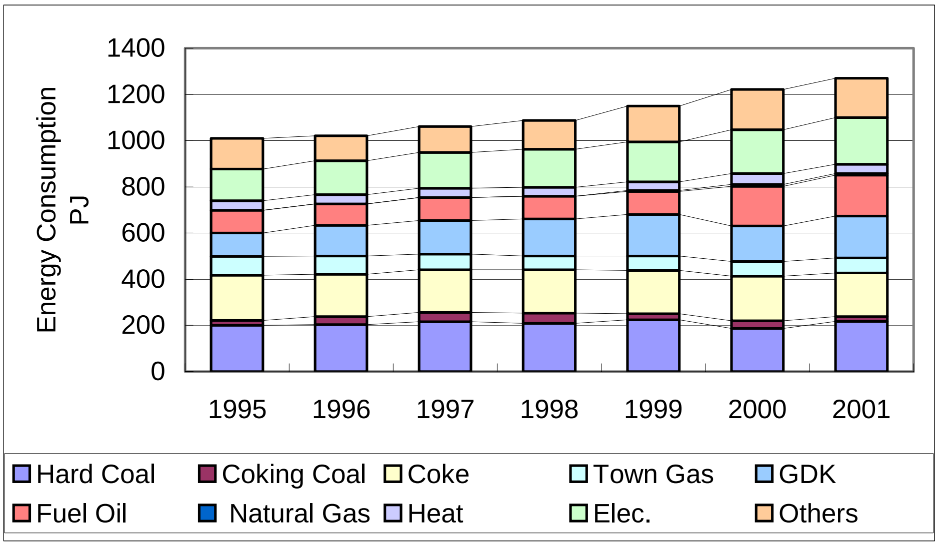

Figure 3-2 Energy consumption in Shanghai by energy carrier, 1995-2001

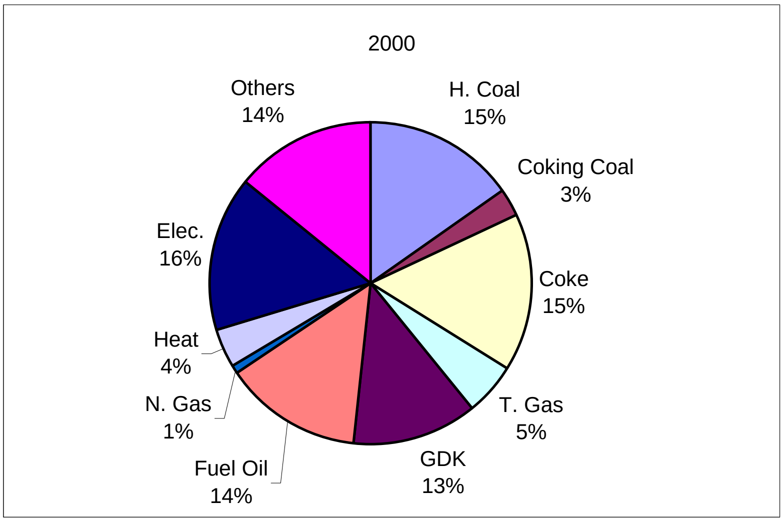

Figure 3-3 Energy consumption in Shanghai by energy carrier, 2000

5. Main Energy-Consuming Industries

As mentioned earlier, from 1995 to 2000 Shanghai's industrial sector's final energy consumption stayed relatively stable, staying basically around 790-820 PJ. Nonetheless, the industrial sector's energy use is still a main part of energy consumption in Shanghai. In 2000, 75 percent of energy consumed by industry was in the form of coal and coal products; 25 percent, oil products; and only 0.2-0.4 percent, natural gas (see Figure 3-4).

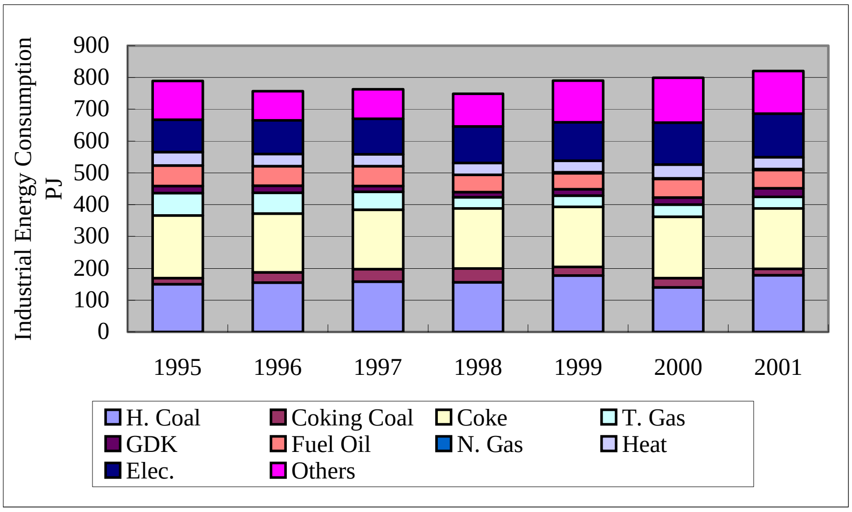

Figure 3-4 Shanghai industrial energy consumption by energy carrier, 1995-2001

The nine highest energy-consuming industrial sub-sectors—including smelting and pressing of ferrous metals, and chemical fibre manufacturing—accounted for almost 85 percent of the entire industrial sector's total energy consumption. In specific, in 2000 the smelting and pressing of ferrous metals accounted for 44 percent of the industrial sector's total energy consumption; chemical fibre manufacturing, 17 percent; raw chemical materials and chemical products, 9 percent; petroleum processing and coking products, 6 percent; and other industries, less than 5 percent.

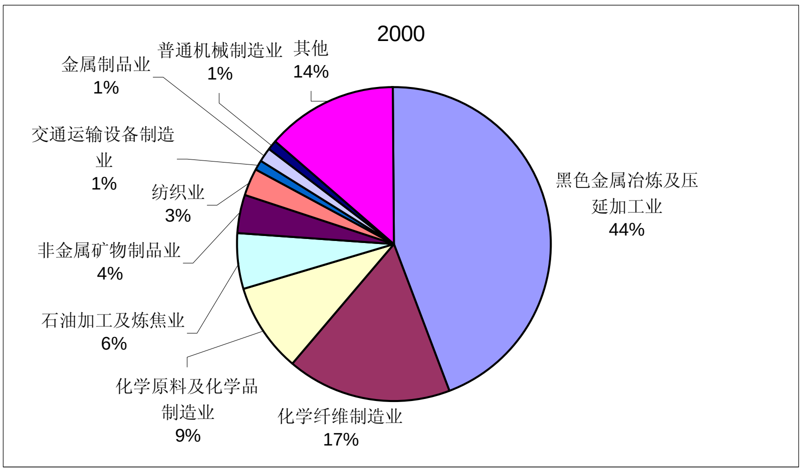

Figure 3-5 Share of energy consumption by Shanghai sub-industries, 2000

6. Summary

The energy flow chart shown below summarizes the preceding research. Shanghai imported a total of 2963 PJ in 2000, with 1105 PJ coming from coal, 535 PJ from crude oil, and 1293 PJ from other sources; Shanghai exported a total of 1356 PJ in 2000. Shanghai's energy supply approached 1612 PJ, 35 percent of which was coal; 34 percent, crude oil; and 1 percent, other energies.

The flow chart also depicts how energy is consumed in Shanghai. The energy processing and transformation sector consumes 22 percent of the total; primary industry, less than 2 percent; secondary industry, 52 percent; tertiary industry, 16 percent; and the residential sector, 6 percent. Although the proportion of energy consumed by industry has declined every year since 1990, it is still the single largest energy-consuming sector in Shanghai.

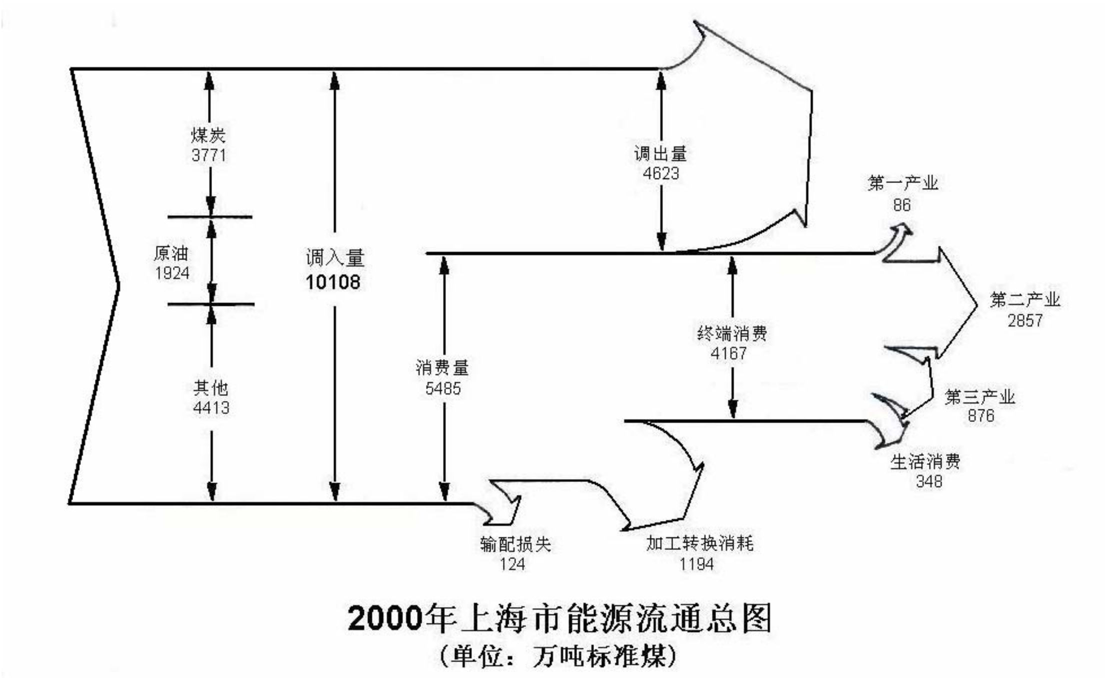

Figure 3-6 Shanghai energy flow chart, 2000

Chapter 4. Energy Consumption and Air Quality

1. Energy Consumption by Various Combustion Processes

In 2000, 2,720 PJ of energy was consumed in various energy conversion processes in Shanghai. Secondary energy conversion consumed 1,461 PJ; fire generation, 520 PJ; heating systems, 50 PJ; coking and gasification processes, 339 PJ; and oil refining, nearly 552 PJ. After these processes, the total amount of final energy available for consumption was 1,221 PJ.

2. Pollutants Emitted through Various Combustion Processes

In order to estimate total air pollutant and CO_2 emissions, we collected the pollutant emission factors for power plants, industrial boilers, the commercial sector, residential energy equipment, and steel manufacture. These emission factors appear in Tables 4-1 to 4-5.

3. Emissions by Shanghai's Energy-Using Sectors

3.1. SO_2 Emissions

Calculated using pollutant emission factors, Shanghai's total SO_2 emissions in 2000 were 470,000 metric tons. Of this, 220,000 metric tons were emitted by power plans; 28,000 metric tons by heating systems; 140,000 metric tons by industry; about 50,000 metric tons by tertiary industry; and nearly 20,000 metric tons by residences.

Secondary energy conversion created the majority of SO_2 emissions (54 percent). Power plants alone created 47 percent of SO_2 emitted in Shanghai, and heating systems created the additional 6 percent. SO_2 emissions in final energy consumption accounted for 46 percent of total emissions: industry created 30 percent of total emissions; tertiary industry, 12 percent; the residential sector, 3 percent; and agriculture and construction, 1 percent.

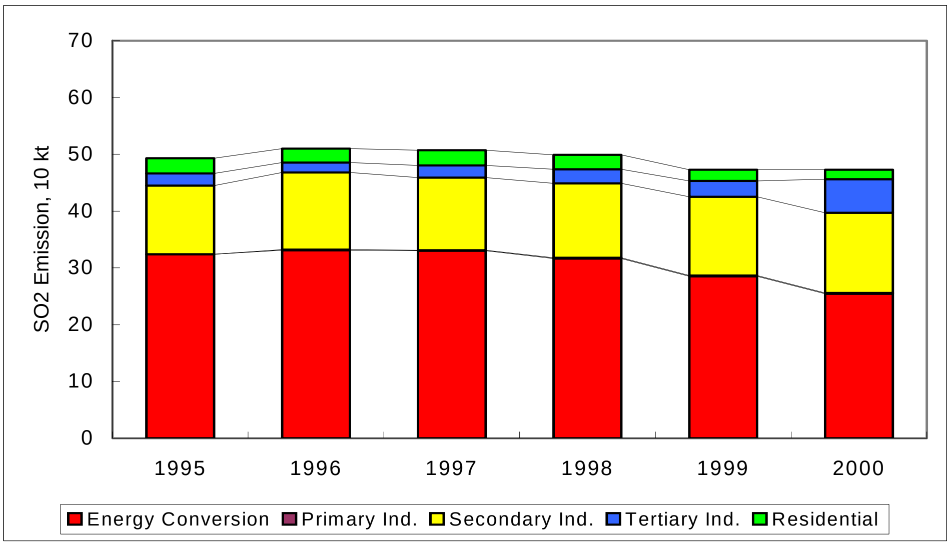

Figure 4-1 Shanghai SO_2 emissions, 1995-2000

3.2. NO_x Emissions

A total of 430,000 metric tons of NO_x was emitted in Shanghai in 2000. Of this, 200 kt of NO_x were emitted by power plants; 18 kt by heating systems; 2.9 kt by coking and gas-making; nearly 100 kt by secondary industries; nearly 6 kt by tertiary industries; another nearly 6 kt by the residential sector; and 100 kt by transportation.

Secondary energy conversion created the majority of NO_x emissions (51 percent). Power plants alone created 47 percent of NO_x emitted in Shanghai, and heating systems created the additional 4 percent. NO_x emissions in final energy consumption accounted for 49 percent of total emissions: industry created 24 percent; tertiary industry, 0.2 percent; the residential sector, 1.5 percent; agriculture and construction, 0.1 percent; and urban transport, 23 percent.

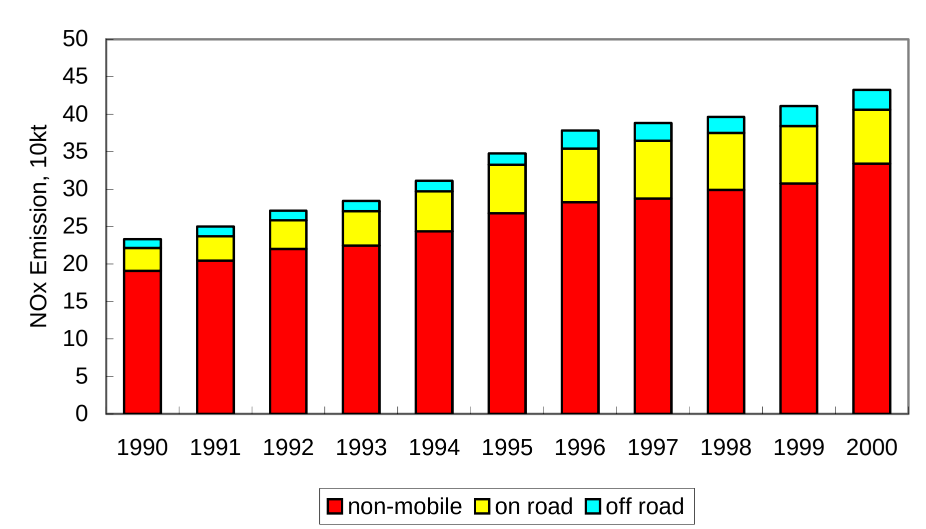

Figure 4-2 Shanghai mobile and non-mobile NO_x emissions, 1990-2000

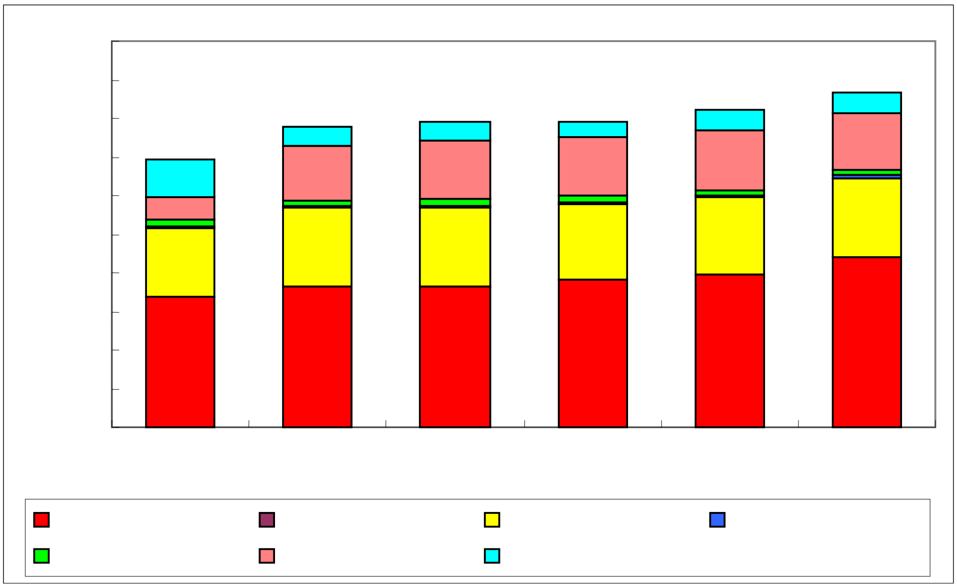

Figure 4-3 Shanghai NO_x emissions, 1995-2000

3.3. Soot and Dust Emission

Using the ash content in coal and dust removal efficiency, soot emission can be calculated as follows:

$$G = B \times A \times d_{fh} (1 - \eta),$$

G = soot emission; B = coal burning amount; A = ash content in coal (%);

d_{fh} = soot in smoke ash (%); η = dust removal efficiency (%)

Dust removal efficiency (η) is 99 percent for power plants and 95 percent for industry boilers.

The coal used in Shanghai is imported from the coal mines in Shanxi, Inner Mongolia, Shandong, and Anhui provinces. The properties of the coal from each of these mines are shown below.

Table 4-1 Properties of coal imported into Shanghai

Province	Coal mine	Total sulphur content (%)	Ash content (%)	Combustible volatile content (%)	Thermal value (kcal/kg)
Shanxi	Datong Mineral Administration Bureau	1.5	4-16	31	6000-6500
	Yangquan Mineral Administration Bureau	1.0	24-36	10	5000-5700
	Xishan Mineral Administration Bureau	1.0-2.5	16-32	14-17	6300-6800
	Fenxi Mineral Administration Bureau	0.5-4.0	14-30	25-32	5500-6600
	Xuangang Mineral Administration Bureau	0.9-1.5	18-43	34	4200-6400
	Lu'an Mineral Administration Bureau	0.4-0.5	16-18	18	7100
	Jincheng Mineral Administration Bureau	0.4		8	7000
	Huoxian Mineral Administration Bureau	0.5	18-22	32	6800
Inner Mongolia	Wuda Mineral Administration Bureau	1.0-4.0	14-36	30-34	5000-6000
	Bohaiwan Mineral Administration Bureau	0.6-2.6	20-32	25-30	4800-6300
	Baotou Mineral Administration Bureau	0.5-1.0	20-28	17-37	5100-5800
Anhui	Huainan Mineral Administration Bureau	1.0	18-28	36	5500-6300
	Huaibei Mineral Administration Bureau	0.5	16-32	10-34	4700-5800
Shandong	Zibo Mineral Administration Bureau	1.2-4.0	18-43	15-20	4000-6000
	Zaozhuang Mineral Administration Bureau	1.0-5.0	12-49	32-36	3000-6100

	Feicheng Mineral Administration Bureau	0.6-4.0	20-49	38-46	4100-5800
	Xinwen Mineral Administration Bureau	3.0-4.0	20-28	40-43	5000-5500
	Laiwu Mineral Administration Bureau	3.0-4.1	22-26	38	5700
	Yanzhou Mineral Administration Bureau	1.0-3.0	14-18	39-46	5600
	Fangzi Coal Mine	1.2-1.5	32-19	10-16	3800-4600

The percent of soot in smoke ash (d_{fh}) for various boilers is shown in Table 4-2.

Table 4-2 d_{fh} values for various boilers

Boiler type	d_{fh}, %
hand-fired boiler	15-20
chain boiler	15-20
cyclone boiler	20-40
fluosolid furnace	40-60
pulverized coal boiler	70-80
reciprocating boiler	15-20
blast cupola	25-35

Figure 4-4 shows soot emission levels in Shanghai in recent years. Recent soot emission control measures have met some success: soot emissions decreased almost every year between 1995 and 2001. In 2001, energy conversion created 37 percent of soot emitted in Shanghai; primary industry, 10 percent; secondary industry, 23 percent; tertiary industry, 1 percent; and the residential sector, 29 percent. Agricultural and residential soot emissions were disproportionately high due to the lack of pollutant control measures in these sectors.

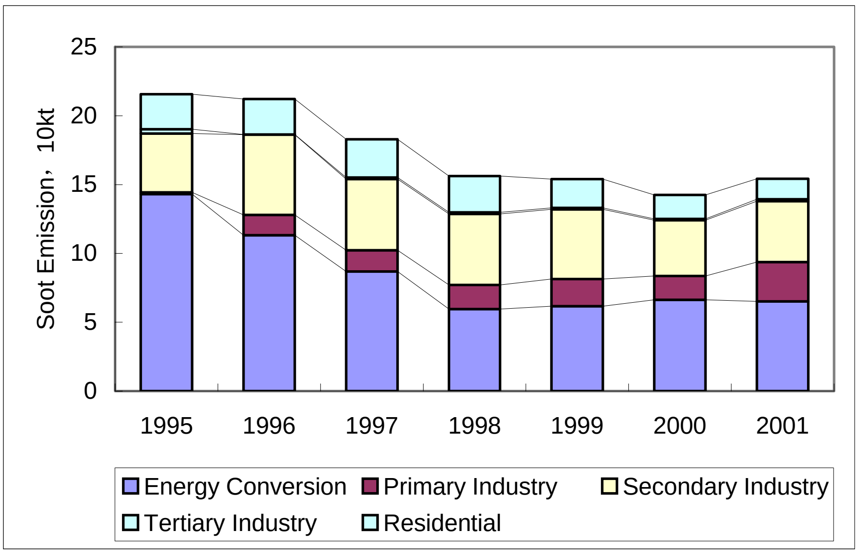

Figure 4-4 Soot emissions in Shanghai, 1995-2001

3.4. CO_2 Emissions

(1) Calculation Method

We calculated various energy sectors' CO_2 emission levels in Shanghai using the following formula:

$$CO_2 \text{ emission in sector}_{\boldsymbol{i}} = \sum (\text{Energy } \boldsymbol{j} \text{ consumption in sector}_{\boldsymbol{i}} \times CO_2 \text{ emission factor of energy}_{\boldsymbol{j}})$$

CO_2 emission factors are shown in Table 4-3.

Table 4-3 CO_2 emission factors by energy carrier

Energy Carrier	CO_2 emission factor (Mt/PJ)
Coal	0.094
Coking Coal	0.094
Coke	0.11
Coal Gas	0.12
Other Gas	0.12
Crude Oil	0.073-0.075
Gasoline	0.056
Kerosene	0.073
Diesel	0.073
Fuel Oil	0.073
LGP	0.073

(2) CO_2 Emissions

Because of increased natural gas imports from gas fields in the East China Sea and the reduction of coal consumption, CO_2 emissions in Shanghai increased rather moderately, from 118 Mt to 138 Mt, between 1995 and 2000. The average annual growth rate of CO_2 emissions, 3.2 percent, was lower than the 4.1 percent growth rate of energy consumption.

Energy conversion created 37 percent of Shanghai's total CO_2 emissions; primary industry, 1 percent; secondary industry, 45 percent; tertiary industry, 11 percent; and the residential sector, 6 percent. Thus, industrial final consumption is the single largest producer of CO_2, and energy conversion and industrial final consumption together account for a massive proportion of total CO_2 emissions, 81 percent.

4. Air Quality

4.1. SO_2 Pollution

Over the last several years, because of measures taken to control pollutant content in fuels and limit coal-burning pollution, annual average SO_2 concentration in Shanghai has decreased every year. In 2000, average annual SO_2 concentration in Shanghai's urban area was 45μg/m^3, a 15 percent reduction from 1995 and low enough to satisfy the Grade II National Standard for Ambient Air Quality.

4.2. NO_x Pollution

Despite years of energy and environmental policies seeking to lower coal-burning pollution, there has been little impact on NO_x levels. Between 1986 and 1995, the annual average NO_x concentration in Shanghai urban areas stayed between 60 and 80μg/m^3; from 1995 to 1997, NO_x concentration passed the 80μg/m^3 mark, reaching a peak of 105μg/m^3 in 1997. Then, in 1997, the use of unleaded gasoline and stricter vehicle emission standards led to reduced NO_x concentrations. By 2000, the annual average concentration of NO_x in the Shanghai urban area had decreased to 84 μg/m^3.

Table 4-4 Annual average NO_x levels in Shanghai, 1986-2000 (1986=100)

Year	Entire City Area	Urban Area
1986	100	100
1990	93	95
1995	119	112
2000	130	138

4.3. PM Pollution

PM pollution in Shanghai has been decreasing in recent years after the implementation of several coal-burning pollution standards, including dust removal, non-black smoke areas, and smoke control areas, as well as residential gas promotion measures. Total suspended particulates (TSP) concentration has also decreased significantly: from 1990 to 2000, average TSP concentration decreased 44 percent in Shanghai as a whole and 56 percent in the Shanghai urban area. Average TSP concentrations in Shanghai have reached the Grade II National Standard for Ambient Air Quality.

Table 4-5 Annual average TSP levels in Shanghai, 1990-2000 (1990=100)

Year	City Area	Urban Area
1990	100	100
1995	83	69
2000	55	44

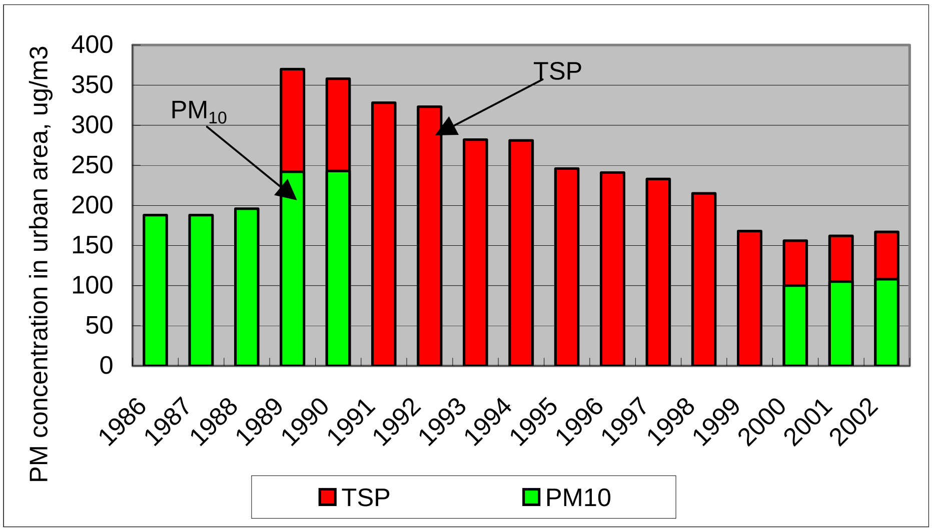

Figure 4-5 PM-10 and TSP concentrations in the Shanghai urban area, 1986-2002

5. Summary

From the preceding analysis, we can conclude the following:

(1) Fuel sulfur content has been strictly controlled in recent years in Shanghai. As a result, despite rapid growth in energy consumption, SO_2 emissions have remained relatively stable. In 2000, total SO_2 emission in Shanghai was about 0.47 Mt. Of this total, power plants produced 47 percent; other secondary energy transformation, 6 percent; industry, 30 percent; tertiary industry, 10 percent; the residential sector, 4 percent; and others, 3 percent.

(2) Unlike SO_2 levels, NO_x levels continue to increase unabated. In 2000, total NO_x emissions neared 0.45 Mt. Of this, power plants produced 46 percent; other secondary energy transformation, 5 percent; industry, 23 percent; transportation, 23 percent; and residential and tertiary industry combined, 3 percent.

(3) CO_2 emission in Shanghai was to 136 Mt in 2000. Power plants produced 37 percent of this total; industry, 45 percent; the residential sector, 5 percent; and others, 13 percent.

(4) Due to several successful measures, coal-burning pollution in Shanghai is under control and decreases each year. Concentrations of SO_2 and TSP, however, are still higher than in European cities.

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Chapter 5. Future Energy Demand Forecast

1. Urban Population Development Scale

Shanghai's 2000 census counted 16.41 million people living in Shanghai, of which 81 percent, 13.22 million, were registered citizens. If the city's plans and *China's Agenda 21: Shanghai Action Plan* are realized, Shanghai's should have 13.5 million registered and 16.0 million permanent residents by 2005, including 1-1.5 million permanent residents from other cities.

2. Macroeconomic Development and Industrial Structure

2.1. GDP Growth Scenario Design

Shanghai's economy is growing rapidly: GDP annual growth rate has been above 10% since 1992. Shanghai's economy will most likely continue to develop at a stable, fast rate into the future.

Taking 2000 as the starting point, this study designed high, medium, and low GDP growth rate scenarios, and predicted the GDP growth of Shanghai over the subsequent 30 years.

Table 5-1 Shanghai GDP growth design, 2000-2030

Year	High Growth	Medium Growth	Low Growth
2000	10.0 %	10.0 %	10.0 %
2005	12.0 %	9.0 %	8.0 %
2010	12.0 %	8.0 %	6.4 %
2015	10.0 %	7.0 %	5.1 %
2020	7.5 %	6.5 %	4.0 %
2025	6.3 %	6.2 %	3.2 %
2030	6.0 %	6.0 %	2.5 %

2.2. Industrial Structure Adjustment

In the future, Shanghai will keep the development order of "tertiary, secondary, primary" industry to shift its industrial structure. This means that Shanghai wishes to (1) accelerate tertiary industry growth, (2) increase the proportion of advanced-technology businesses in secondary industry, (3) modernize "brace industries," (4) strengthen clean, energy-efficient industry, and (5) improve urban agriculture. Shanghai wants to see significant growth in both secondary and tertiary industry.

Table 5-2 Shanghai economic structure, 1995-2030

Industries	1995	2000	2010	2030
Primary Industry	2.4 %	1.8 %	1.9 %	2.0 %

Secondary Industry	57.5 %	47.5 %	43.5 %	40.0 %
Tertiary Industry	40.1 %	50.6 %	54.6 %	58.0 %

2.3. GDP Growth Forecast

Our three GDP growth rate scenarios indicate that Shanghai's GDP will reach 2,179-6,384 billion RMB (2000 prices) by 2030.

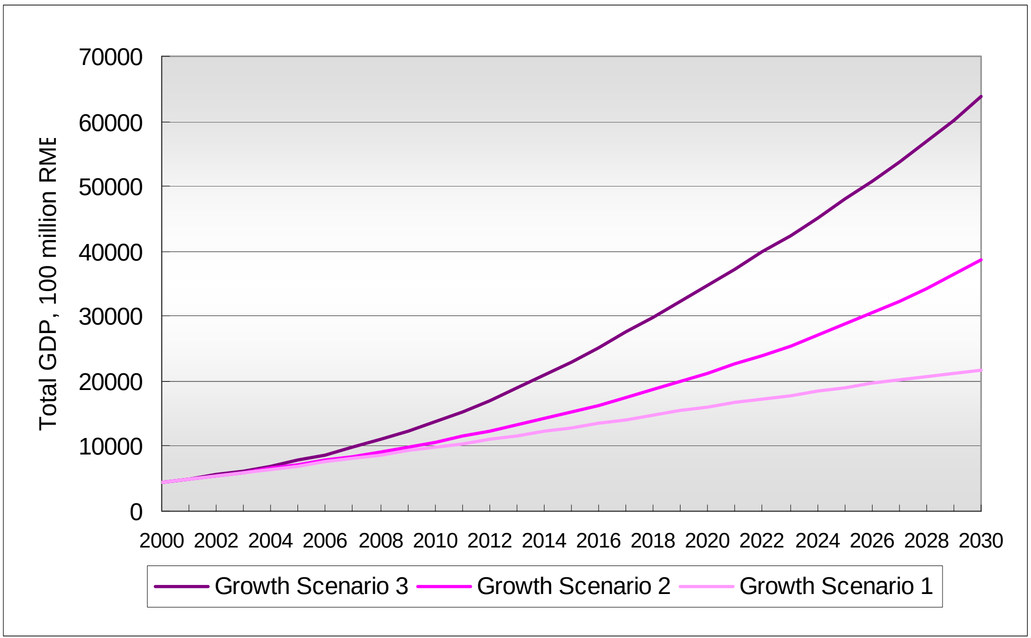

Figure 5-1 Shanghai GDP growth scenarios

Using projected GDP growth rates and industrial structure composition, we can predict the GDP growth of every industrial sector. Shanghai's primary industry GDP will increase from 8.3 billion RMB in 2000 to 44-128 billion RMB in 2030; secondary industry GDP will increase from 216.4 billion to 872-2,554 billion RMB; tertiary industry GDP will increase from 230.4 billion to 1,264-3,703 billion RMB.

3. Agricultural Energy Demand

We also forecasted agricultural energy demand using energy elasticity figures. Projections are shown in Table 5-3 below.

Table 5-3 Agricultural energy demand, 2000-2030

Year	Agricultural GDP (100 million RMB in 2000 prices)			Agricultural Energy Demand (PJ)		
	High Growth	Medium Growth	Low Growth	High Growth	Medium Growth	Low Growth
2000	83	83	83	25	25	25
2005	145	134	130	44	40	40
2010	262	203	187	79	62	57
2015	443	294	249	134	89	75

2020	677	413	313	205	125	95
2025	948	568	376	287	172	114
2030	1277	772	436	387	234	132

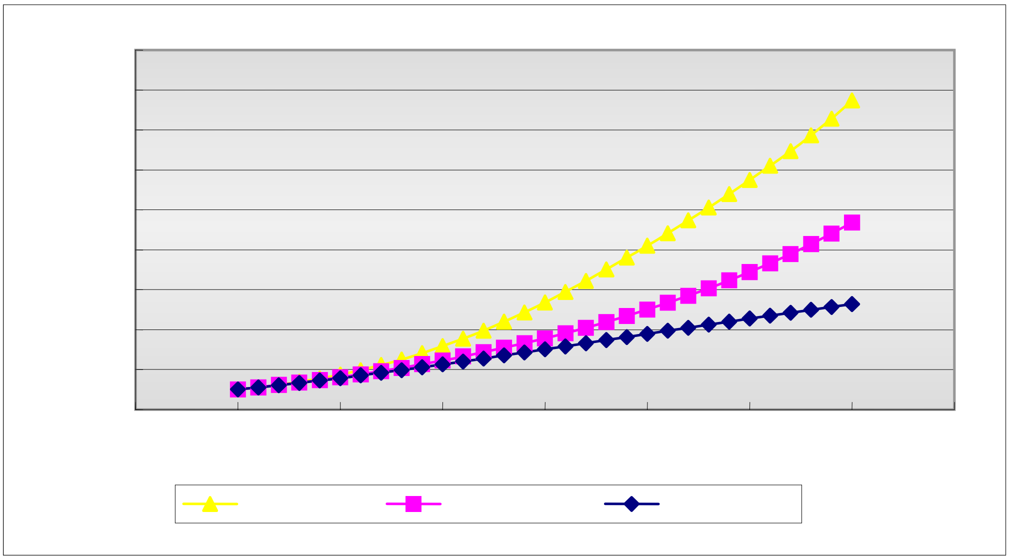

Figure 5-2 Agricultural energy demand, 2000-2030

4. Industrial Energy Demand

The industrial sector can be divided into thirty branches or sub-sectors. Energy elasticity figures can be then used to predict energy demand. Using this process, industrial energy demand is projected to increase from 793 PJ in 2000 to 2,167-4,627 PJ in 2030. The average annual energy demand growth rate in the industrial sector as a whole should be 3.4-6.1 percent.

Table 5-4 Industrial energy demand, 2000-2030, Unit: PJ

Year	High Growth	Medium Growth	Low Growth
2000	793	793	793
2005	1223	1184	1173
2010	1705	1508	1452
2015	2298	1820	1672
2020	3023	2195	1879
2025	3757	2610	2028
2030	4627	3152	2167

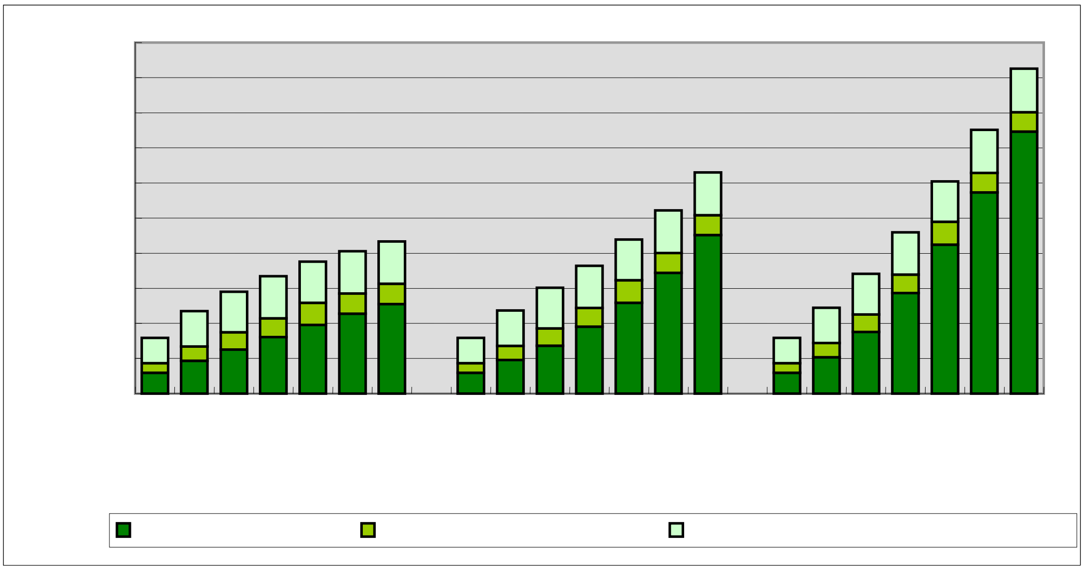

Figure 5-3 Industrial energy demand, 2000-2030

5. Construction Energy Demand

Using the elasticity coefficient of energy consumption, Shanghai's construction energy demand is calculated to increase from 4 PJ in 2000 to 17-50 PJ in 2030. The average annual growth rate will be 4.8-8.6 percent. Details are shown in Table 5-5 and Figure 5-4.

Table 5-5 Construction energy demand, 2000-2030

Year	Construction GDP (100 million RMB in 2000 prices)			Construction Energy Demand (PJ)		
	High Growth	Medium Growth	Low Growth	High Growth	Medium Growth	Low Growth
2000	207	207	207	4	4	4
2005	339	312	305	7	6	6
2010	573	445	410	12	9	8
2015	938	624	527	19	13	11
2020	1388	847	640	28	17	13
2025	1878	1125	744	38	23	15
2030	2443	1478	834	50	30	17

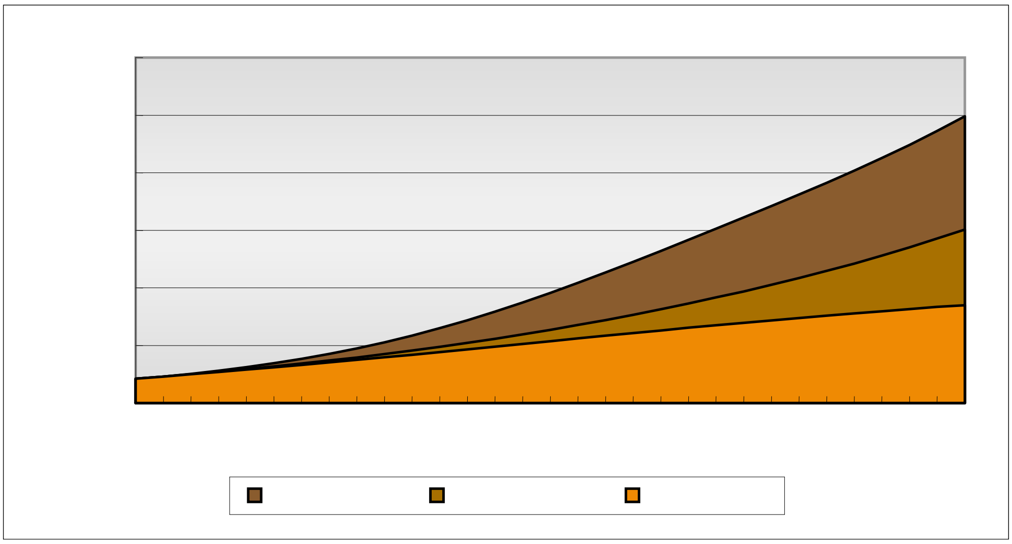

Figure 5-4 Construction energy demand, 2000-2030

6. Commercial Energy Demand

Table 5-6 and Figure 5-5 show Shanghai's projected commercial energy demand. Commercial energy demand will increase from 62 PJ in 2000 to 343-1,004 PJ in 2030, with an average annual growth rate of 5.8-9.7 percent.

Table 5-6 Commercial energy demand, 2000-2030

Year	Commercial GDP (100 million RMB in 2000 prices)			Commercial Energy Demand (PJ)		
	High Growth	Medium Growth	Low Growth	High Growth	Medium Growth	Low Growth
2000	485	485	485	62	62	62
2005	862	794	776	111	102	100
2010	1584	1231	1132	204	159	146
2015	2686	1786	1509	346	230	194
2020	4119	2513	1901	530	324	245
2025	5780	3463	2290	745	446	295
2030	7798	4717	2662	1004	608	343

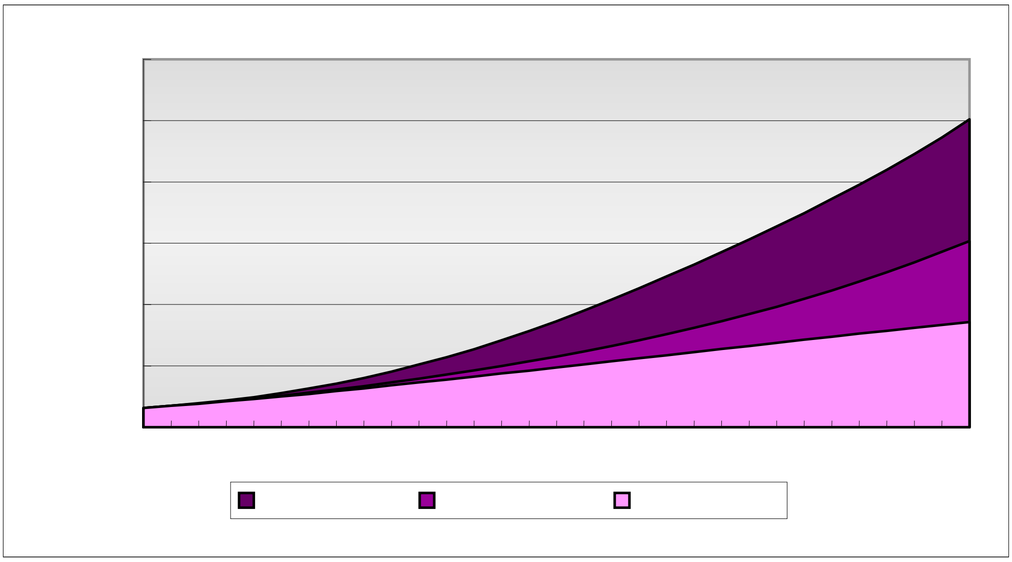

Figure 5-5　Commercial energy demand, 2000-2030

7. Transportation Energy Demand

7.1. Non-Ground Transportation Energy-Demand Forecast

The projected energy use of rail, water, and air transportation in Shanghai between 2000 and 2030 is shown in Table 5-7 and Figure 5-6.

Table 5-7　Energy demand of rail, water, and air transportation, 2000-2030

Year	Rail		Water		Air		Total
	10,000 tons	PJ	10,000 tons	PJ	10,000 tons	PJ	PJ
2000	1.92	0.82	249	104	54	23	128
2005	1.92	0.82	249	104	152	66	171
2010	1.92	0.82	299	125	206	89	215
2015	1.92	0.82	338	142	255	110	252
2020	1.92	0.82	377	158	322	139	298
2025	1.92	0.82	377	158	351	151	310
2030	1.92	0.82	377	158	380	164	323

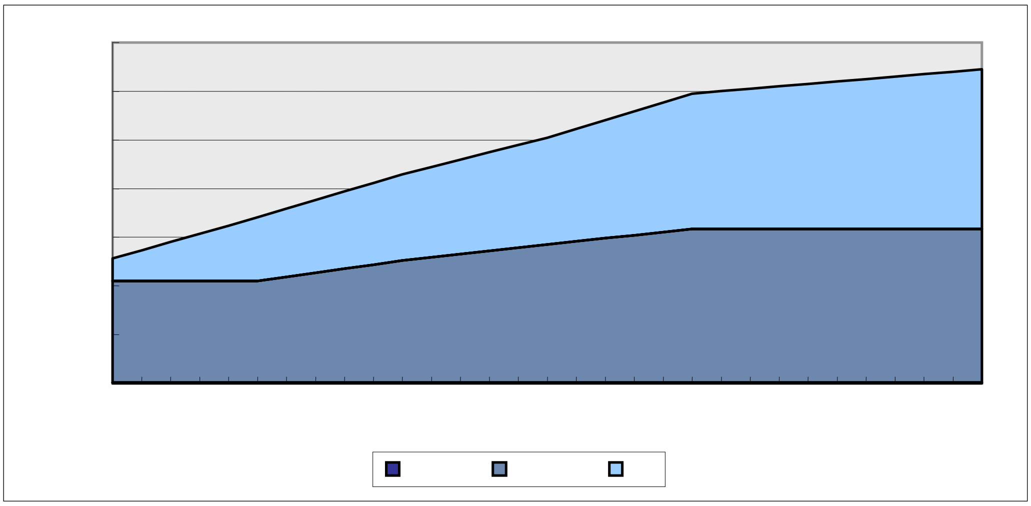

Figure 5-6 Energy demand of non-ground transportation, 2000-2030

7.1.1. Rail Transportation Energy-Demand Forecast

Railway freight capacity stayed between 49.10 and 64.16 million metric tons in 1990-2000, with an average annual capacity of 56.50 million metric tons. Railway passenger capacity increased steadily in 1990-2000, reaching 29.80 million persons in 2000. Railway diesel consumption in 2000 was 19,150 metric tons, nearly 0.82 PJ. Railway freight and passenger capacity is projected to remain basically constant.

7.1.2. Water Transportation Energy-Demand Forecast

Shanghai harbor’s handling capacity grew significantly from 1990 to 2000. Its handling capacity in 2000 was 204.4 million metric tons, 46 percent greater than in 1990. Import traffic accounted for 137.91 million metric tons, 67.5 percent of the total; exports accounted for 66.49 million metric tons, 32.5 percent of the total. Energy consumption on Shanghai’s harbor in 2000 was 0.36 Mtce, nearly 104.2 PJ.

Shanghai harbor’s handling capacity is projected to increase in the future, with a concomitant increase in energy demand. Energy demand on Shanghai’s harbor should increase to 158 PJ in 2030, a 52 percent increase from 2000 (see Figure 5-6).

7.1.3. Air Transportation Energy-Demand Forecast

Shanghai’s air freight and passenger capacities have been increasing in recent years. Air freight capacity increased from 0.88 million metric tons in 1999 to one million metric tons in 2000, a 14 percent increase; passenger capacity increased from 8.92 million persons in 1999 to 10.42 million persons in 2000, a 17 percent increase.

According to *Shanghai’s 2001 Annual Energy Report*, Shanghai Airlines and Eastern Airlines had a combined fleet of 81 airplanes in 2000. Air transportation’s kerosene consumption decreased from 564,900 metric tons in 1999 to 540,300 metric tons, nearly 13.3 PJ, in 2000 due to increased energy-efficiency management.

Based on 1998 traffic figures for Shanghai's Hongqiao airport, as well as the plans for Pudong International Airport, *Shanghai's Energy Options and Health Impact Research* forecasts growing use of civil aviation in Shanghai's future. This study projects Shanghai's air transportation energy demand will increase to 163.8 PJ in 2030, nearly 7 times the energy demand in 2000.

7.2. Ground Transportation Energy-Demand Forecast

7.2.1. Prediction Method

Assuming annual energy consumption per vehicle for every vehicle type does not change, we can calculate future ground transportation energy demand as follows:

$$\text{Energy demand of ground transport in year } y = \sum_{i=1}^{n} (\text{vehicle population of type } i \text{ in year } y \times \text{annual energy consumption per vehicle of type } i),$$

where n is the number of vehicle types.

7.2.2. Vehicle Population Forecast

Assuming high-speed vehicle population growth, Shanghai's vehicle population—including cars, light-duty vehicles (LDV), buses, heavy-duty vehicles (HDV), and motorcycles (MC)—will reach 3.5 million in 2020[1]. Combining these predictions with our own predictions for the population of light motorcycles (LMC) and mopeds we arrived at a comprehensive prediction for total vehicle population during 2000-2030.

Table 5-8 Vehicles in Shanghai, 2000-2030, Unit: 10,000 vehicles

Year	Car	LDV	Bus	HDV	MC	LMC	Moped	TOTAL
2000	23.4	12.8	2.8	2	11.5	51.9	40.5	144.9
2005	49.1	26.9	3.2	2.3	3.8	14	18	117.3
2010	84.8	46.4	3.4	2.6	3.4	12.7	16.2	169.5
2015	120.4	66	3.7	3.1	3.1	11.5	14.7	222.5
2020	156.1	85.6	4	3.6	2.8	10.4	13.3	275.8
2025	191.8	105.2	4.3	4.1	2.5	9.4	12	329.3
2030	227.5	124.8	4.6	4.8	2.3	8.5	10.8	383.3

7.2.3. Energy Demand Forecast

Using the figures for projected vehicle population, we can calculate future energy

[1] Shanghai Academy of Environmental Sciences. *The Integrated Assessment of Energy Options and Health Benefit*, December 2001.

demand for ground transportation in Shanghai. Ground transportation energy demand is expected to increase from 84 PJ in 2000 to 818 PJ in 2030, an almost ten-fold increase, with an average annual growth rate of 7.9 percent (see Table 5-9).

Table 5-9 Ground transportation energy demand, 2000-2030, Unit: PJ

Year	Car	LDV	Bus	HDV	MC	LMC	Moped	TOTAL
2000	44	18	9	8	5	10	6	100
2005	91	39	10	10	2	3	1	155
2010	158	67	11	11	1	2	1	251
2015	224	95	12	13	1	2	1	347
2020	290	123	13	15	1	2	0	444
2025	356	151	14	17	1	2	0	542
2030	423	179	15	20	1	2	0	640

8. Residential Energy Demand

Using urban population growth and energy intensity predictions, we forecasted residential energy demand in both urban and rural areas.

Residential energy demand is projected to be 111.5 PJ in 2030, with urban areas using 89 percent (99.7 PJ) and rural areas using 11 percent (11.8 PJ). Residential electricity demand in 2030 is projected at 25.5 PJ, nearly 7.1 billion kWh, 94 percent of which (6.8 billion kWh) will be used in urban areas.

Table 5-10 Residential energy demand, 2000-2030, Unit: PJ

Year	Urban			Rural			TOTAL
	elec.	others	total	elec.	others	total	
2000	16.4	51.3	67.7	2.8	20.1	22.9	90.6
2005	17.4	54.8	72.2	2.5	18.0	20.5	92.7
2010	18.6	58.4	77.0	2.2	16.1	18.4	95.4
2015	19.9	62.3	82.2	2.0	14.4	16.4	98.6
2020	21.2	66.5	87.6	1.8	12.9	14.7	102.3
2025	22.6	70.9	93.5	1.6	11.6	13.1	106.6
2030	24.1	75.6	99.7	1.4	10.3	11.8	111.5

9. Summary

In this chapter, we used economic growth rate, industrial structure change, and population growth projections to predict Shanghai's energy demand over the 30 year period 2000-2030. This forecast included the following:

(1) By 2030, Shanghai's final energy demand will reach 3,734-7,143 PJ, 3.1-5.9 times more than final energy demand in 2000. The final energy demand of

construction will increase 4.3-12.5 times; commerce, 5.5-16.1 times; ground transportation, 6.4 times; non-ground transportation, 2.5 times; and residences, 1.2 times.

(2) By 2030, agricultural final energy demand will account for 4-5 percent of total final energy demand; industrial, 58-65 percent; construction, 0.5-0.7 percent; commercial, 9-14 percent; transportation, 26-13 percent; and residential, 3-2 percent.

(3) Shanghai's average annual final energy demand growth rate is projected to be 3.8-6.1 percent over the 2000-2030 period. The average annual final energy demand growth rate for agriculture is projected to be 5.7-9.6 percent; industry, 3.4-6.1 percent; construction, 4.8-8.8 percent; commerce, 5.9-9.7 percent; transportation, 4.9 percent; and residences, 0.7 percent.

Chapter 6. LEAP Model Framework and BAU Scenario

1. Foreword

In order to study the effect of low-carbon development scenarios on the growth rates of local air pollutant (LAP) and CO_2 emissions, we used the Long-Range Energy Alternatives Planning (LEAP) system. LEAP is an analytical model for energy and environmental scenarios. LEAP uses different social and economics figures—e.g. population, economic growth rate, technology improvement, and price fluctuation—to calculate changes in air pollutant and greenhouse gas emission levels caused by energy flow and consumption.

This analysis can be used to improve Shanghai's air quality management and develop medium- and long-term strategic frameworks for Shanghai's low-carbon development.

2. LEAP Model Framework

LEAP model framework includes social and economic factors, final energy demand, energy transformation and processing, and resource storage information. This study used economic growth, city development scale, industrial structure, and vehicle population forecasts to predict Shanghai's future energy demand and LAP and CO_2 emissions.

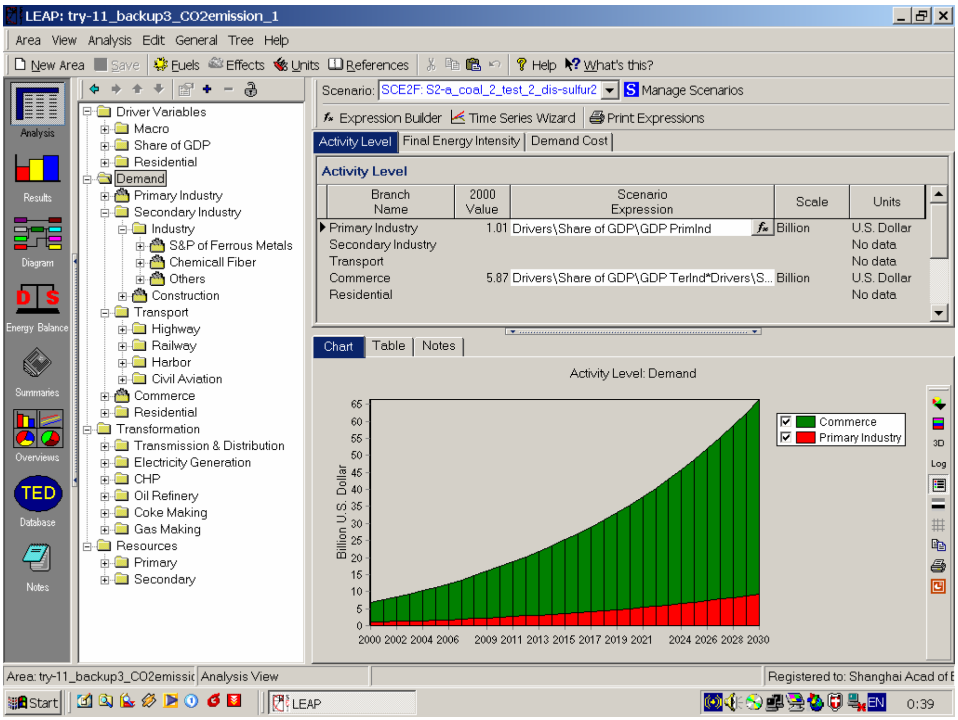

Figure 6-1 Analysis view of Shanghai LEAP model

2.1. Energy Carriers

In total, the Shanghai LEAP model used 20 energy carriers. These carriers included both primary and secondary energy carriers (see Table 6-1).

Table 6-1 Energy carriers in Shanghai LEAP model

Primary Energy Carriers	Secondary Energy Carriers
Crude Oil Hard Coal Coking Coal Natural Gas Hydro Wind Biomass	Fuel Oil Gasoline Diesel Kerosene LPG Dry Gas from Refineries Other Petrol Products Coke Other Coke Products Coke Oven Gas Other Coal Gas Electricity Heat Others

2.2. Final Demand Sectors

LEAP model divides final energy demand into five demand sectors, primary industry, secondary industry, transportation, the commercial sector, and the residential sector. Primary industry refers to agriculture; secondary industry, industry and construction; transportation, both on and off-ground transportation; and residential, both urban and rural residential areas.

2.3. Energy Transformation Sector

The energy transformation sector in LEAP model has six branches, transmission and distribution, power generation, combined heat and power (CHP), oil refinement, coking, and gas making. Each of these branches is then further divided into transformation process and energy output.

3. Energy Demand in BAU Scenario

3.1. Energy Demand in Final Consumption Sector

The Shanghai LEAP model uses 2000 as the base year and assumes an intermediate economic growth rate to forecast future energy demand. Table 6-2 and Figure 6-2 show energy demand in the final energy consumption sector for the in the business as usual (BAU) scenario.

Final energy demand will increase at a brisk pace in the BAU scenario. By 2030, energy demand will reach 5,097 PJ, equal to 174 Mtce, 3.2 times final energy demand in 2000. The average annual final energy demand growth rate over the 2000-2030 period is 4.9 percent. Due to burgeoning private vehicle demand, demand for gasoline and diesel will increase dramatically, with average annual growth rates above six percent.

Coal demand by final sectors in the BAU scenario reaches 1,014 PJ, 45.38 million metric tons of coal, by 2030; 916 PJ (41.69 million metric tons) of this demand will be for hard coal; 97 PJ (3.69 million metric tons), for coking coal. Coal consumption in 2030 will be 3.6 times more than in 2000.

Final sector total primary energy demand will reach 1,069 PJ in 2030. Demand for coal represents 94.8 percent of this total; crude oil, 0.2 percent; and natural gas, 5 percent.

Table 6-2a Final energy demand in BAU scenario, Unit: PJ

Energy Carriers	2000	2005	2010	2015	2020	2025	2030
Solid Fuel	415	595	735	862	988	1182	1407
Liquid Fuel	299	428	597	767	961	1125	1317
Gaseous Fuel	155	223	289	356	438	525	638
Other Fuels	98	146	184	215	265	284	328
Electricity	191	288	393	520	678	878	1135
Heat	48	74	101	132	174	216	274
TOTAL	1204	1751	2298	2850	3505	4209	5097

Table 6-2b Final energy demand in BAU scenario, Unit: PJ

Sectors	2000	2005	2010	2015	2020	2025	2030
Primary Industry	25	40	62	89	125	172	234
Secondary Industry	797	1190	1517	1832	2212	2632	3182
Commerce	63	102	158	230	324	446	608
Transport	229	326	466	600	742	852	962
Residential	91	93	95	99	102	107	111
TOTAL	1204	1752	2298	2850	3505	4209	5097

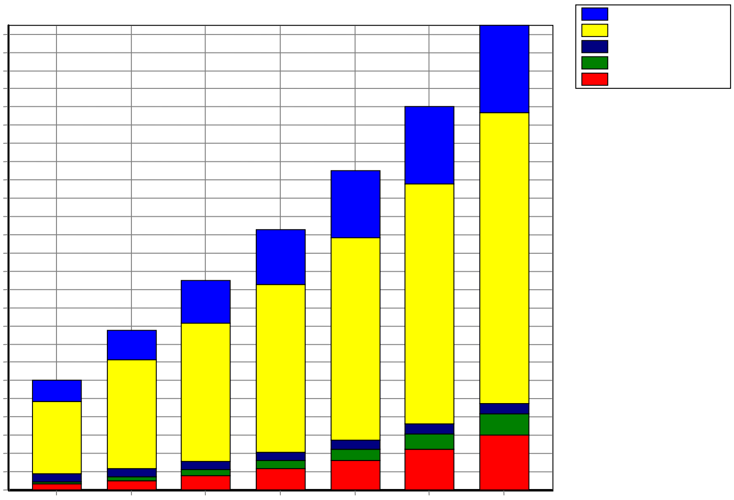

Figure 6-2 Final energy demand in BAU scenario

3.2. Energy Input and Output

As shown in Table 6-3 and Figure 6-3, total energy input into the energy transformation sector under the BAU scenario in 2030 will reach 2,493 PJ (85 Mtce), of which 1653 PJ worth (72.91 million metric tons) is coal. Combined with final consumption coal demand (see Section 3.1), Shanghai's total coal demand will reach 120 million metric tons in 2030.

In 2030, total primary energy input in the energy transformation sector in the BAU scenario will amount to 2,397 PJ, 69.0 percent of which is coal and 31.0 percent of which is crude oil.

Table 6-3 Energy transformation inputs in BAU scenario, Unit: PJ

Energy Carriers	2000	2005	2010	2015	2020	2025	2030
Solid Fuel	831	886	1036	1165	1320	1473	1666
Liquid Fuel	582	782	782	781	782	783	785
Gaseous Fuel	17	18	20	21	23	26	28
Other Fuels	13	15	15	15	15	15	15
TOTAL	1442	1699	1852	1981	2140	2296	2493

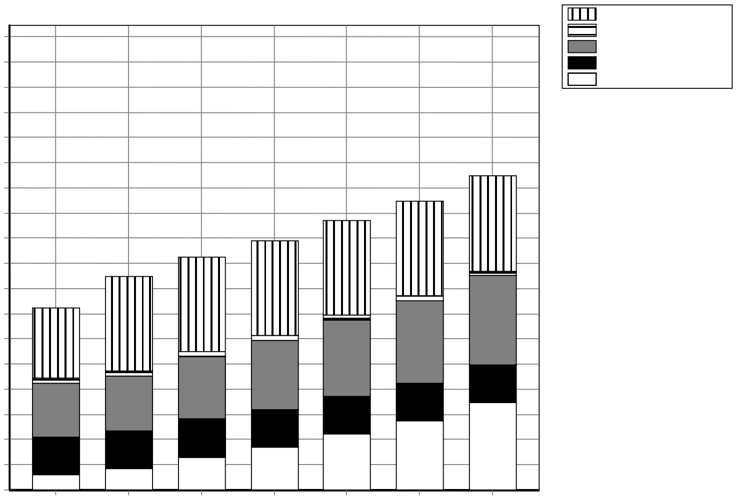

Figure 6-3 Energy transformation inputs in BAU scenario

4. Air Pollutant and CO_2 Emissions in BAU Scenario

As Shanghai's economy grows and energy consumption increases, air pollutant and CO_2 emissions in Shanghai will rise. CO_2 emissions in 2030 in the BAU scenario reach 436 million metric tons, 3.2 times more than in 2000 (136 million metric tons). This represents an average annual growth rate of 4.0 percent.

Table 6-4 CO_2 emission in BAU Scenario, Unit: million metric tons

Sectors	2000	2005	2010	2015	2020	2025	2030
Primary Industry	1	2	4	5	7	10	14
Secondary Industry	59	87	108	127	147	171	202
Commerce	2	3	5	7	10	13	18
Transport	16	22	31	40	49	56	63
Residential	7	7	7	8	8	8	8
Electricity Generation	51	56	71	83	98	113	131
TOTAL	136	177	226	269	319	372	436

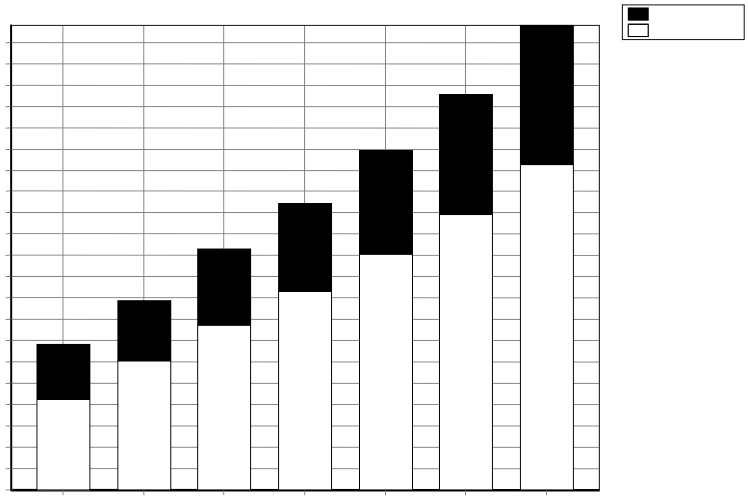

Figure 6-4 CO_2 emission in BAU scenario

Table 6-5 and Figure 6-5 show SO_2 emissions in the BAU scenario. SO_2 emissions increase from 0.46 million metric tons in 2000 to 1.63 million metric tons in 2030, an increase of 3.5 times. This represents an average annual growth rate of 4.3 percent.

Table 6-5 SO_2 emission in BAU scenario, Unit: 10,000 metric tons

Sectors	2000	2005	2010	2015	2020	2025	2030
Primary Industry	0.2	0.4	0.5	0.8	1.1	1.5	2.1
Secondary Industry	17.7	27.1	36.0	46.2	58.5	73.6	92.7
Commerce	0.3	0.4	0.7	1.0	1.4	1.9	2.6
Transport	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Residential	2.7	2.6	2.6	2.5	2.5	2.6	2.6
Electricity Generation	25.0	27.4	34.3	40.1	47.2	54.3	63.1
Gas Making	0.3	0.3	0.3	0.3	0.3	0.3	0.3
TOTAL	46.1	58.3	74.5	90.9	111.1	134.2	163.4

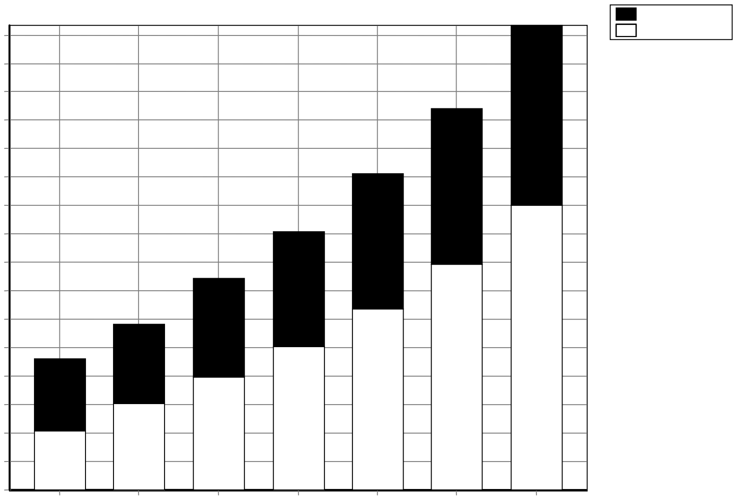

Figure 6-5 SO_2 emission in BAU scenario

Table 6-6 and Figure 6-6 show PM emissions in Shanghai's BAU scenario. PM emissions increase from 0.14 million metric tons in 2000 to 0.59 million metric tons in 2030, an increase of 4.1 times. This represents an average annual growth rate of 4.8 percent.

Table 6-6 PM emission in BAU scenario, Unit: 10,000 metric tons

Sectors	2000	2005	2010	2015	2020	2025	2030
Secondary Industry	6.3	9.9	13.4	17.7	22.8	29.5	37.8
Commerce	0.0	0.1	0.1	0.1	0.2	0.3	0.4
Transport	0.4	0.5	0.7	0.9	1.1	1.3	1.5
Residential	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Electricity Generation	7.2	7.9	10.0	11.8	13.9	16.0	18.7
TOTAL	14.4	18.8	24.7	31.0	38.6	47.6	58.9

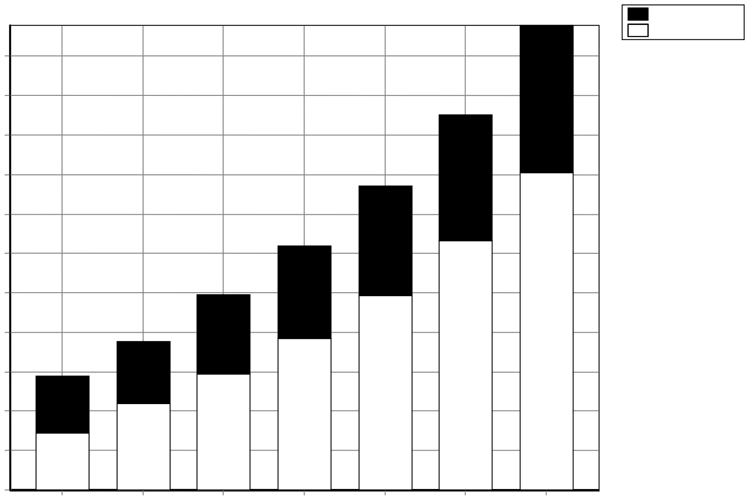

Figure 6-6 PM emission in BAU Scenario

5. Summary

This chapter describes the results of our LEAP analysis of Shanghai's BAU scenario, assuming an intermediate economic development rate (described in chapter 5). The analysis predicted future energy demand, as well as local air pollutant and CO_2 emission levels. Noteworthy results include the following:

(1) By 2030, Shanghai's total final energy demand will reach 5,097 PJ, 3.2 times energy demand in 2000. Final energy demand in primary industry will be 8.3 times year 2000 final energy demand; in secondary industry, 3.0 times; in commerce, 8.7 times; in transportation, 3.2 times; and in the residential sector, 0.2 times.

(2) By 2030, primary industry final energy demand will account for 5 percent of total final energy demand; secondary industry, 62 percent; commercial, 12 percent; transportation, 19 percent; and residential, 2 percent.

(3) By 2030, energy input into the energy transformation sector will come to 2,493 PJ, energy output, 1,832 PJ, representing a transformation rate of 73 percent.

(4) Air pollutant and CO_2 emissions will increase significantly in the BAU scenario. Between 2000 and 2030, CO_2 emission will increase at an average annual rate of 4.0 percent, reaching 436 million metric tons by 2030, more than twice 2000 emission levels. SO_2 emission will increase at an average annual rate of 4.3 percent, reaching 1.63 million metric tons by 2030, 2.5 times 2000 levels. PM emissions will increase at an average annual rate of 4.8 percent, reaching 0.59 million metric tons in 2030, 3.1 times 2000 levels.

Chapter 7. Low-Carbon Emission Scenarios

1. Preface

The previous chapter showed that under business as usual (BAU) practices air pollutant and CO_2 emissions will continue to increase at a rapid pace. In this chapter we again apply the Long-Range Energy Alternatives Planning (LEAP) model to evaluate the effect low-carbon policies would have on air pollutant and CO_2 emission levels. We will use LEAP to analyze the effects of several measures, including energy-efficiency improvement, energy-technology development, low-carbon energy switch, and low-carbon electricity generation.

2. Scenario definition

The following documents were consulted in the development of our low-carbon policy scenarios:

(1) *Shanghai Action Plan for China's Agenda 21*, 1999;

(2) *The Tenth Five-Year Special Plan for Energy Development in Shanghai*, 2001;

(3) *The Tenth Five-Year Plan for Atmospheric Environmental Protection*, 2002;

(4) *The Eleventh Five-Year Plan and 2020 Research Aims for Shanghai Power Supply*, June 2003

While analyzing scenarios using LEAP, we designed high, medium, and low economic growth rate scenarios, and we used the medium one in the BAU scenario. Scenario details are shown in table 7-1.

Table 7-1 Scenario definitions for LEAP Shanghai

	Name	Name in LEAP	Definition
Economic Growth Rate	Scenario 1	Scenario 1	Low economic growth
	Scenario 2	Scenario 2	Medium economic growth
	Scenario 3	Scenario 3	High economic growth
Low-carbon Scenarios	BAU	Scenario 2-BAU	BAU (medium economic growth)
	EE	S2_EE_only	Energy intensity reduction (i.e., energy efficiency improvement, energy technology update)
	COAL+GAS	S2_COAL_GAS	Natural gas shift for coal and pipe coal gas
	ELEC+WIND	S2_ELEC_WIND	Natural gas and wind electricity generation (low-carbon electricity)
End Pipe Treatment	SO_2	S2_ELEC_WIND_SO2a	Natural gas and wind electricity generation (low-carbon electricity) + sulfur smoke removal

Scenarios		S2_EE_COAL_GAS_ELEC _WIND_SO2b	Energy efficiency + natural gas shift for coal and pipe coal gas + natural gas and wind electricity generation + sulfur smoke removal + fuel sulfur content control
	PM	S2_EE_COAL_GAS_ELEC _WIND_SO2b_PM	Energy efficiency + natural gas shift for coal and pipe coal gas + natural gas and wind electricity generation + sulfur smoke removal + fuel sulfur content control + soot control
Combined Scenario	2010 Expo	S2_EE_COAL_GAS_ELEC _WIND_SO2c_PM	Most effective scenario: PM scenario + additional fuel sulfur content control

We calculated and analyzed the effect each of the above low-carbon development scenarios would have on energy consumption and pollutant emissions in Shanghai.

3. Low-Carbon Scenario Analysis

3.1. EE Scenario

This scenario assumes 2 percent energy conservation per year. This would be accomplished through updating energy technology in final energy use sectors and implementing other energy-efficiency measures.

3.1.1. Final Energy Demand

Table 7-2 lists the final energy demand for respective energy carriers in the EE scenario. Assuming 2 percent energy conservation per year, Shanghai's final energy demand would grow at an average annual rate of 3.7 percent over the 2000-2030 period, teaching 3,591 PJ (nearly 123 Mtce) in 2030. This is a decrease of 29.5 percent from the BAU scenario (5097 PJ, see Chapter 6).

Final coal consumption in the EE scenario is 602 PJ (26.84 Mt of coal) in 2030, 530 PJ (24.11 Mt) of which is hard coal and 72 PJ (2.73 Mt) of which is coking coal. This is a drop of 18.54 Mt of coal from the BAU scenario.

Table 7-2 Final energy demand in EE scenario, Unit: PJ

Energy Carriers	2000	2005	2010	2015	2020	2025	2030	Growth rate
Solid Fuel	415	565	669	742	790	876	954	2.8%
Liquid Fuel	299	418	575	723	887	1007	1137	4.6%
Gaseous Fuel	155	212	265	310	361	403	453	3.6%
Other Fuels	98	142	173	194	230	228	244	3.1%
Electricity	191	260	329	398	472	553	645	4.1%
Heat	48	66	84	101	123	137	157	4.0%
TOTAL	1204	1662	2093	2466	2862	3203	3591	3.7%

Table 7-3 indicates each final sector's energy demand in the EE scenario. The industrial sector uses 2042 PJ of energy, accounting for 57 percent of total energy use; the transportation sector is next at 962 PJ, accounting for nearly 27 percent of total energy use.

Table 7-3 Final sector energy demand in EE scenario, Unit: PJ

	2000	2005	2010	2015	2020	2025	2030
Primary	25	37	50	66	83	104	127
Secondary	797	1115	1353	1533	1718	1872	2058
Commercial	63	93	129	170	216	269	332
Transport	228	326	466	600	742	852	962
Residential	91	93	95	99	102	107	111
TOTAL	1204	1662	2093	2467	2862	3203	3591

3.1.2. Primary Energy Demand

Primary energy imports in the EE scenario, shown in Table 7-4 and Figure 7-1, would total 2752 PJ in 2030. Coal demand represents 1976 PJ (71.8 percent) of this total, crude oil 745 PJ (27.1 percent), and natural gas 31 PJ (1.1 percent).

Table 7-4 Primary energy demand in EE scenario, Unit: PJ

	2000	2005	2010	2015	2020	2025	2030
Crude oil	545	744	745	745	745	745	745
Natural gas	8	11	14	17	21	26	31
Coal	1040	1167	1342	1493	1652	1805	1976
TOTAL	1593	1922	2100	2255	2418	2576	2752

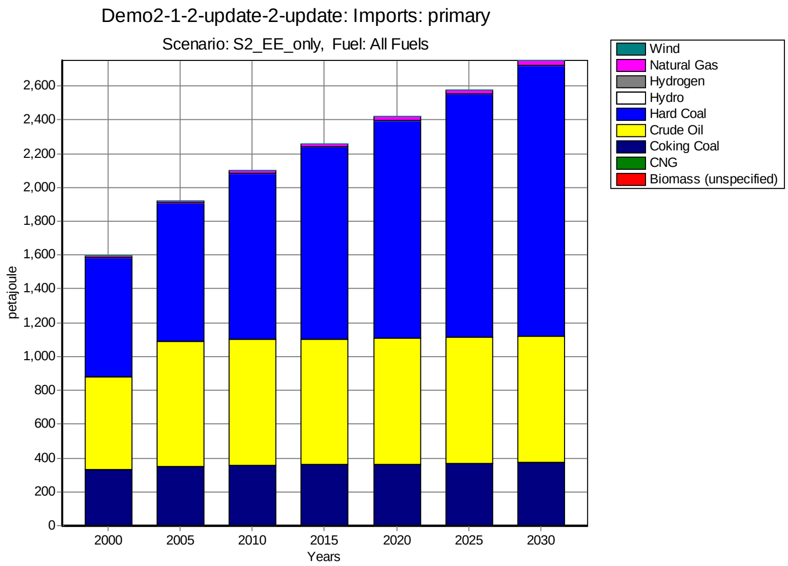

Figure 7-1 Primary energy demand in EE scenario

3.1.3. CO_2 Emission

Because improved energy efficiency reduces energy demand, CO_2 and other air pollutant emissions greatly decrease (relative to BAU) in the EE scenario (see Table 7-5 and Figure 7-2).

Total CO_2 emission in Shanghai in 2030 would be 332 Mt. Although an increase of 2.4 times from 2000, this amount is 23.9 percent lower than CO_2 emission in the BAU scenario. Industry would emit 42 percent of this total; the power generation sector, 31 percent; and the transportation sector, 19 percent.

Table 7-5 CO_2 emission in EE scenario, Unit: million metric tons

	2000	2005	2010	2015	2020	2025	2030
Final sector	85	116	144	166	188	208	229
Primary	1	2	3	4	5	6	7
Secondary	59	83	99	110	120	129	140
Commercial	2	3	4	5	6	8	10
Transportation	16	22	31	40	49	56	63
Residential	7	7	7	8	8	8	8
Transformation sector	51	56	67	76	86	94	104
TOTAL	136	173	211	242	274	302	332

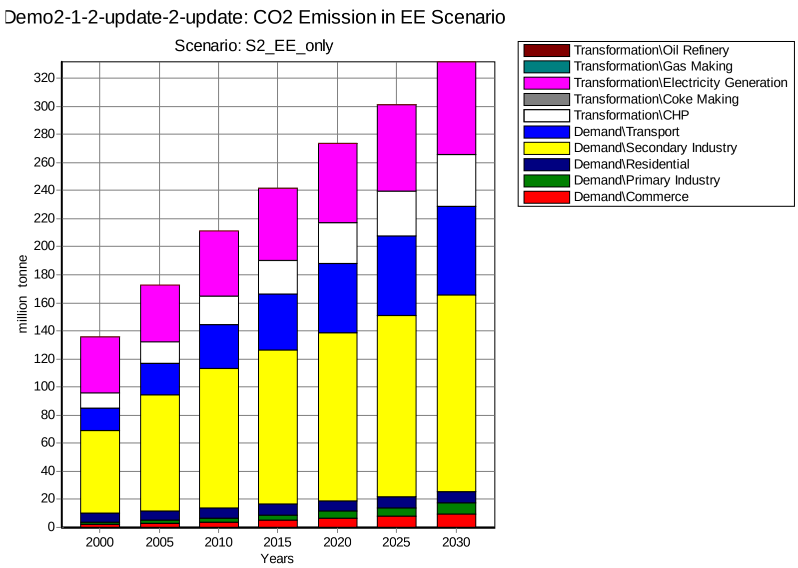

Figure 7-2 CO_2 emission in EE scenario

3.1.4. SO_2 Emission

Total SO_2 emission in Shanghai in 2030 would be 1.09 Mt in the EE scenario. Although an increase of 2.4 times from 2000, this is a reduction of 33.4 percent from the BAU scenario (1.63 Mt). The industrial sector would emit 49.2 percent of this total; the electricity generation sector, 45.8 percent.

Table 7-6 SO_2 emission in EE scenario, Unit: 10,000 metric tons

	2000	2005	2010	2015	2020	2025	2030
Final sector	20.8	27.8	33.9	39.5	45.4	51.6	58.6
Primary	0.2	0.3	0.4	0.6	0.7	0.9	1.1
Secondary	17.7	24.5	30.3	35.7	41.2	47.0	53.5
Commercial	0.3	0.4	0.6	0.7	0.9	1.1	1.4
Transportation	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Residential	2.7	2.6	2.6	2.5	2.5	2.6	2.6
Transformation sector	25.3	27.8	32.7	36.9	41.7	45.6	50.2
TOTAL	46.1	55.5	66.6	76.4	87.1	97.2	108.8

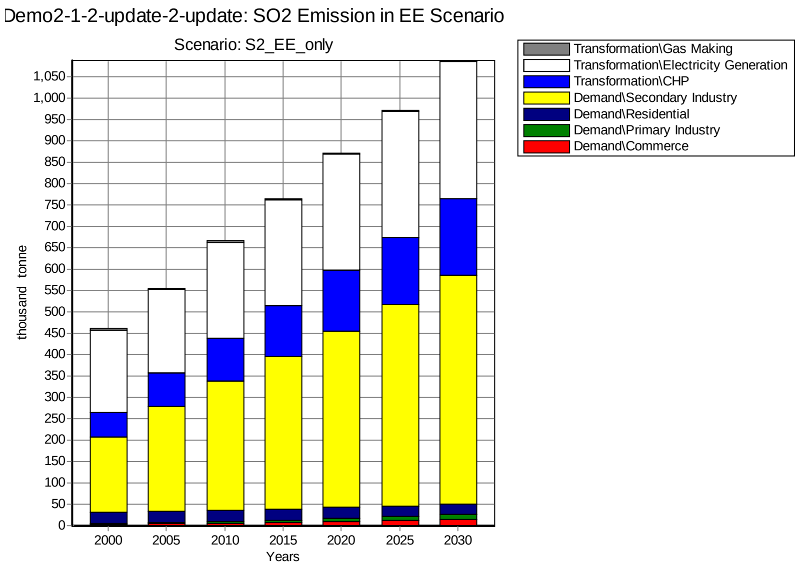

Figure 7-3 SO_2 emission in EE scenario

3.1.5. PM Emission

Total PM emissions in Shanghai in 2030 would be 378 Kt in the EE scenario. Although an increase of 2.6 times from 2000, this is a 35.8 percent decrease from the BAU scenario (589 Kt). The industrial sector would emit 54.9 percent of this total; the electricity generation sector 39.2 percent.

Table 7-7 PM emission in EE scenario, Unit: 10,000 metric tons

	2000	2005	2010	2015	2020	2025	2030
Final sector	7.2	9.8	12.2	14.6	17.1	19.9	23.0

Primary	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Secondary	6.3	8.7	10.9	13.1	15.3	17.9	20.8
Commercial	0.0	0.1	0.1	0.1	0.1	0.2	0.2
Transportation	0.4	0.5	0.7	0.9	1.1	1.3	1.5
Residential	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Transformation sector	7.2	7.9	9.5	10.8	12.2	13.4	14.8
TOTAL	14.4	17.7	21.6	25.4	29.3	33.3	37.8

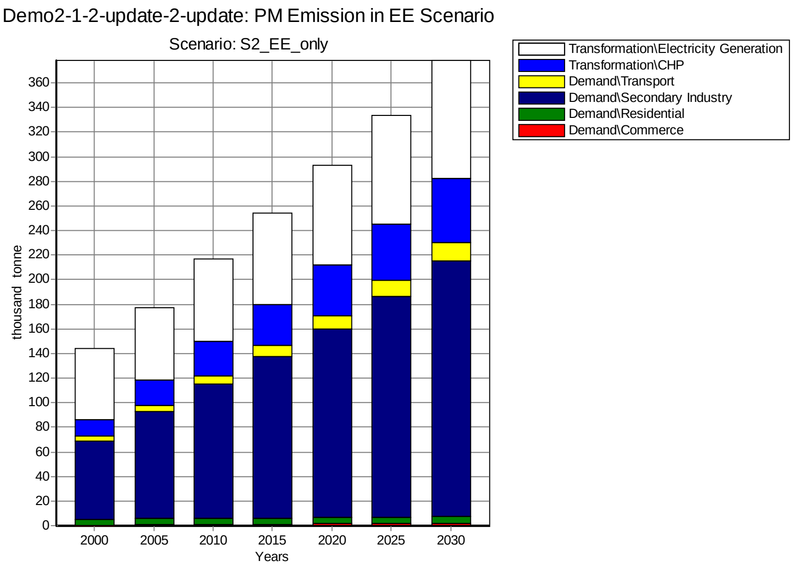

Figure 7-4　PM emission in EE scenario

3.2. COAL+GAS Scenario

In the COAL+GAS scenario, low-carbon energy carriers are used to shift the final sector energy utilization structure. Most of the measures in this scenario are concerned with increasing natural gas usage in the commercial and residential sectors, while decreasing the usage of hard coal and pipe coal gas. In detail, the COAL+GAS scenario includes the following:

- In primary industry, hard coal’s share among total energy carriers falls five percent each year.
- Excluding the steel and chemical fiber sectors, hard coal’s share in total energy carriers in industrial sectors decreases by 0.5 percent each year between 2001 and 2005 and 13 percent each year after 2005. Hard coal’s share in the steel sector will fall 8 percent each year.
- In the commercial sector, hard coal’s share among total energy carriers decreases five percent each year; coke oven gas and other coal gases will cease to be used after 2005.

- In the residential sector, hard coal use in both urban and rural areas decreases 5 percent each year between 2001 and 2005 and 10 percent each year after 2005; In addition, in urban areas, the use of coal gas decreases 5 percent yearly.

3.2.1. Final Energy Demand

In the COAL+GAS scenario, since energy efficiency remains the same, energy demand is unchanged from the BAU scenario.

Final coal consumption in the COAL+GAS scenario is 159 PJ in 2030 (6.5 Mt of coal), 62 PJ (2.82 Mt) of which is hard coal and 97 PJ (3.68 Mt) of which is coking coal. Final coal consumption in the COAL+GAS scenario is an extraordinary 38.88 Mt lower than the BAU scenario in 2030.

In this scenario, natural gas use in final sectors will experience vast growth. Natural gas use will reach 30 PJ (nearly 800 million m^3) in 2005 and 939 PJ (about 24.1 billion m^3) in 2030.

Table 7-8 Final energy demand in COAL+GAS scenario, Unit: PJ

Energy Carriers	2000	2005	2010	2015	2020	2025	2030	Annual Growth
Solid Fuel	415	583	576	549	519	535	553	1.0%
Liquid Fuel	299	428	597	767	961	1125	1317	5.1%
Gaseous Fuel	155	234	448	668	908	1173	1492	7.8%
Other Fuels	98	146	184	215	265	284	328	4.1%
Electricity	191	288	393	520	678	878	1135	6.1%
Heat	48	74	101	132	174	216	274	6.0%
TOTAL	1204	1751	2298	2850	3505	4209	5097	4.9%

3.2.2. Primary Energy Demand

The primary energy imports in the COAL+GAS scenario are 3497 PJ in 2030, very close to the amount in the BAU scenario. However, because of the shift in final sector energy-use structure, the distribution of primary energy carriers used in Shanghai in the COAL-GAS scenario is very different from that used in the BAU scenario (see Table 7-9 and Figure 7-5). In the COAL-GAS scenario, coal demand is 1812 PJ, 51.8 percent of total final primary demand, in 2030; crude oil is nearly 746 PJ, 21.3 percent of total primary energy demand; and natural gas 939 PJ, 26.9 percent of primary energy demand. In the BAU scenario, coal is 76.9 percent of total primary energy demand; oil, 21.5 percent; and natural gas, 1.5 percent.

Table 7-9 Primary energy demand in COAL+GAS scenario, Unit: PJ

	2000	2005	2010	2015	2020	2025	2030

Crude oil	545	744	745	745	745	746	746
Natural gas	8	30	187	352	522	715	939
Coal	1040	1182	1280	1361	1483	1623	1812
TOTAL	1593	1956	2211	2458	2750	3083	3497

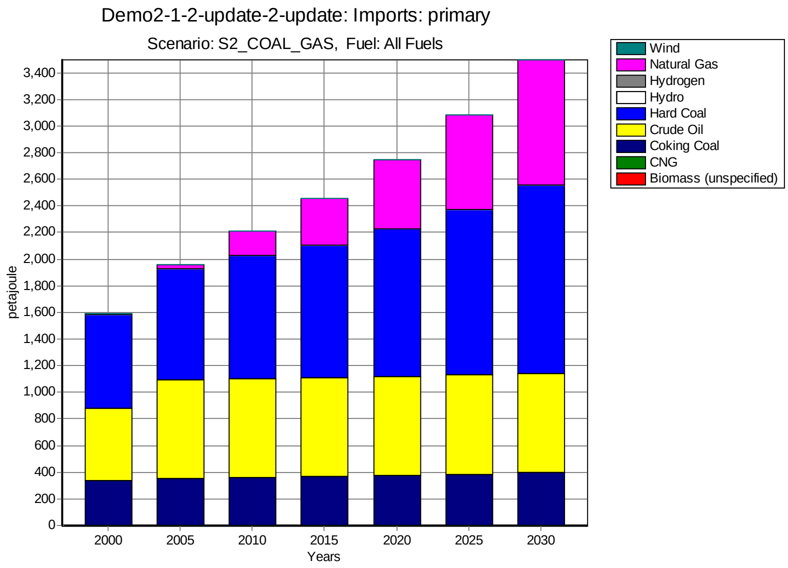

Figure 7-5 Primary energy demand in COAL+GAS scenario

3.2.3. CO_2 Emission

In the COAL+GAS scenario, the substitution of natural gas for coal reduces CO_2 emissions somewhat (see Table 7-10 and Figure 7-6).

In this scenario, total CO_2 emissions in Shanghai reach 402 Mt in 2030, a three-fold increase from 2000, but a 7.8 percent decrease from BAU scenario levels (436 Mt). The industrial sector emits 43 percent of this CO_2; electricity-generation sector, 33 percent; and transportation sector, 16 percent.

Table 7-10 CO_2 emission in COAL+GAS scenario, Unit: million metric tons

	2000	2005	2010	2015	2020	2025	2030
Final sector	85	120	148	173	202	233	271
Primary	1	2	4	5	7	10	13
Secondary	59	87	103	116	131	149	172
Commercial	2	3	5	7	9	12	17
Transportation	16	22	31	40	49	56	63
Residential	7	6	6	6	6	6	6
Transformation sector	51	56	71	83	98	113	131
TOTAL	136	176	219	256	300	345	402

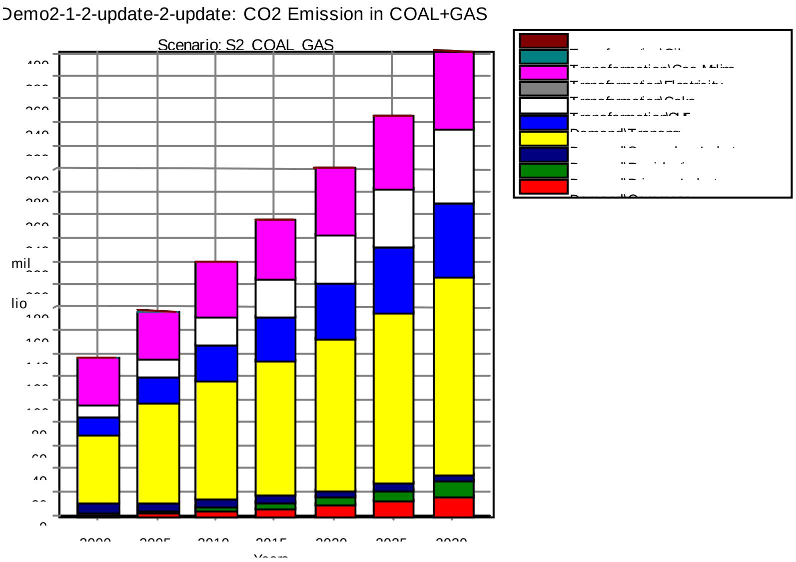

Figure 7-6 CO_2 emission in COAL+GAS scenario, Unit: million metric tons

3.2.4. SO_2 Emission

Total SO_2 emission in Shanghai in the COAL+GAS scenario is greatly reduced compared to the BAU scenario. In the COAL+GAS scenario, SO_2 emissions are 0.84 Mt in 2030, an increase of 1.8 times from 2000, but a decrease of 48.5 percent from the BAU scenario (1.63 Mt). In the COAL+GAS scenario, the industrial sector generates 23.2 percent of SO_2 emissions; the electricity generation sector, 75.1 percent.

Table 7-11 SO_2 emission in COAL+GAS scenario, Unit: 10,000 metric tons

	2000	2005	2010	2015	2020	2025	2030
Final sector	20.8	29.4	25.1	21.5	20.0	19.4	20.7
Primary	0.2	0.3	0.3	0.4	0.4	0.4	0.4
Secondary	17.7	26.7	23.2	20.0	18.7	18.3	19.5
Commercial	0.3	0.3	0.4	0.5	0.5	0.5	0.6
Transportation	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Residential	2.7	2.0	1.2	0.7	0.4	0.2	0.1
Transformation sector	25.3	27.8	34.6	40.4	47.6	54.6	63.5
TOTAL	46.1	57.1	59.7	61.9	67.5	74.0	84.1

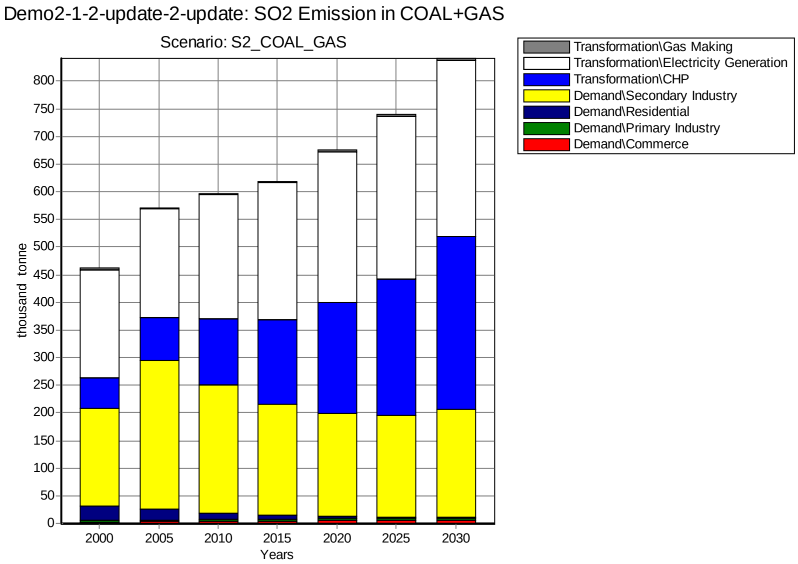

Figure 7-7 SO_2 emission in COAL+GAS scenario

3.2.5. PM Emission

The COAL+GAS scenario also has a large impact on PM pollutant levels. Total PM emission in the COAL+GAS scenario is 245 Kt in 2030, an increase of 1.7 times from 2000, but a decrease of 58.4 percent from the BAU scenario (589 Kt). In this scenario, the industrial sector generates 16.6 percent of PM emissions; the electricity generation sector, 76.4 percent.

Table 7-12 PM emission in COAL+GAS scenario, Unit: 10,000 metric tons

	2000	2005	2010	2015	2020	2025	2030
Final sector	7.2	10.6	8.7	7.1	6.0	5.7	5.8
Primary	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Secondary	6.3	9.7	7.6	5.9	4.7	4.2	4.1
Commercial	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Transportation	0.4	0.5	0.7	0.9	1.1	1.3	1.5
Residential	0.5	0.4	0.3	0.2	0.2	0.1	0.1
Transformation sector	7.2	7.9	10.0	11.8	13.9	16.0	18.7
TOTAL	14.4	18.6	18.7	18.8	19.9	21.7	24.5

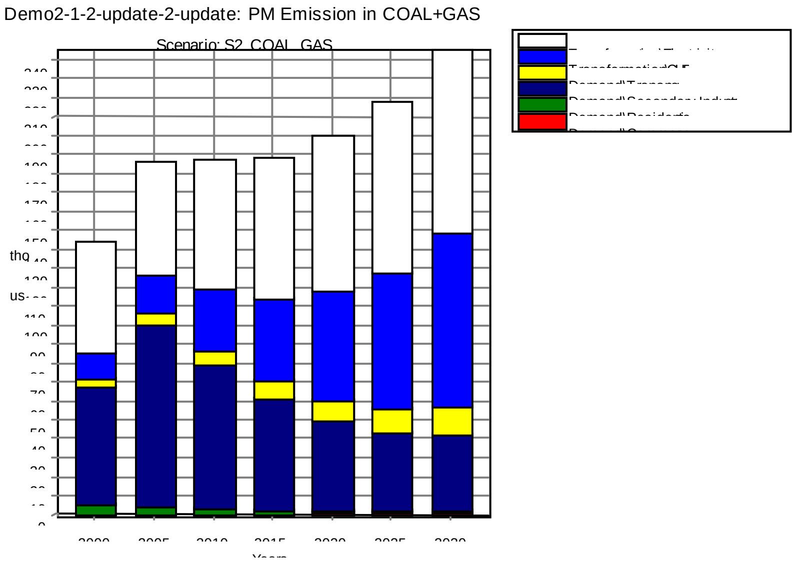

Figure 7-8 PM emission in COAL+GAS scenario, Unit: 1,000 metric tons

3.3. ELEC+WIND Scenario

The ELEC+WIND scenario adopts low-carbon electricity generation measures outlined in *The Eleventh Five-Year Plan for Shanghai Power Supply*. The bulk of these measures substitute natural gas and wind capacity for coal. The details are shown in Table 7-13 below.

Table 7-13 Electricity generation capacity in ELEC+WIND scenario, Unit: 10,000 KW

	Year	Coal	Natural gas	Wind	Total
Power Plants	2006	699.9	50	20	769.9
	2010	805.9	50	20	875.9
	2030	1165.9	50	60	1275.9
Combined Heat and Power	2006	447.5	150	0	597.5
	2010	747.5	150	0	897.5
	2030	2347.5	150	0	2497.5
TOTAL	2006	1147.4	200	20	1367.4
	2010	1553.4	200	20	1773.4
	2030	3513.4	200	60	3773.4

3.3.1. Final Energy Demand

Final energy demand in the ELEC+WIND scenario is unchanged from the BAU scenario (see Chapter 6).

3.3.2. Primary Energy Demand

Table 7-14 and Figure 7-9 show the total primary energy imports in the ELEC+WIND scenario. Primary energy demand in 2030 is 3351 PJ, of which 2491 PJ (74.3 percent) is coal. 746 PJ (22.3 percent) is hard coal, and 114 PJ (3.4 percent) is natural gas.

Table 7-14 Primary energy demand in ELEC+WIND scenario, Unit: PJ

	2000	2005	2010	2015	2020	2025	2030
Crude oil	545	744	745	745	745	746	746
Natural gas	8	62	77	79	87	98	114
Coal	1040	1099	1322	1547	1811	2115	2491
TOTAL	1593	1906	2143	2371	2644	2959	3351

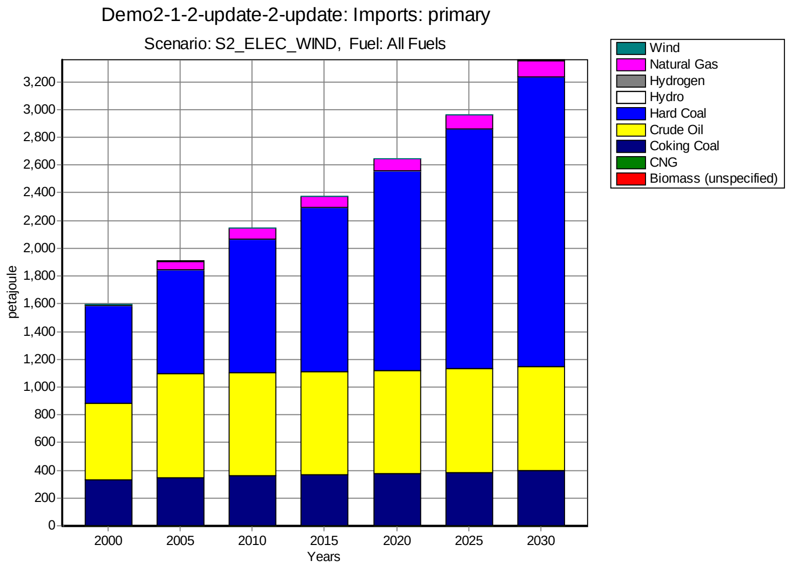

Figure 7-9 Primary energy demand in ELEC+WIND

3.3.3. CO_2 Emission

In the ELEC+WIND scenario, total CO_2 emission in Shanghai is 423 Mt in 2030, an increase of 3.1 times from 2000, and decrease of 3.0 percent from the BAU scenario (436 Mt). Industry emits 48 percent of this total; electricity generation, 28 percent; and the transportation sector, 15 percent.

Table 7-15 CO_2 emission in ELEC+WIND scenario, Unit: million metric tons

	2000	2005	2010	2015	2020	2025	2030
Final sector	85	121	155	186	221	259	305
Primary	1	2	4	5	7	10	14

Secondary	59	87	108	127	147	171	202
Commercial	2	3	5	7	10	13	18
Transportation	16	22	31	40	49	56	63
Residential	7	7	7	8	8	8	8
Transformation sector	51	50	63	74	88	101	118
TOTAL	136	171	218	260	309	360	423

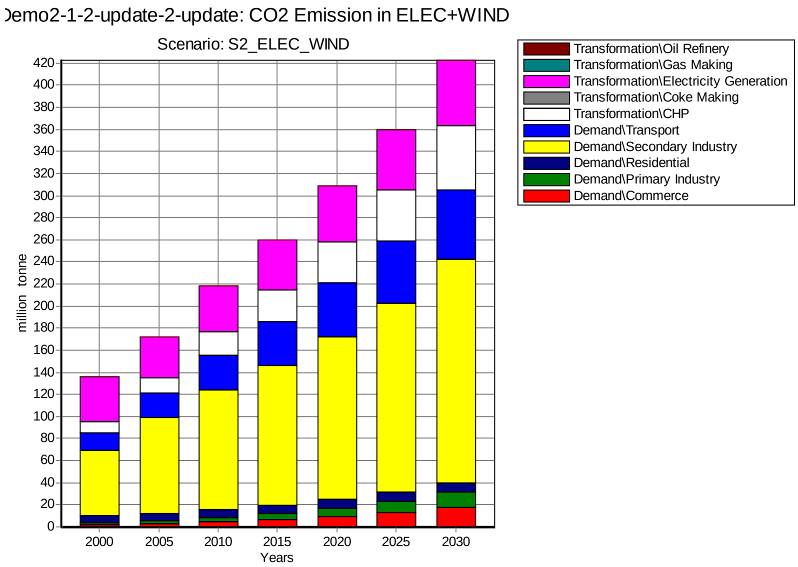

Figure 7-10 CO_2 emission in ELEC+WIND scenario

3.3.4. SO_2 Emission

In the ELEC+WIND scenario, total SO_2 emission of Shanghai is 1.55 Mt in 2030, an increase of 3.4 times from 2000, and a decrease of 4.9 percent from the BAU scenario (1.63 Mt). Industry emits 59.7 percent of total SO_2; electricity generation, 35.5 percent.

Table 7-16 SO_2 emission in ELEC+WIND scenario, Unit: 10,000 metric tons

	2000	2005	2010	2015	2020	2025	2030
Final sector	20.8	30.5	39.8	50.5	63.5	79.6	100.0
Primary	0.2	0.4	0.5	0.8	1.1	1.5	2.1
Secondary	17.7	27.1	36.0	46.2	58.5	73.6	92.7
Commercial	0.3	0.4	0.7	1.0	1.4	1.9	2.6
Transportation	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Residential	2.7	2.6	2.6	2.5	2.5	2.6	2.6
Transformation sector	25.3	23.4	29.3	34.7	41.1	47.5	55.5
TOTAL	46.1	53.9	69.1	85.2	104.6	127.0	155.4

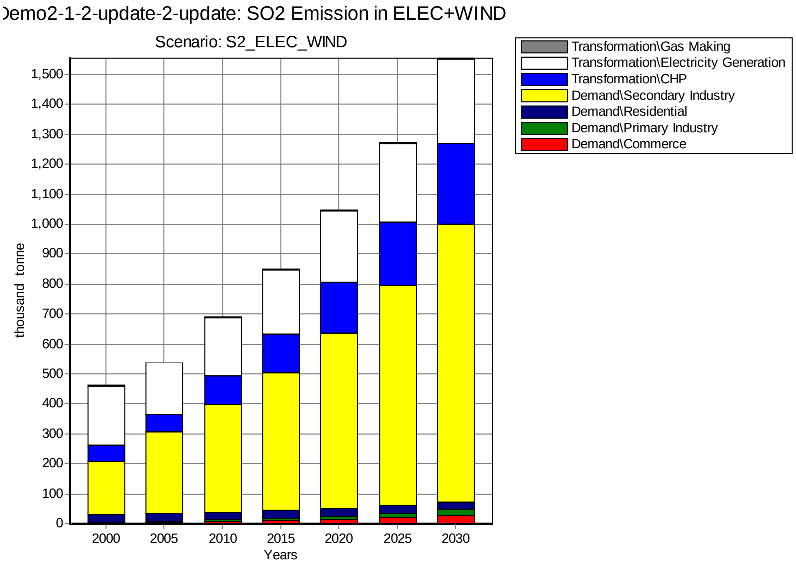

Figure 7-11 SO_2 emission in ELEC+WIND scenario

3.3.5. PM Emission

Table 7-17 and Figure 7-12 show PM pollutant levels in the ELEC+WIND scenario. In this scenario, total Shanghai PM emission is 565 Mt in 2030, 3.9 times more than in 2000, and 4 percent less than in the BAU scenario (589 Mt). Industry emits 66.9 percent of this total; the electricity generation sector, 28.9 percent.

Table 7-17 PM emission in ELEC+WIND scenario, Unit: 10,000 metric tons

	2000	2005	2010	2015	2020	2025	2030
Final sector	7.2	10.9	14.7	19.2	24.6	31.6	40.2
Primary	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Secondary	6.3	9.9	13.4	17.7	22.8	29.5	37.8
Commercial	0.0	0.1	0.1	0.1	0.2	0.3	0.4
Transportation	0.4	0.5	0.7	0.9	1.1	1.3	1.5
Residential	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Transformation sector	7.2	6.6	8.4	10.1	12.0	13.9	16.3
TOTAL	14.4	17.5	23.1	29.3	36.7	45.5	56.5

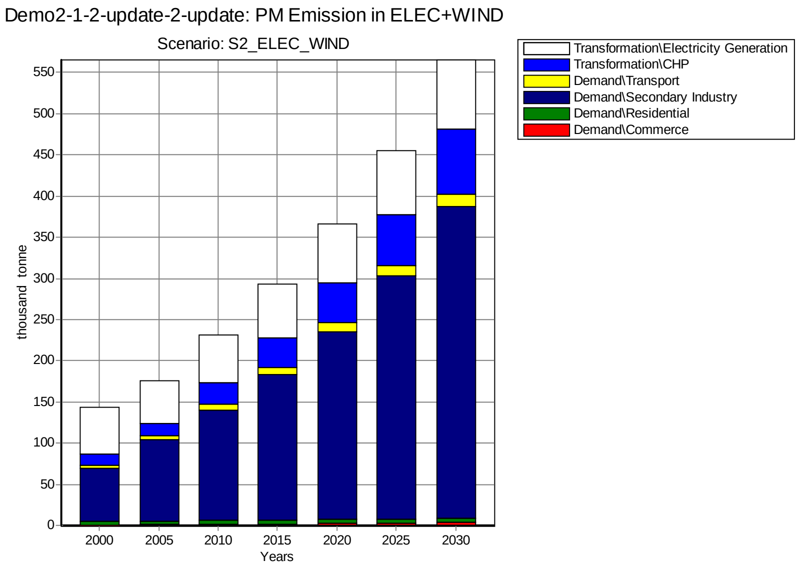

Figure 7-12　PM emission in ELEC+WIND scenario

3.4. Comprehensive Low-Carbon Development Scenario

This comprehensive low-carbon development scenario combines all the low-carbon policies we just looked at, EE, COAL, GAS, ELEC, and WIND. That is, this scenario includes final consumption energy-efficiency improvement, energy technology update, final direct coal-burning reduction, substitution of natural gas for pipe coal gas, and natural gas and wind power generation.

3.4.1. Final Energy Demand

Table 7-18 shows Shanghai's final energy demand by energy carrier in the comprehensive low-carbon scenario. In this scenario, final energy demand is grows at an average annual rate of 3.7 percent over the 2000-2030 period, reaching 3591PJ (123 Mtce) in 2030. Final energy consumption in 2030 is 29.5 percent lower than in the BAU scenario (5097 PJ, see Chapter 6).

Final coal consumption in this scenario is 113 PJ (4.58 Mt) in 2030; final hard coal consumption is 41 PJ (1.85 Mt), and final coking coal consumption is 72 PJ (2.73 Mt). Final coal consumption in this scenario is 40.8 Mt lower than in the BAU scenario.

Table 7-18　Final energy demand in low-carbon scenario, Unit: PJ

Energy Carriers	2000	2005	2010	2015	2020	2025	2030	Annual Growth
Solid Fuel	415	553	538	505	465	467	465	0.4%
Liquid Fuel	299	418	575	723	887	1007	1137	4.6%
Gaseous Fuel	155	223	397	547	686	811	942	6.2%

Other Fuels	98	142	173	194	230	228	244	3.1%
Electricity	191	260	329	398	472	553	645	4.1%
Heat	48	66	84	101	123	137	157	4.0%
TOTAL	1204	1662	2093	2466	2862	3203	3591	3.7%

Table 7-19 shows final energy demand by sector. In this scenario, by 2030 industry energy consumption is 2042 PJ, 57 percent of total final consumption; transportation energy consumption is 962 PJ, 27 percent of total final consumption.

Table 7-19 Energy demand in final sectors in low-carbon scenario, Unit: PJ

	2000	2005	2010	2015	2020	2025	2030
Primary	25	37	50	66	83	104	127
Secondary	797	1115	1353	1533	1718	1872	2058
Commercial	63	93	129	170	216	269	332
Transportation	228	326	466	600	742	852	962
Residential	91	93	95	99	102	107	111
TOTAL	1204	1662	2093	2467	2861	3203	3591

3.4.2. Primary Energy Demand

Total primary energy import in this comprehensive low-carbon scenario is 2685 PJ in 2030 (see Table 7-20 and Figure 7-13). Coal demand is 1350 PJ, 50.3 percent of total primary energy demand; crude oil demand is 745 PJ, 27.8 percent of total primary energy demand; and natural gas demand is 590 PJ, 22.0 percent of total primary energy demand.

Natural gas demand rises from 79 PJ (two billion m^3) in 2005 to 590 PJ (15.1 billion m^3) in 2030.

Table 7-20 Primary energy demand in low-carbon scenario, Unit: PJ

	2000	2005	2010	2015	2020	2025	2030
Crude oil	545	744	745	745	745	745	745
Natural gas	8	79	209	318	412	502	590
Coal	1040	1060	1101	1142	1205	1268	1350
TOTAL	1593	1884	2055	2204	2361	2514	2685

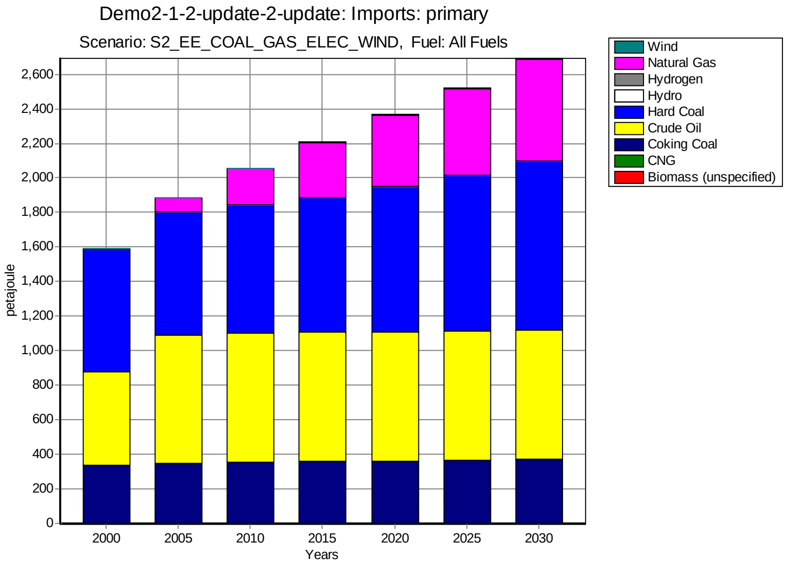

Figure 7-13 Primary energy demand in low-carbon scenario

3.4.3. CO_2 Emission

Table 7-21 and Figure 7-14 illustrate CO_2 emissions in future Shanghai under the comprehensive low-carbon scenario. Total CO_2 emission reaches 304 Mt in 2030, 2.2 times of the emission level in 2000, but a reduction of 30.3 percent from the BAU scenario (436 Mt). Industry emits 40 percent of this total; the power generation sector, 32 percent; and the transportation sector, 21 percent.

Table 7-21 CO_2 emission in low-carbon scenario, Unit: million metric tons

	2000	2005	2010	2015	2020	2025	2030
Final sector	85.0	115.5	138.5	156.1	174.4	190.3	208.0
Primary	1.4	2.1	2.9	3.8	4.8	5.9	7.0
Secondary	59.2	82.4	94.9	101.8	108.9	115.2	123.0
Commercial	1.9	2.6	3.6	4.8	6.1	7.5	9.2
Transportation	15.6	22.0	31.3	40.0	49.0	56.1	63.2
Residential	6.9	6.4	5.8	5.7	5.6	5.6	5.6
Transformation sector	51.2	50.7	60.6	69.2	79.1	86.9	95.9
TOTAL	136.2	166.2	199.1	225.3	253.5	277.2	303.9

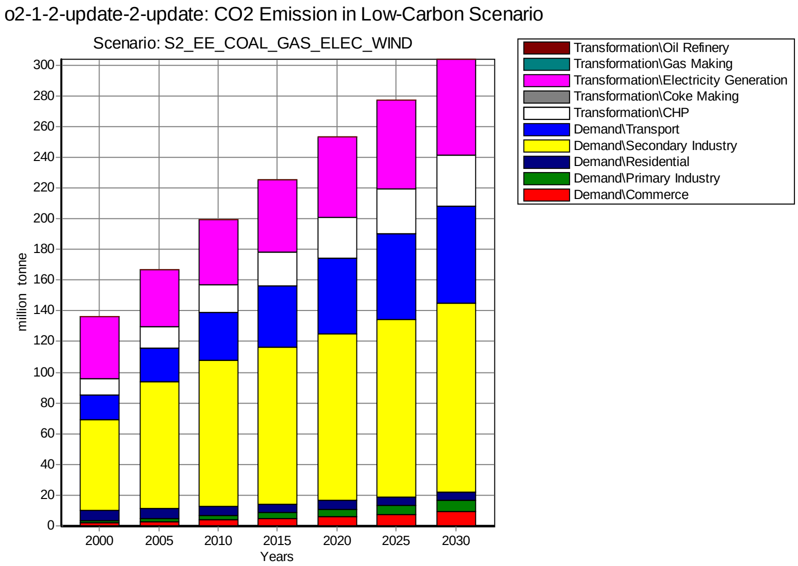

Figure 7-14 CO_2 emission in low-carbon scenario

3.4.4. SO_2 Emission

In the comprehensive low-carbon scenario, total SO_2 emission is 594 Kt in 2030, 1.3 times 2000 emission levels, and a 63.6 percent reduction from the BAU scenario (1.63 Mt). Industry emits 20.1 percent and electricity generation 77.3 percent of this total.

Table 7-22 SO_2 emission in low-carbon scenario, Unit: 10,000 metric tons

	2000	2005	2010	2015	2020	2025	2030
Final sector	20.8	26.7	21.7	17.5	15.2	13.7	13.2
Primary	0.2	0.3	0.3	0.3	0.3	0.3	0.2
Secondary	17.7	24.2	19.9	16.2	14.3	12.9	12.5
Commercial	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Transportation	0	0	0	0	0	0	0
Residential	2.7	2.0	1.2	0.7	0.4	0.2	0.1
Transformation sector	25.3	23.8	28.6	33.0	37.8	41.7	46.2
TOTAL	46.1	50.5	50.3	50.5	53.0	55.4	59.4

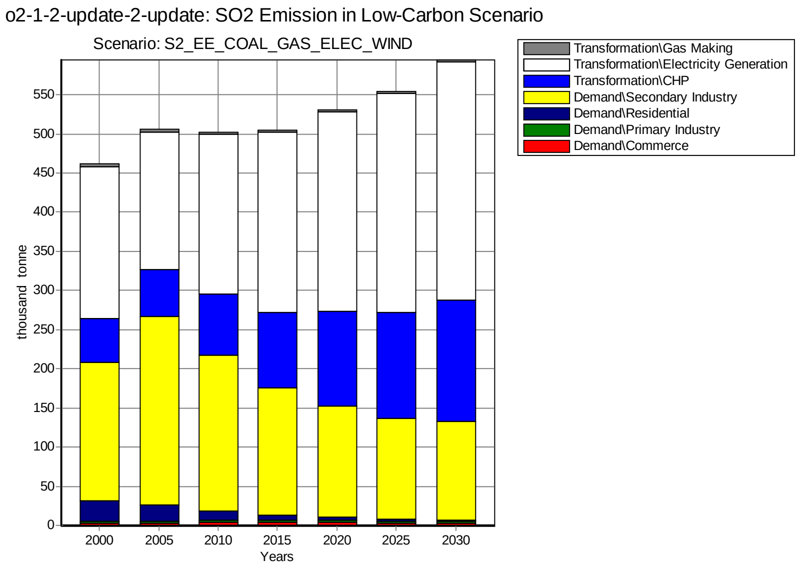

Figure 7-15 SO_2 emission in low-carbon scenario, Unit: 1,000 metric tons

3.4.5. PM Emission

Table 7-23 and Figure 7-16 show PM emission levels in the comprehensive low-carbon scenario. Total PM emission in Shanghai is 171 Kt in 2030, an increase of 1.2 times from 2000, and a decrease of 71.0 percent from the BAU scenario (589 Kt). Industry emits 12.3 percent and electricity generation 76.3 percent of this total.

Table 7-23 PM emission in low-carbon scenario, Unit: 10,000 metric tons

	2000	2005	2010	2015	2020	2025	2030
Final sector	7.2	9.5	7.4	5.7	4.7	4.2	4.1
Primary	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Secondary	6.3	8.6	6.3	4.6	3.4	2.7	2.4
Commercial	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Transportation	0.4	0.5	0.7	0.9	1.1	1.3	1.5
Residential	0.5	0.4	0.3	0.2	0.2	0.1	0.1
Transformation sector	7.2	6.7	8.0	9.3	10.7	11.8	13.1
TOTAL	14.4	16.2	15.4	15.0	15.4	16.0	17.1

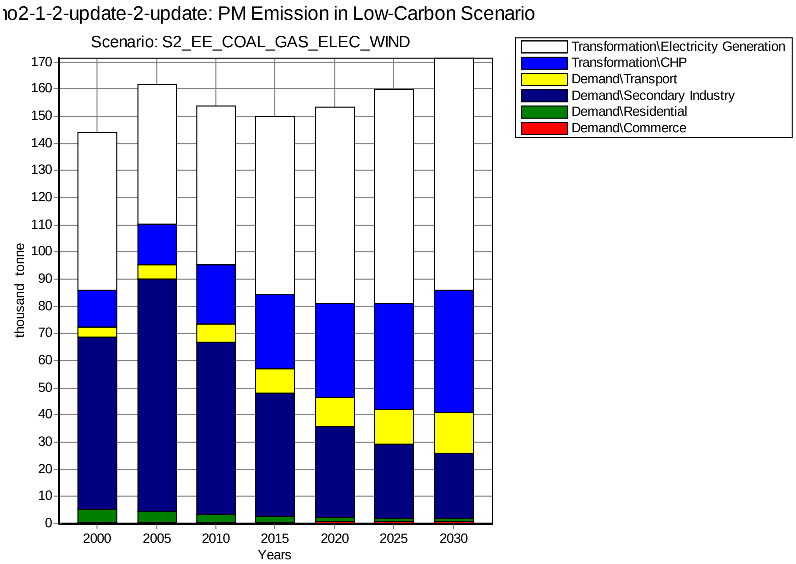

Figure 7-16　PM emission in low-carbon scenario

4. Comprehensive Low-Carbon Development and End-Treatment Scenarios

As Shanghai electricity use grows, so will coal use and SO_2 emissions from coal-burning power plants. The integrated scenarios discussed here combine low-carbon energy production with end-pipe power plant sulfur removal to better control SO_2 levels.

In the first such scenario, which enacts smoke desulfuration policies, total SO_2 emission in Shanghai is reduced from 484 Kt in 2005 to 319 Kt in 2030, an 80.5 percent reduction from 2030 BAU scenario levels (1634 Kt). Industry emits 37.3 percent and power plants emit 57.8 percent of this total.

Table 7-24　SO_2 emission in "Low-Carbon+SO2a" scenario, Unit: 10,000 metric tons

	2000	2005	2010	2015	2020	2025	2030
Final sector	20.8	26.7	21.7	17.5	15.2	13.7	13.2
Primary	0.2	0.3	0.3	0.3	0.3	0.3	0.2
Secondary	17.7	24.2	19.9	16.2	14.3	12.9	12.5
Commercial	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Transportation	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Residential	2.7	2.0	1.2	0.7	0.4	0.2	0.1
Transformation sector	25.3	21.7	21.2	20.3	19.9	19.1	18.7
TOTAL	46.1	48.4	42.9	37.8	35.2	32.8	31.9

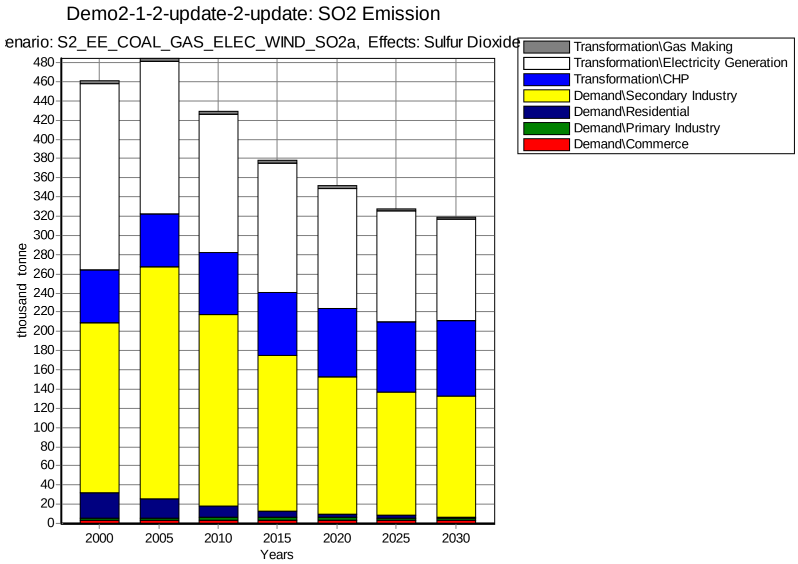

Figure 7-17 SO_2 emission in "Low-Carbon+SO2a" scenario, Unit: 1,000 metric tons

To further reduce SO_2 emission and improve air quality, a second scenario, which combines fuel oil and coal sulfur-content control with the previous scenario's smoke desulfuration policies, was also analyzed. In this scenario, fuel oil sulfur content must be less than one percent, and final direct burning coal sulfur content must be less than eight percent. If such restrictions were implemented, SO_2 emission in Shanghai would be 285 Kt in 2030, a reduction of nearly 83 percent from the BAU scenario and 60 percent 2000 emission levels.

Table 7-25 SO_2 emission in "Low-Carbon+SO2b" scenario, Unit: 10,000 metric tons

	2000	2005	2010	2015	2020	2025	2030
Final sector	20.8	17.7	14.8	12.4	11.2	10.3	10.2
Primary	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Secondary	17.7	16.1	13.7	11.6	10.6	9.8	9.8
Commercial	0.3	0.2	0.2	0.2	0.2	0.2	0.2
Transportation	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Residential	2.7	1.3	0.7	0.4	0.3	0.2	0.1
Transformation sector	25.3	21.5	20.9	20.0	19.6	18.7	18.3
TOTAL	46.1	39.2	35.8	32.4	30.8	29.1	28.5

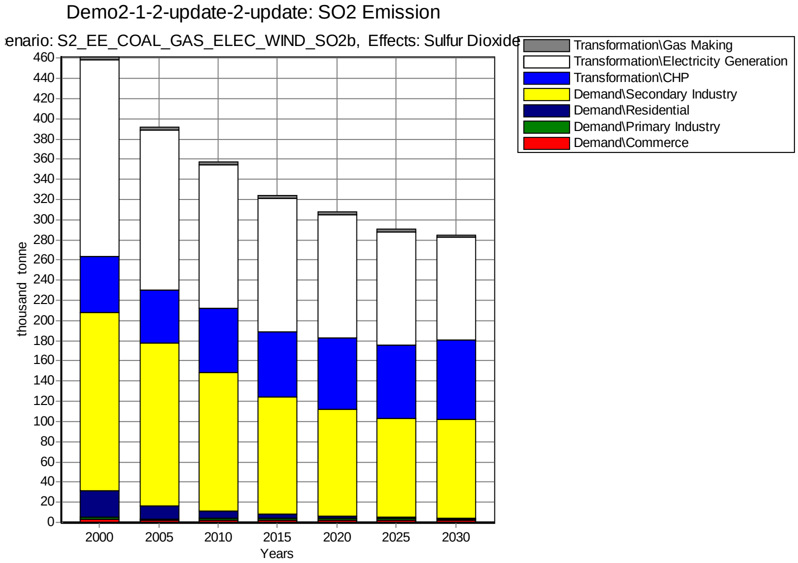

Figure 7-18 SO_2 emission in "Low-Carbon+SO2b" scenario, Unit: 1,000 metric tons

A third scenario combines the preceding measures with increased PM emission control. Under this scenario, PM emission in Shanghai falls to 57 Kt in 2030, a 60 percent reduction from 2000 levels (144 Kt). PM emissions from final sectors fall to 29 Kt, 28 Kt of which is from power plants (see Table 7-26 and Figure 7-19).

Table 7-26 PM Emission in "Low-Carbon+SO2b+PM" scenario, Unit: 10,000 metric tons

	2000	2005	2010	2015	2020	2025	2030
Final sector	7.2	6.3	4.9	3.9	3.3	3.0	2.9
Primary	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Secondary	6.3	5.3	4.0	3.0	2.3	2.0	2.0
Commercial	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Transportation	0.4	0.5	0.6	0.7	0.7	0.8	0.8
Residential	0.5	0.4	0.3	0.2	0.2	0.1	0.1
Transformation sector	7.2	5.9	6.0	5.7	5.2	4.1	2.8
TOTAL	14.4	12.1	10.9	9.6	8.4	7.1	5.7

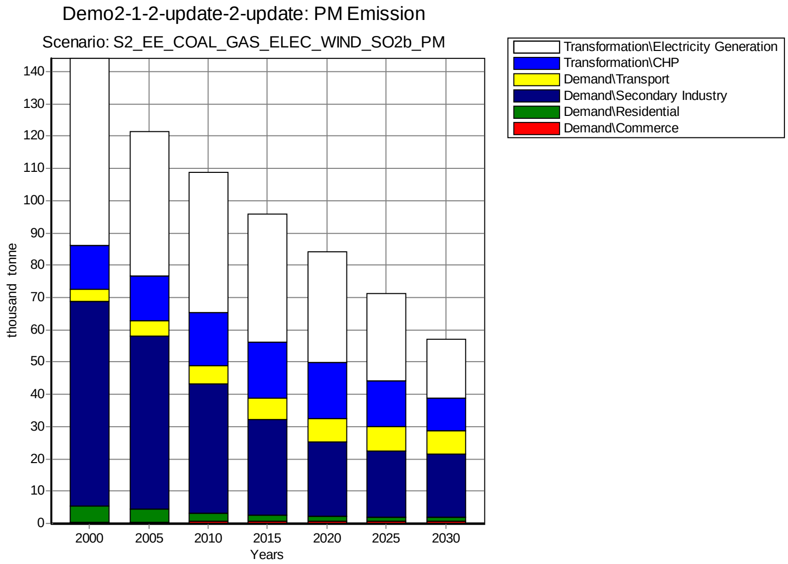

Figure 7-19 PM emission in “Low-Carbon+SO2b+PM” scenario, Unit: 1,000 metric tons

We developed one final scenario with heightened SO_2 emission control designed to meet the needs of the 2010 World Expo. In this scenario, SO_2 emission in 2010 is 338 Kt, 131 Kt of which is from final sectors and 206 Kt of which is from the energy transformation sector. By 2030, SO_2 emission drops to 183 Kt, 51 Kt of which is from final sectors and 132 Kt of which is from the energy transformation sector.

Table 7-27 SO_2 emission in “Expo” scenario, Unit: 10,000 metric tons

	2000	2005	2010	2015	2020	2025	2030
Final sector	20.8	17.5	13.1	9.8	7.7	6.1	5.1
Primary	0.2	0.2	0.2	0.1	0.1	0.1	0.1
Secondary	17.7	15.9	12.1	9.1	7.3	5.8	4.9
Commercial	0.3	0.2	0.2	0.2	0.1	0.1	0.1
Transportation	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Residential	2.7	1.3	0.7	0.4	0.2	0.1	0.0
Transformation sector	25.3	21.4	20.6	18.5	16.9	14.9	13.2
TOTAL	46.1	38.9	33.8	28.3	24.6	21.0	18.3

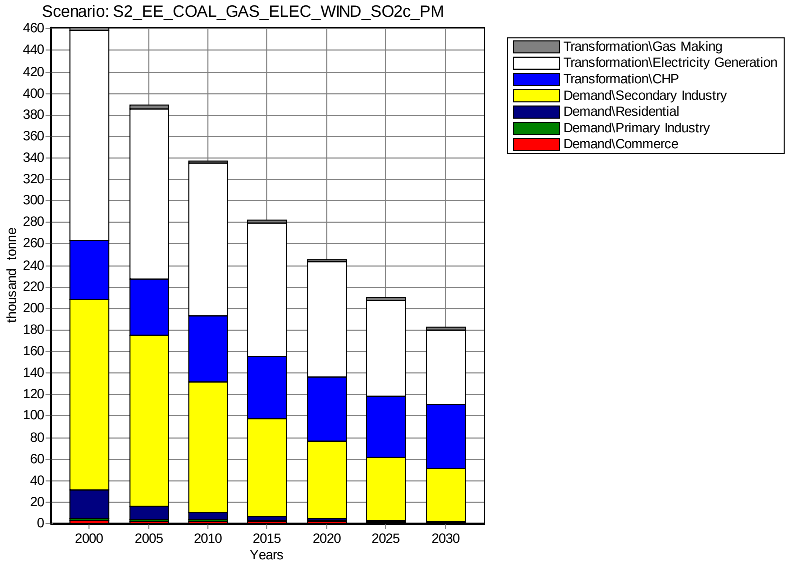

Figure 7-20 SO_2 emission in “Expo” scenario, Unit: 1,000 metric tons

5. Summary

In this chapter we analyzed several low-carbon development and end-treatment policy scenarios. Policies considered included final sector energy intensity reduction (energy efficiency and technology improvements), low-carbon energy switch (substitution of natural gas for hard coal and pipe coal gas), low-carbon power generation (natural gas and wind power generation), and end-pipe treatment (power plant sulfur removal, fuel sulfur content control, and soot emission control). This analysis yielded the following results:

(1) While economic growth and Shanghai’s industrial structure ensure energy demand and CO_2 emission will increase in the future, other factors can significantly influence the rates of such growth. These factors include energy production processes and technology, energy-efficiency policies, and Shanghai’s energy consumption structure.

(2) Comparison of the tested scenarios shows energy-efficiency policy implementation and energy technology update can substantially reduce final sector energy demand and lower emissions. In the EE scenario, final energy demand in 2030 is 30 percent lower than in the BAU scenario; CO_2 emission is 24 percent lower; SO_2 emission is 33 percent lower; and PM emission is 36 percent lower.

(3) Substituting the use of low-carbon energy sources, such as natural gas, for final direct coal burning would substantially reduce traditional air pollutant and CO_2 emissions. In the low-carbon development scenario, final coal demand in 2030 is only 6.5 Mt, 38.88 Mt less than in the BAU scenario. In this scenario, SO_2

emissions are 49 percent less than in the BAU scenario, and PM emissions are 58 percent less.

(4) In the low-carbon development scenario, as natural gas replaces coal use, natural gas substantially increases. Natural gas demand reaches 79 PJ (nearly 2.0 billion m^3) by 2005. Natural gas will be imported from western China, the East China Sea, and foreign countries to meet this demand.

(5) Combining the comprehensive low-carbon development scenario with end-pipe treatment is the most effective way to reduce emissions. In these scenarios, coal consumption is 50 Mt in 2005. CO_2 emission growth rates are reduced: CO2 emissions grow at an average annual rate of 2.7 percent over the 2000-2030 period, reaching 306 Mt in 2030. This is a 30 percent reduction from the BAU scenario.

In the combined "SO_2b+PM" scenario, SO_2 emissions are reduced at an average annual rate of 1.6 percent, falling to 285 Kt by 2030. This is a decrease of 83 percent from the BAU scenario. PM emissions are reduced by an average annual rate of 3.0 percent, falling to 57 Kt by 2030 and yielding an overall reduction of 90 percent from the BAU scenario.

(6) The Expo scenario reduces SO_2 emissions even further. In this scenario, SO_2 emissions in 2010 would be 338 Kt, 131 Kt of which is from final sectors and 206 Kt of which is from the energy transformation sector. SO_2 emissions would drop to 183 Kt by 2030, 51 Kt of which is from final sectors and 132 Kt of which is from the energy transformation sector.

(7) Table 7-28, below, compares energy consumption and emission levels in 2010 and 2020 in the scenarios we analyzed.

Table 7-28a Scenario comparison of energy use and emissions in 2010

Scenario		Final (PJ)	Primary (PJ)	Total Use (PJ)	Coal Use (10,000 t)	CO_2 emission (100 Mt)	SO_2 emission (10,000 t)	PM emission (10,000 t)
2000		1204	1593	1546	4478	1.36	46.1	14.4
2010	A	2298	2200	2733	6274	2.26	74.5	24.7
	B	2093	2100	2512	5834	2.11	66.6	21.6
	C	2093	2111	2512	5234	2.05	54.4	16.8
	D	2093	2055	2480	4740	1.99	50.3	15.4
	E	2093	2059	2480	4766	2.00	42.9	15.5
	F	2093	2059	2480	4766	2.00	35.8	15.5
	G	2093	2059	2480	4766	2.00	35.8	10.9
	H	2093	2059	2480	4766	2.00	33.8	10.9

A--BAU

B--EE

C--EE+COAL+GAS

D--EE+COAL+GAS+ELEC+WIND

E--EE+COAL+GAS+ELEC+WIND+SO2a

F--EE+COAL+GAS+ELEC+WIND+SO2b

G--EE+COAL+GAS+ELEC+WIND+SO2b+PM

H--EE+COAL+GAS+ELEC+WIND+SO2c+PM

Table 7-28b Scenario comparison of energy use and emissions in 2020

Scenario		Final (PJ)	Primary (PJ)	Total Use (PJ)	Coal Use (10,000 t)	CO_2 emission (100 Mt)	SO_2 emission (10,000 t)	PM emission (10,000 t)
2000		1204	1593	1546	4478	1.36	46.1	14.4
2020	A	3505	2728	4071	8599	3.19	111.1	38.6
	B	2862	2418	3380	7243	2.74	87.1	29.3
	C	2862	2438	3380	5757	2.60	56.9	16.9
	D	2862	2361	3341	5204	2.54	53.0	15.4
	E	2862	2374	3341	5266	2.55	35.2	15.5
	F	2093	2059	3341	4766	2.00	30.8	15.5
	G	2093	2059	3341	4766	2.00	30.8	8.4
	H	2093	2059	3341	4766	2.00	24.6	8.4

A--BAU

B--EE

C--EE+COAL+GAS

D--EE+COAL+GAS+ELEC+WIND

E--EE+COAL+GAS+ELEC+WIND+SO2a

F--EE+COAL+GAS+ELEC+WIND+SO2b

G--EE+COAL+GAS+ELEC+WIND+SO2b+PM

H--EE+COAL+GAS+ELEC+WIND+SO2c+PM

Chapter 8. Low Carbon Development and Air Pollution Exposure

1. Air Pollution Prediction Model

In this study, we used ATMOS[1,2] to make Shanghai air quality projections. ATMOS is a Linux-based air-quality model system developed by the University of Iowa. We used the system to predict concentration distributions of air pollutants based on the emission data provided by LEAP and provide pollution exposure figures for estimating pollution's public health impact.

We created a concentration matrix representing unit source strength of SO_2 and PM_{10} for a 6341 km^2 area (30.655^o S to 31.855^o N latitude; 121.983^o E to 120.814^o W longitude) of Shanghai. This area encloses 924 32-by-28 grids (only inhabited grids are considered for pollution exposure in this project). This concentration matrix was linked to the Windows-based transfer matrix system used for low-carbon development scenario analysis using Shanghai Air Pollution Sources geographic information system (GIS). This obviates the need to manually model air quality for each scenario; instead, the transfer matrix system automatically shows pollution exposure projections based on each scenario.

The ATMOS model is a Lagrangian plume trajectory model with three vertical layers. The model calculates ambient concentrations, and wet and dry deposition of SO_2, sulfates, and PM_{10} resulting from area and large point sources. Within the modeling domain, SO_2 and PM_{10} emission plumes are modeled as puffs released every three hours from the emission source location. Each puff is assigned a mass proportional to the source strength, and is assumed to mix uniformly in the vertical throughout an assigned layer and diffuse according to a Gaussian distribution in the horizontal. Area emissions are modeled as surface sources (released at the center of the grid) while large point sources are treated as elevated sources. Individual emission puffs are followed throughout their transport and deposition "lifetimes." Each puff's transport is followed for up to five days (or until the mass falls below a cut-off value). Meteorological data from NOAA-CIRES Climate Diagnostics Center is also put into the model four times per day, in spatial resolution of 2.5 degrees longitude/latitude. The wind field for each calculation time step is calculated by linear interpolation of continuous meteorological data.

2. Low-Carbon Development and Emission Inventory

Of all the scenarios analyzed using the LEAP model, only six representative ones were selected for further air quality prediction: BAU, EE, EE+COAL+GAS, EE+ COAL+GAS+ELEC+WIND, EE+COAL+GAS+ELEC+WIND+SO_2b+PM, and EE+COAL+GAS+ELEC+WIND+SO_2c+PM (see Table 8-1). The year 2000 was set as the base year, and air quality projections were made for the subsequent 30 years, in five-year intervals.

Pollution locations and the distribution of industry among its subsectors were predicted using data from 2000, along with Shanghai's urban development and industrial re-structuring plans. Emission levels were adjusted in three areas of Shanghai: the main urban area, the area between the inner and outer ring roads, and the area outside the outer ring road. Using the year 2000 Shanghai Air Pollution Sources GIS, emissions data from the LEAP model were divided among 8 (sub)sectors—power plants, energy transfer, industrial furnaces, medium and small boilers, motor vehicles, commerce, housing, and agriculture.

In Table 8-2 summarizes total SO_2 and PM_{10} emissions for each of the six tested scenarios. Only in the fifth and sixth scenarios do emissions actually decrease from their 2000 levels.

Table 8-1 Low-carbon scenarios for pollution exposure prediction

	Scenarios	Definitions
1	BAU	BAU (medium economy growth)
2	EE	Energy intensity reduction
3	EE+COAL+GAS	Energy intensity reduction + natural gas shift for coal and pipe coal gas
4	EE+COAL+GAS+ELEC+WIND	Energy intensity reduction + natural gas shift for coal and pipe coal gas+ natural gas and wind electricity generation
5	EE+COAL+GAS+ELEC+WIND+SO_2b+PM	Energy intensity reduction + natural gas shift for coal and pipe coal gas+ natural gas and wind electricity generation + sulfur smoke removal + fuel sulfur content control + soot control
6	EE+COAL+GAS+ELEC+WIND+SO_2c+PM	Most effective scenario: Previous scenario + additional fuel sulfur content control

Table 8-2 SO_2 and PM_{10} emissions for selected scenarios, Unit: 1,000 metric tons/year

Scenarios \ Year		2000	2005	2010	2015	2020	2025	2030
Scenario 1	SO_2	461	583	745	909	1111	1342	1634
	PM_{10}	144	188	247	310	386	476	589
Scenario 2	SO_2	461	555	666	764	871	972	1088
	PM_{10}	144	177	216	254	293	333	378
Scenario 3	SO_2	461	545	544	544	569	592	633
	PM_{10}	144	174	168	165	169	176	189
Scenario 4	SO_2	461	505	503	505	530	554	594
	PM_{10}	144	162	154	150	154	160	171
Scenario 5	SO_2	461	392	358	324	308	291	285
	PM_{10}	144	121	109	96	84	71	57
Scenario 6	SO_2	461	389	338	283	246	210	183

	PM_{10}	144	121	109	96	84	71	57

3. Pollution Exposure Forecasts

3.1. Pollution Exposure and Population Distribution in 2000

3.1.1. SO_2 and PM_{10} Pollution Exposure in 2000

Total SO_2 emission in 2000 was 461,000 metric tons. As depicted in our model, Shanghai's northern suburban area has relatively high SO_2 concentrations, and average SO_2 concentration in Shanghai's central urban areas is higher than in the outskirts (see Figure 8-1). The average annual concentration of SO_2 in urban areas was 0.044 mg/m^3; in the city as a whole, 0.018 mg/m^3.

In northern Baoshan, annual SO_2 concentration in one grid exceeded the Grade II national criterion of 0.06 mg/m^3; annual SO_2 concentration in 3216 km^2 of Shanghai fell between the Grade I and Grade II criteria (< 0.06 mg/m^3 and >= 0.02 mg/m^3). In the rest of the city, SO_2 concentrations satisfied the Grade I national criterion.

Ambient PM_{10} concentration is composed of primary and secondary PM_{10}. Total PM_{10} concentration is the sum of background PM_{10} concentration and LEAP's projected primary PM_{10} emission concentrations. In 2000, total primary PM_{10} emission was about 144,000 metric tons. The simulated concentration of PM_{10} in urban areas was 0.108 mg/m^3, and in the city as a whole, 0.087 mg/m^3. No grid exceeded the PM_{10} Grade III national criterion of 0.150 mg/m^3; a 1168 km^2 area of Shanghai exceed the Grade II national criterion of 0.100 mg/m^3; a 1536 km^2 area had a concentration falling between 0.090 and 0.100 mg/m^3; Shanghai's remaining 5088 km^2 had a PM_{10} concentration falling between 0.07 and 0.09 mg/m^3.

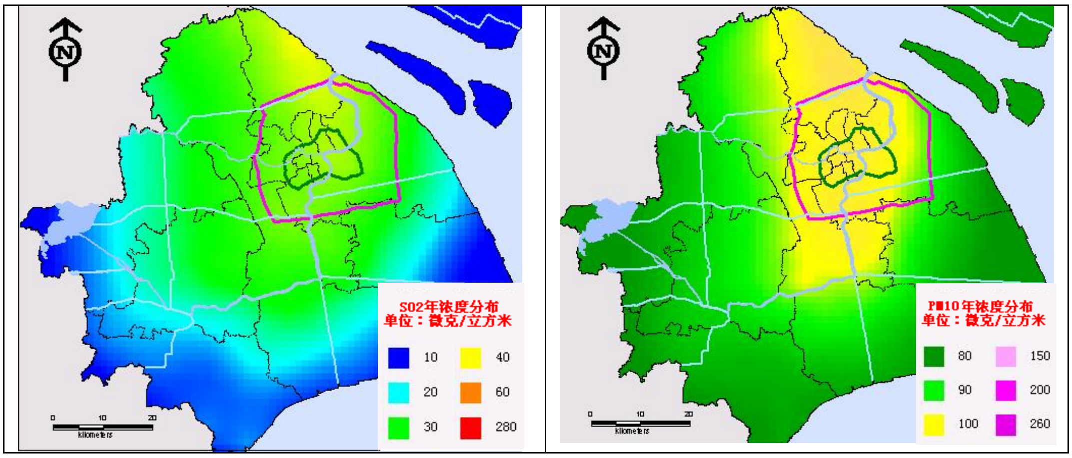

Figure 8-1 SO_2 and PM_{10} exposure levels in Shanghai, 2000

Table 8-3 Annual concentrations of SO_2 and PM_{10} in Shanghai, 2000, Unit: µg/m^3

	SO_2		PM_{10}	
Annual Concentration	City wide	18	City wide	87
	Urban	44	Urban	108
	Concentration	Area	Concentration	Area
Area (km^2)	>100	0	>150	0
	60-100	16	100-150	1168
	20-60	3216	90-100	1536
	0-20	4560	70-90	5088
	Total	7792	Total	7792

3.1.2. Population Distribution in 2000

Figure 8-2 shows the population distribution of Shanghai in 2000. Population data was obtained through a census conducted in 100 counties and townships. The population assigned to each grid is an area-weighted average of the counties and townships it encloses.

All located downtown, 13 squares covering 208 km^2 in total area have extremely high population density. Among these, Huangpu, Hongkou, Luwan, and Zhabei districts have the very highest population density, 36,000-57,000 persons/km^2. Five squares, mainly are distributed in Zhabei and Yangpu districts, have a population density of 21,000-24,000 persons/km^2. Four squares, mainly distributed in Changning and Yangpu districts, have a population density of 15,800-16,700 persons/km^2. Population density is lower, 1,000-3,000 persons/km^2, in Baoshan, Jiading, the Pudong new area, and Minhang, all located outside the outer ring road. The suburban areas Qingpu, Jinshan, Nanhui, and Fengxian are relatively sparsely populated, with a population density of about 800-1,000 persons/km^2. Chongming county has the lowest population density, less than 600 persons/km^2.

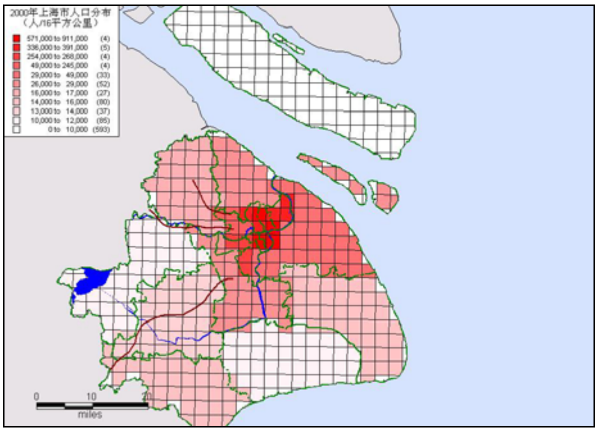

Figure 8-2 Shanghai population distribution, 2000

We also calculated the population-weighted concentrations of SO_2 and PM_{10} in

2000. City-wide population-weighted SO_2 concentration was 0.033 mg/m^3, an 83 percent increase from the un-weighted 0.018 mg/m^3. Population-weighted SO_2 concentration in central urban areas was 0.045 mg/m^3, a two percent increase from the un-weighted 0.044 mg/m^3.

City-wide population-weighted SO_2 concentration was significantly higher than the arithmetic mean concentration, reflecting the close relationship between population density and SO_2 concentration distribution. Also, SO_2 concentrations in high-population urban areas are much higher than those in relatively sparsely-populated suburban areas; thus, more people live in seriously polluted areas than in lightly-polluted areas.

Population-weighted PM_{10} concentration, on the other hand, was not significantly different from the arithmetic mean concentration. City-wide population-weighted PM_{10} concentration was 0.100 mg/m^3, only 15 percent higher than the un-weighted 0.087 mg/m^3. Population-weighted PM_{10} concentration in central urban areas was 0.110 mg/m3, only a 2 percent increase from the un-weighted 0.108 mg/m^3. The spatial distribution of PM_{10} is relatively uniform and has no obvious correlation with population distribution.

Table 8-4 Population-weighted concentration of SO_2 and PM_{10} in Shanghai, Unit: mcg/m^3

		SO_2	PM_{10}
City wide	Average concentration	18	87
	Population-weighted mean	33	100
Urban	Average concentration	44	108
	Population-weighted mean	45	110

3.2. Exposure Levels under Low-Carbon Development Scenarios

3.2.1. BAU scenario

Under the BAU scenario, average annual urban SO_2 concentration will increase dramatically, reaching 0.247 mg/m^3 by 2030, 5.6 times SO_2 concentration in 2000. Total land area exceeding the SO_2 Grade II national standard will increase from 16 km^2 in 2000 to 5424 km^2 in 2030. The majority of Shanghai will exceed this criterion by 2030, with only some areas along Hangzhou bay in Jinshan, Fengxian, and Nanhui districts meeting the standard (see Figure 8-3).

Average annual urban PM_{10} concentration will also greatly increase under the BAU scenario, reaching 0.249 mg/m^3 by 2030, 2.3 times PM_{10} concentration in 2000. The area exceeding the PM_{10} Grade II national standard will increase from 16 km^2

in 2000 to 7792 km^2 in 2030, covering essentially the entirety of Shanghai.

Table 8-5 Predicted annual concentration of SO_2 in Shanghai under the BAU scenario, Unit: mcg/m^3

Year		2000	2005	2010	2015	2020	2025	2030
Annual average concentration, city wide		18	30	39	48	60	74	91
Annual average concentration, urban		44	79	103	129	161	199	247
Area Distribution (km^2)	Concentration	Area						
	>100	0	0	400	1024	1680	2288	3152
	60-100	16	1120	1504	1664	1872	2160	2272
	20-60	3216	4352	5008	5104	4240	3344	2368
	0-20	4560	2320	880	0	0	0	0
	Total	7792	7792	7792	7792	7792	7792	7792

Table 8-6 Predicted annual concentration of PM_{10} in Shanghai under the BAU scenario, Unit: mcg/m^3

Year		2000	2005	2010	2015	2020	2025	2030
Annual average concentration, city wide		87	93	101	109	119	131	146
Annual average concentration, urban		108	123	141	160	184	212	249
Area Distribution (km^2)	Concentration	Area						
	>150	0	0	64	656	1360	2160	3136
	100-150	16	2288	3488	4368	5216	5632	4656
	90-100	3216	1968	2512	2768	1216	0	0
	70-90	4560	3536	1728	0	0	0	0
	Total	7792	7792	7792	7792	7792	7792	7792

3.2.2. EE Scenario

Under the EE scenario, average annual urban SO_2 concentrations are significantly better than in the BAU scenario. SO_2 concentrations are 0.089, 0.119, and 0.152 mg/m^3, down from 0.103, 0.161, and 0.247 mg/m^3 under BAU scenario, in 2010, 2020, and 2030, respectively. These concentrations are 2.0, 2.7, and 3.4 times the urban SO_2 concentration in 2000. The total area exceeding the SO_2 Grade II national standard increases from 16 km^2 in 2000 to 1504 km^2 in 2010, 2432 km^2 in 2020, and 3408 km^2 in 2030. The majority of Shanghai will exceed the standard criterion in 2030 (see Figure 8-5).

Average annual PM_{10} concentrations in urban areas will also improve, relative to the BAU scenario, under the EE scenario. PM_{10} levels under the BAU scenario reached 0.249 mg/m^3 by 2030; under the EE scenario, levels with reach only 0.179 mg/m^3 by 2030 (an increase of 1.7 times from 2000). Under the EE scenario, areas exceeding the PM_{10} Grade II national standard, however, will still increase sizably—from 16 km^2 in 2000 to 6224 km^2 in 2030—with the majority of Shanghai exceeding the standard. In fact, average PM_{10} concentration in 2030 would be more than twice the Grade II national standard of 0.100 mg/m^3.

Table 8-7 Predicted annual concentration of SO_2 in Shanghai under the EE scenario, Unit: mcg/m^3

Year		2000	2005	2010	2015	2020	2025	2030
Annual average concentration, city wide		18	28	34	39	45	51	57
Annual average concentration, urban		44	73	89	104	119	135	152
Area Distribution (km^2)	Concentration	Area						
	>100	0	0	112	416	784	1184	1504
	60-100	16	912	1392	1504	1648	1712	1904
	20-60	3216	4320	4656	5024	5200	4896	4384
	0-20	4560	2560	1632	848	160	0	0
	Total	7792	7792	7792	7792	7792	7792	7792

Table 8-5 Predicted annual concentration of PM_{10} in Shanghai under the EE scenario, Unit: mcg/m^3

Year		2000	2005	2010	2015	2020	2025	2030
Annual average concentration, city wide		87	92	97	102	106	112	118
Annual average concentration, urban		108	119	131	142	153	166	179
Area Distribution (km^2)	Concentration	Area						
	>150	0	0	0	96	480	880	1296
	100-150	16	1888	2800	3600	4048	4496	4928
	90-100	3216	1968	2352	2512	2752	2416	1568
	70-90	4560	3936	2640	1584	512	0	0
	Total	7792	7792	7792	7792	7792	7792	7792

3.2.3. EE+COAL+GAS Scenario

In the EE+COAL+GAS scenario, natural gas, imported from western China and the East Sea, is substituted in increasing amounts for coal in terminal sectors. This further lowers SO_2 concentrations from the EE scenario: average annual urban SO_2 concentration attains Grade II national standard levels in 2010 and reaches 0.055 mg/m^3 in 2030 (compared to 0.152 mg/m^3 under the EE scenario). However, average urban annual concentration of SO_2 will still be 30 percent higher in 2030 than in 2000, with the area exceeding the Grade II national standard increasing from 16 km^2 in 2000 to 544 km^2 in 2030. Most of this non-attainment area lies north of the city center.

In the EE+COAL+GAS scenario, average annual urban PM_{10} concentration will also decrease relative to the EE scenario, reaching 0.112 mg/m^3 in 2030 (down from 0.179 mg/m^3 under the EE scenario). This is just a 3 percent increase from 2000 PM_{10} levels and no area of Shanghai would exceed 0.150 mg/m^3 PM_{10}. However, total area exceeding the PM_{10} Grade II national standard increases from 16 km^2 in 2000 to 1600 km^2 in 2030, with most of the non-attainment area lying within the outer ring road and along a belt extending both north and south of the city center. The most heavily polluted area is Wusong.

Table 8-9 Predicted annual concentration of SO_2 in Shanghai under the EE+COAL+GAS scenario, Unit: mcg/m^3

Year		2000	2005	2010	2015	2020	2025	2030
Annual average concentration, city wide		18	27	25	25	23	24	25
Annual average concentration, urban		44	66	60	60	55	55	57
Area Distribution (km^2)	Concentration	Area						
	>100	0	0	0	0	0	0	0
	60-100	16	656	512	512	352	352	544
	20-60	3216	4576	4208	4208	4032	4000	4032
	0-20	4560	2560	3072	3072	3408	3440	3216
	Total	7792	7792	7792	7792	7792	7792	7792

Table 8-10 Predicted annual concentration of PM_{10} in Shanghai under the EE+COAL+GAS scenario, Unit: mcg/m^3

Year		2000	2005	2010	2015	2020	2025	2030
Annual average concentration, city wide		87	91	90	88	88	89	90
Annual average concentration, urban		108	116	112	109	109	110	112
Area Distribution (km^2)	Concentration	Area						
	>150	0	0	0	0	0	0	0
	100-150	16	1808	1568	1328	1328	1440	1600
	90-100	3216	2016	1728	1584	1600	1632	1680
	70-90	4560	3968	4496	4880	4864	4720	4512
	Total	7792	7792	7792	7792	7792	7792	7792

3.2.4. EE+COAL+GAS+ELEC+WIND Scenario

As shown in Table 8-11, in the EE+COAL+GAS+ELEC+WIND scenario, more natural gas will be consumed in the energy transfer and power generation sectors. Due to increased power generation from natural gas and wind, SO_2 emissions in the EE+COAL+GAS+ELEC+WIND scenario will be lower than in the EE+COAL+GAS scenario. However, this gain will only be slight due to a relatively small gas supply and limited natural gas generator capacity: urban SO_2 concentration will be 0.058 mg/m^3 in 2010 (compared to 0.060 mg/m^3 in the EE+COAL+GAS scenario) and 0.053 mg/m^3 in 2020 (compared to 0.055 mg/m^3 in the EE+COAL+GAS scenario). Under the EE+COAL+GAS+ELEC+WIND scenario, annual average urban SO_2 concentration will be 40 percent higher in 2010 than in 2000; 20 percent higher in 2020 than in 2000; and 30 percent higher in 2030 than in 2000. The non-attainment area will be 304, 224, and 352 km^2 in 2010, 2020, and 2030, respectively (see Figure 8-9).

In the EE+COAL+GAS+ELEC+WIND scenario, PM_{10} levels follow a trend similar to SO_2 levels. Annual urban PM_{10} concentrations will decrease relative to the EE+COAL+GAS scenario, with 2030 levels roughly equal to 2000 levels. However, the area exceeding the Grade II National Standard will increase from 16 km^2 in 2000 to 1344 km^2 in 2010; 1104 km^2 in 2020; and 1328 km^2 in 2030. The major non-attainment areas will be distributed inside the outer ring road, with the most heavily polluted area being Wusong (see Figure 8-10).

Table 8-11 Predicted annual concentration of SO_2 in Shanghai under the EE+COAL+GAS+ELEC+WIND scenario, Unit: mcg/m^3

Year		2000	2005	2010	2015	2020	2025	2030
Annual average concentration, city wide		18	26	24	22	22	22	23
Annual average concentration, urban		44	63	58	53	53	52	55
Area Distribution (km^2)	Concentration	Area						
	>100	0	0	0	0	0	0	0
	60-100	16	528	304	224	224	304	352
	20-60	3216	4400	4288	3856	3904	3840	3984
	0-20	4560	2864	3200	3712	3664	3648	3456
	Total	7792	7792	7792	7792	7792	7792	7792

Table 8-12 Predicted annual concentration of PM_{10} in Shanghai under the EE+COAL+GAS+ELEC+WIND scenario, Unit: mcg/m^3

Year		2000	2005	2010	2015	2020	2025	2030
Annual average concentration, city wide		87	90	88	87	87	87	88
Annual average concentration, urban		108	114	110	107	106	106	109
Area Distribution (km^2)	Concentration	Area						
	>150	0	0	0	0	0	0	0
	100-150	16	1632	1344	1168	1104	1168	1328
	90-100	3216	1840	1568	1440	1472	1472	1584
	70-90	4560	4320	4880	5184	5216	5152	4880
	Total	7792	7792	7792	7792	7792	7792	7792

3.2.5. EE+COAL+GAS+ELEC+WIND+SO_2b+PM Scenario

Strict fuel sulfur content control and end-pipe de-sulfurization of flue gas undertaken in the EE+COAL+GAS+ELEC+WIND+SO_2b+PM scenario yield significant air quality improvement. Annual urban SO_2 concentration will decrease greatly relative to the EE+COAL+GAS+ELEC+WIND scenario: SO_2 levels will be 0.040 mg/m^3 in 2010, a 30 percent decrease from EE+COAL+GAS+ELEC+WIND scenario SO_2 levels (0.058 mg/m^3); 0.033 mg/m^3 in 2020, a 37 percent decrease (down from 0.053 mg/m^3); and 0.029 mg/m^3 in 2030, a 47 percent decrease (down from 0.055 mg/m^3). Annual urban SO_2 concentration in the entire city will meet the Grade II National Standard by 2005, and the area with SO_2 concentrations between 0.020 and 0.060 mg/m^3 will decrease from 3216 km^2 in 2000 to 2944, 2208, and 1824 km^2 in 2010, 2020 and 2030, respectively. SO_2 levels within the outer ring road will fall below 0.030 mg/m^3 by 2025.

PM_{10} levels will also decrease significantly in the EE+COAL+GAS+WIND+ SO_2b+PM scenario. Annual urban PM_{10} concentration will be 0.097 mg/m^3 in 2010, down from 0.110 mg/m^3 in the EE+COAL+GAS+ELEC+WIND scenario; 0.091 mg/m^3 in 2020, down from 0.106 mg/m^3; and 0.085 mg/m^3 in 2030, down from 0.109 mg/m^3. By 2030, all of Shanghai will meet the PM_{10} Grade II National Standard, with PM_{10} levels in most of the city under 0.08 mg/m^3 and only a few areas around 0.090 mg/m^3 (see Figure 8-12).

Table 8-13 Predicted annual concentration of SO_2 in Shanghai under the EE+COAL+GAS+ELEC+WIND+SO_2b+PM scenario, Unit: mcg/m^3

Year		2000	2005	2010	2015	2020	2025	2030
Annual average concentration, city wide		18	19	17	15	14	13	13
Annual average concentration, urban		44	46	40	36	33	31	29
Area Distribution (km^2)	Concentration	Area						
	>100	0	0	0	0	0	0	0
	60-100	16	0	0	0	0	0	0
	20-60	3216	3536	2944	2448	2208	1920	1824
	0-20	4560	4256	4848	5344	5584	5872	5968
	Total	7792	7792	7792	7792	7792	7792	7792

Table 8-14 Predicted annual concentration of PM_{10} in Shanghai under the EE+COAL+GAS+ELEC+WIND+SO_2b+PM scenario, Unit: mcg/m^3

Year		2000	2005	2010	2015	2020	2025	2030
Annual average concentration, city wide		87	85	83	81	80	78	77
Annual average concentration, urban		108	102	97	94	91	88	85
Area Distribution	Concentration	Area						
	>150	0	0	0	0	0	0	0

(km^2)	100-150	16	624	176	48	16	0	0
	90-100	3216	1328	1280	976	544	144	0
	70-90	4560	5840	6336	6768	7232	7648	7792
	Total	7792	7792	7792	7792	7792	7792	7792

3.2.6. EE+COAL+GAS+ELEC+WIND+SO_2c+PM Scenario

Even stricter fuel sulfur content controls in the EE+COAL+GAS+ELEC+WIND+ SO_2c+PM scenario yield even better air quality. In this scenario, annual urban SO_2 concentration decreases all the way to 0.016 mg/m^3 in 2030, a 43 decrease from SO_2b SO_2 levels (0.029 mg/m^3). The entire city would satisfy the Grade II National Standard, the area with SO_2 levels between 0.020 and 0.060 mg/m^3 would decrease to 224 km^2 by 2030, and average city-wide SO_2 levels would fall below 0.030 mg/m^3 by 2005.

As shown in Table 8-16, the additional fuel sulfur content control in the EE+ COAL+GAS+ELEC+WIND+SO_2c+PM scenario yields no obvious additional PM_{10} mitigation; there is no change in urban PM_{10} concentration from the SO_2b scenario.

Table 8-15 Predicted annual concentration of SO_2 in Shanghai under the EE+COAL+GAS+ELEC+WIND+SO_2c+PM scenario, Unit: mcg/m^3

Year		2000	2005	2010	2015	2020	2025	2030
Annual average concentration, city wide		18	19	15	12	10	9	7
Annual average concentration, urban		44	42	35	27	23	19	16
Area Distribution (km^2)	Concentration	Area						
	>100	0	0	0	0	0	0	0
	60-100	16	0	0	0	0	0	0
	20-60	3216	3536	2640	1648	1120	528	224
	0-20	4560	4256	5152	6144	6672	7264	7568
	Total	7792	7792	7792	7792	7792	7792	7792

Table 8-16 Predicted annual concentration of PM_{10} in Shanghai under the EE+COAL+GAS+ELEC+WIND+SO_2c+PM scenario, Unit: mcg/m^3

Year		2000	2005	2010	2015	2020	2025	2030
Annual average concentration, city wide		87	85	83	81	80	78	77
Annual average concentration, urban		108	101	97	93	90	87	85
Area Distribution (km^2)	Concentration	Area						
	>150	0	0	0	0	0	0	0
	100-150	16	544	160	48	16	0	0
	90-100	3216	1376	1280	912	480	144	0
	70-90	4560	5872	6352	6832	7296	7648	7792

	Total	7792	7792	7792	7792	7792	7792	7792

4. Summary

(1) We used ATMOS to predict SO_2 and PM_{10} concentration distributions based on LEAP model emission data for six LEAP scenarios: BAU, EE, EE+COAL+GAS, EE+COAL+GAS+ELEC+WIND, EE+COAL+GAS+ELEC+WIND+SO_2b+PM, and EE+COAL+GAS+ELEC+WIND+SO_2c+PM. The year 2000 was taken as the base year.

(2) In 2000, average annual SO_2 concentration in urban areas was 0.044 mg/m^3; in the city as a whole, it was 0.018 mg/m^3. One area in northern Baoshan district had an average annual SO_2 concentration exceeding the Grade II national standard 0.06 mg/m^3. Average annual PM_{10} concentration in urban areas was 0.108 mg/m^3; in the city as a whole, 0.087 mg/m^3. A 1168 km^2 area of Shanghai was exceeding the Grade II national standard 0.100 mg/m^3.

(3) Under the BAU scenario, average annual SO_2 concentrations in urban areas increases to 0.247 mg/m^3 by 2030, 5.6 times year 2000 SO_2 concentration. Average annual PM_{10} in urban areas increases to 0.249 mg/m^3 by 2030, 2.3 times year 2000 PM_{10} concentration. Almost all of Shanghai exceeds SO_2 and PM_{10} Grade II national standards in 2030.

(4) Under the EE+COAL+GAS+ELEC+WIND scenario, the increased use of natural gas in the energy transfer and power generation sectors significantly lowers SO_2 levels relative to the BAU scenario. Average annual SO_2 concentrations in Shanghai’s urban areas will be 40 percent higher in 2010 than in 2000; 20 percent higher in 2020 than in 2000; and 30 percent higher in 2030 than in 2000.

In this same scenario, average annual PM_{10} concentration in urban areas will stay roughly at 2000 levels through 2030. However, the area exceeding the PM_{10} Grade II national standard will increase from 16 km^2 in 2000 to 1328 km^2 in 2030. The major non-attainment areas for both SO_2 and PM_{10} will lie inside the outer ring road, with the most heavily polluted area being Wusong.

(5) Strict fuel sulfur content control and end-pipe de-sulfurization of flue gas taken in the EE+COAL+GAS+ELEC+WIND+SO_2b+PM scenario yield significant air quality improvements. Under this scenario, average annual urban SO_2 concentration decreases every year, attaining the Grade II national standard by 2005 and reaching 0.029 mg/m^3 in 2030, a 34 percent decrease from 2000 levels. SO_2 levels within the outer ring road will fall below 0.030 mg/m^3 by

2025.

PM_{10} concentrations will also fall. Average annual urban PM_{10} concentration decreases every year as well, falling to 0.085 mg/m^3 by 2030 with the entire city attaining the PM_{10} Grade II national standard. Average PM_{10} concentration in the city as a whole would fall below 0.08 mg/m^3 by 2030.

(6) The even more stringent fuel sulfur content controls imposed in the EE+ COAL+GAS+WIND+SO_2c+PM scenario yield even lower SO_2 levels. In this scenario, average urban SO_2 concentration falls to 0.016 mg/m^3 in 2030, 43 lower than the SO_2b scenario and 64 percent lower than 2000 SO_2 levels. Average SO_2 concentrations in the city as a whole would fall below 0.030 mg/m^3 by 2005.

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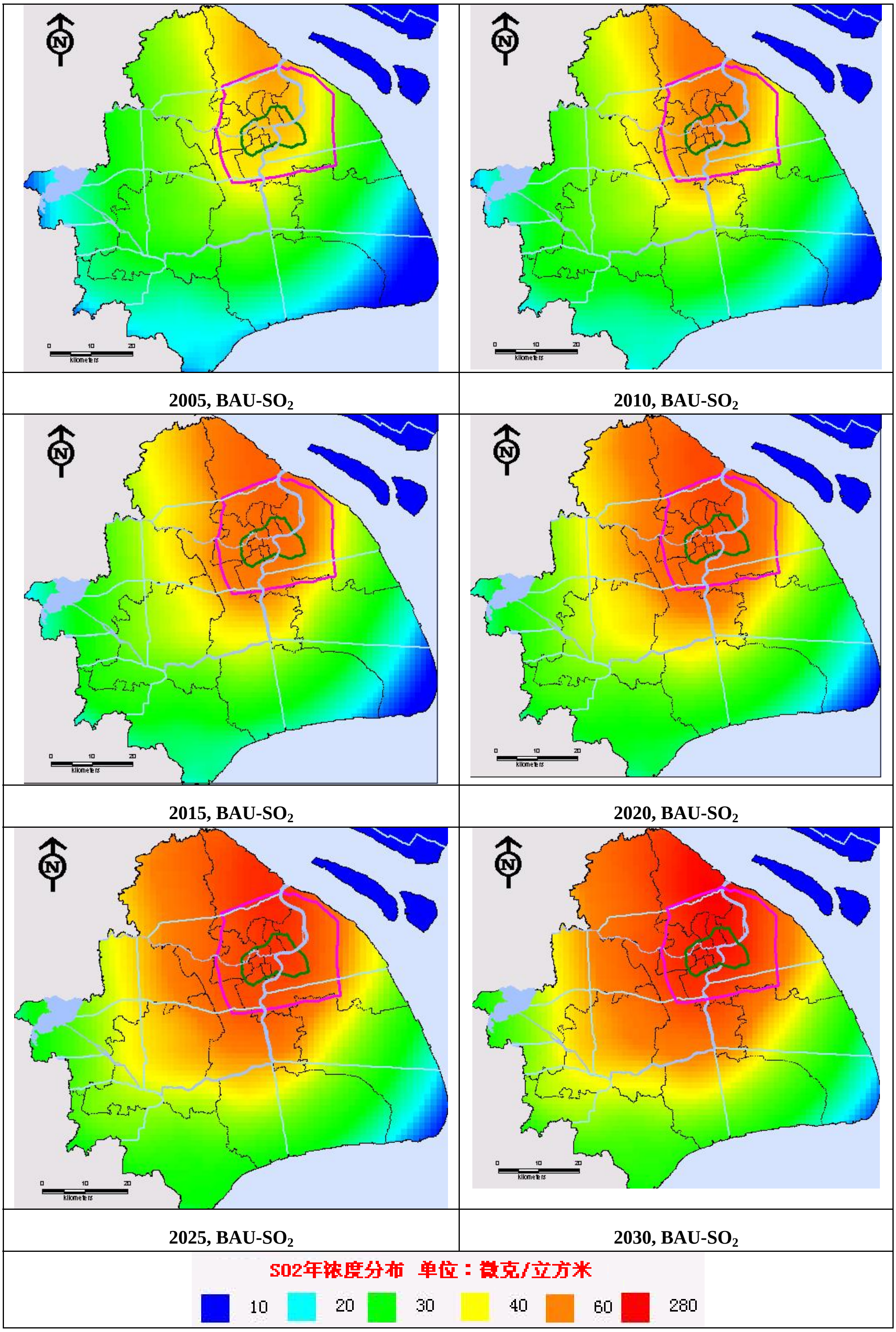


Figure 8-3 SO_2 concentration under BAU scenario

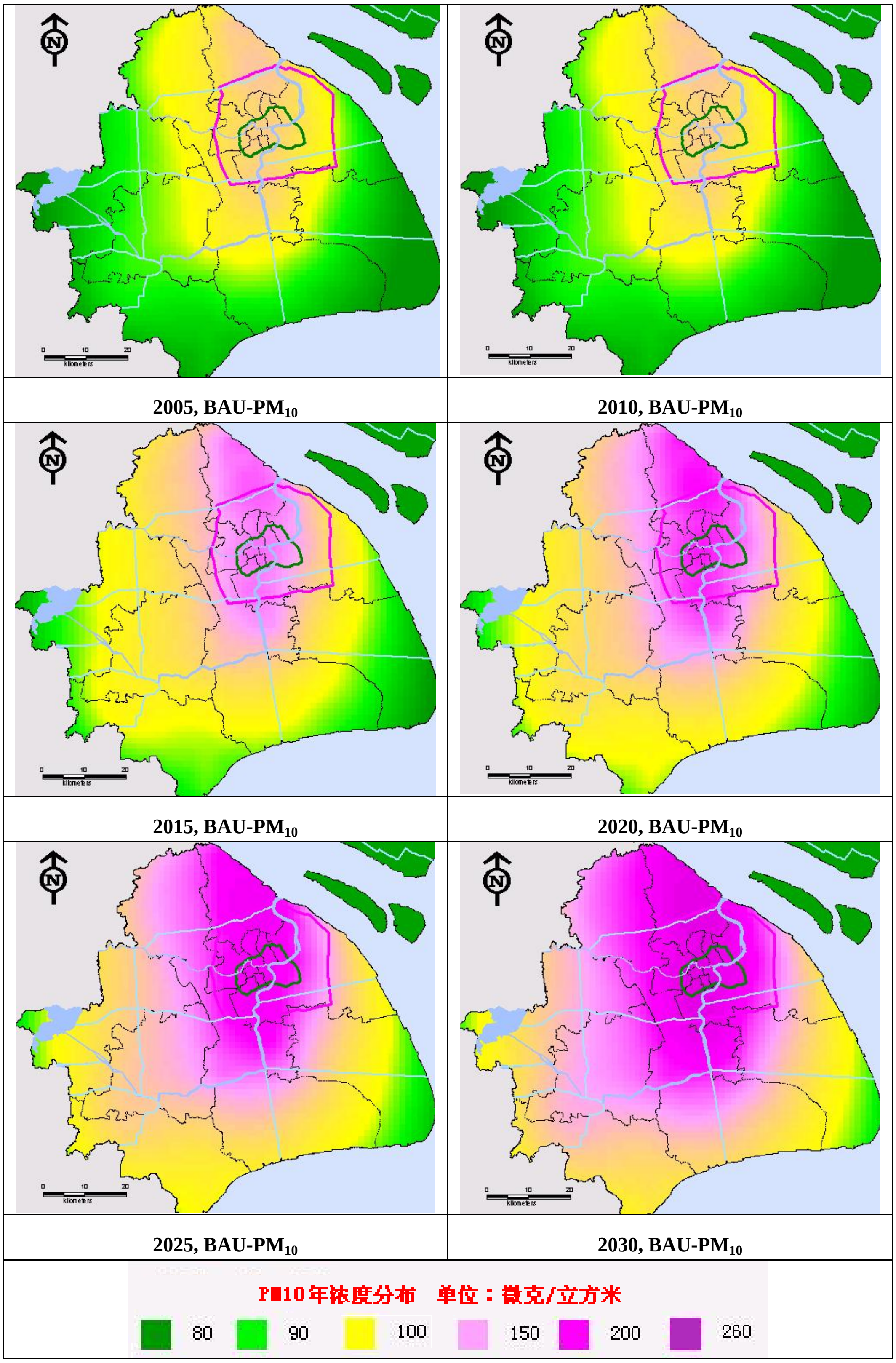


Figure 8-4 PM_{10} concentration under BAU scenario

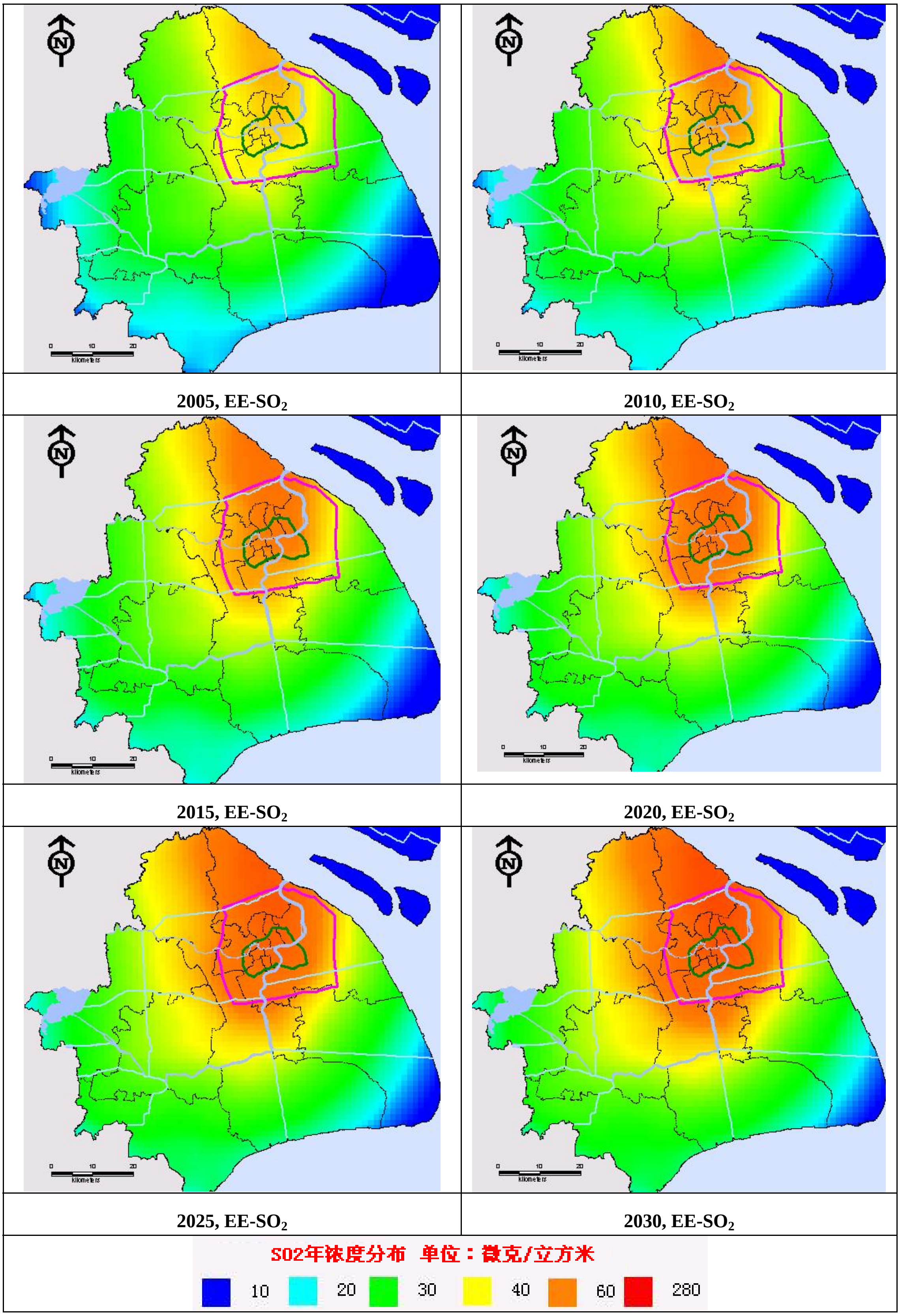


Figure 8-5 SO_2 concentration under EE scenario

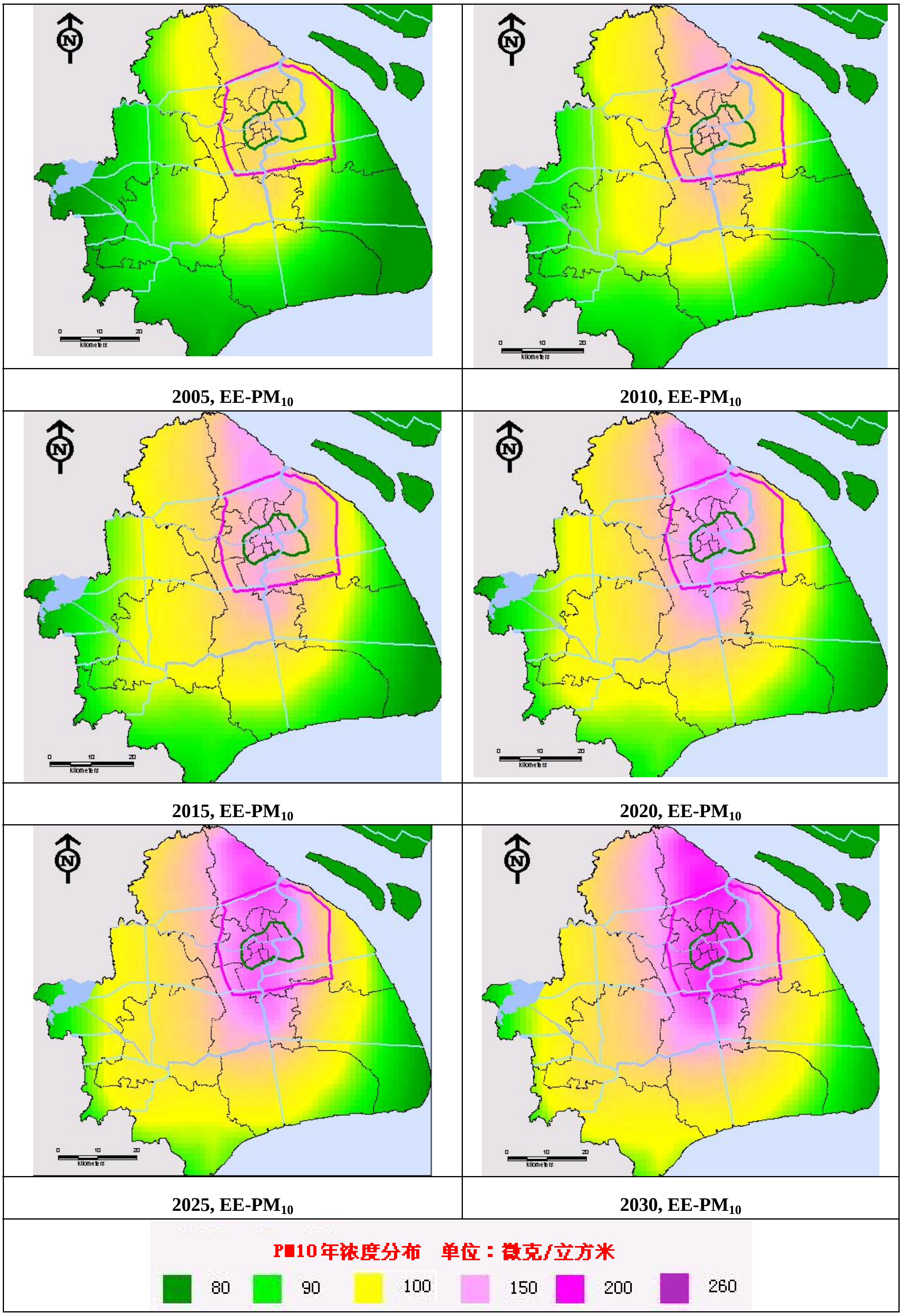


Figure 8-6 PM_{10} concentration under EE scenario

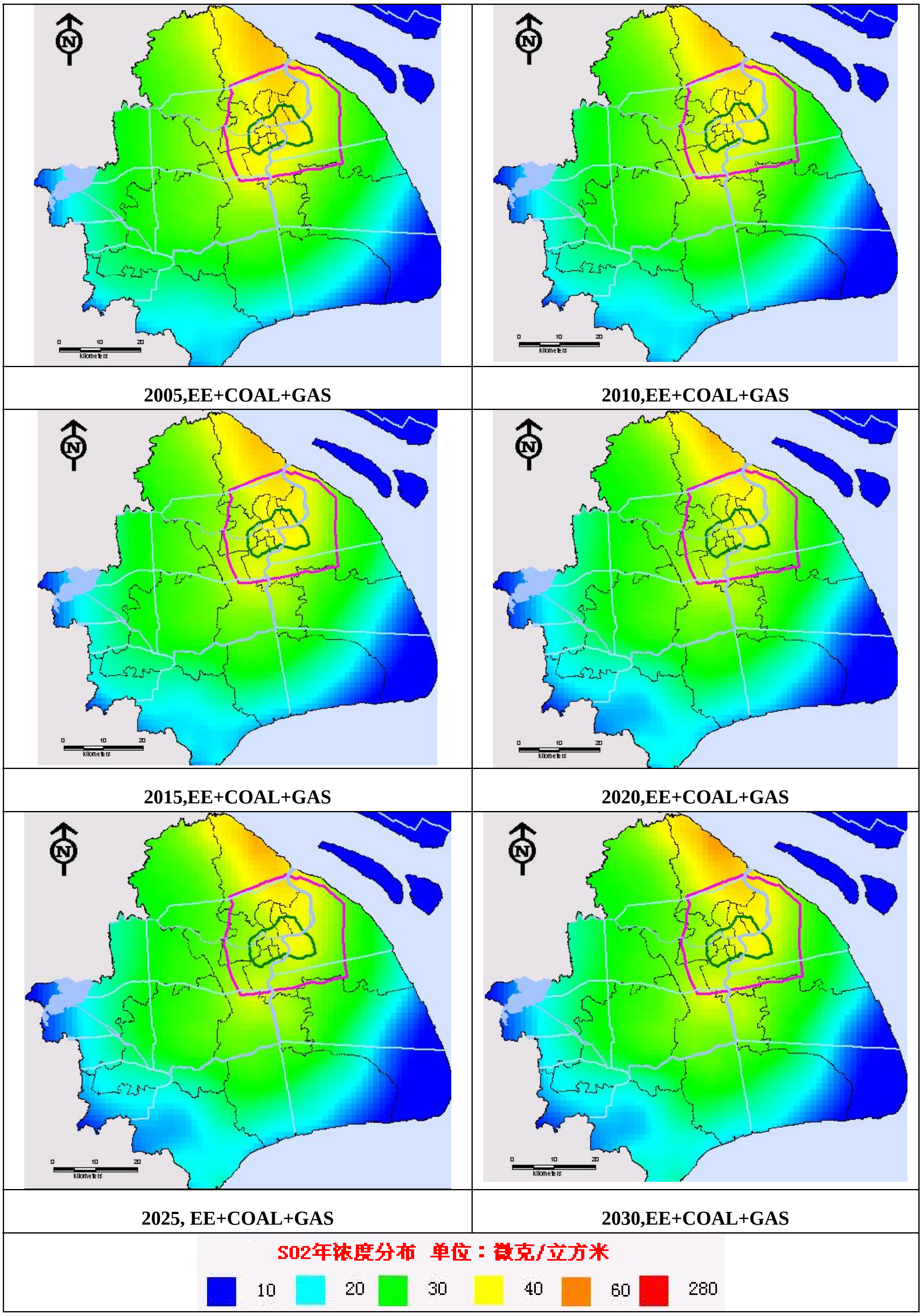


Figure 8-7 SO_2 concentration under EE+COAL+GAS scenario

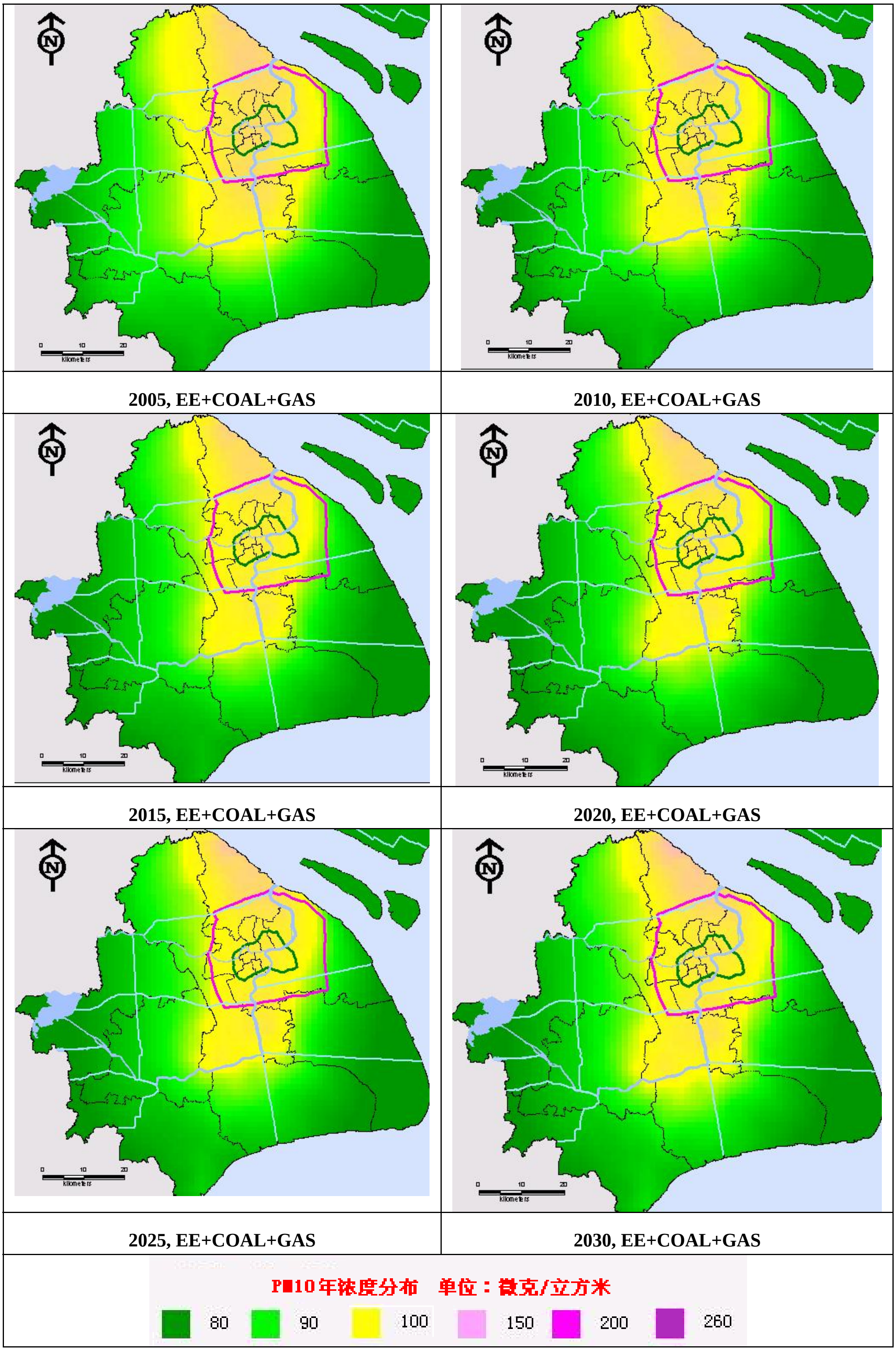
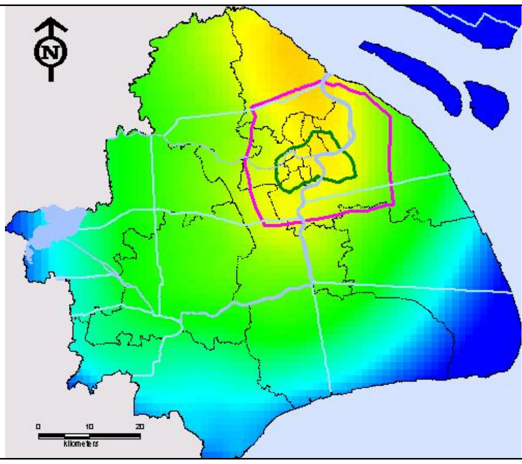
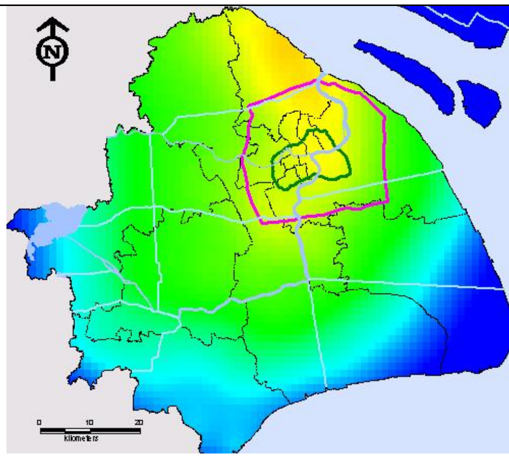


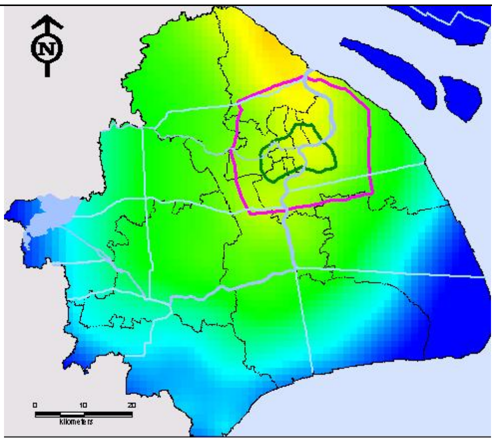
Figure 8-8 PM_{10} concentration under EE+COAL+GAS scenario

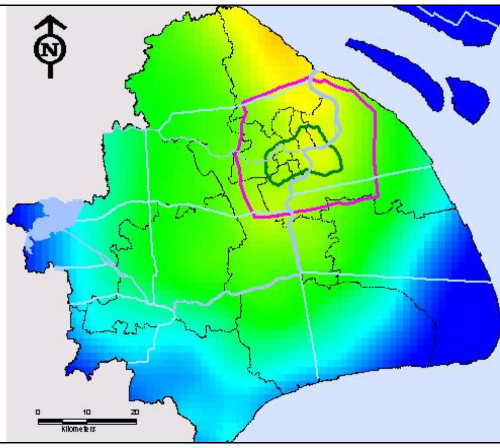




2005, EE+COAL+GAS+ELEC+WIND

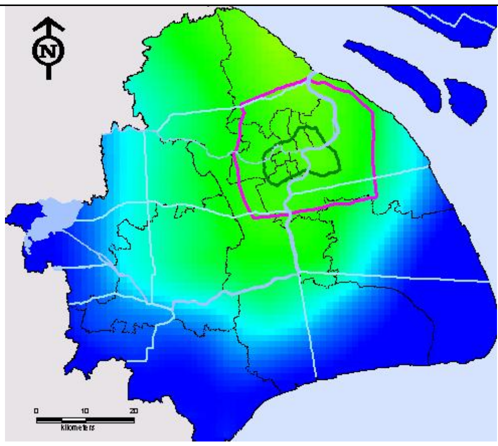
2010, EE+COAL+GAS+ELEC+WIND

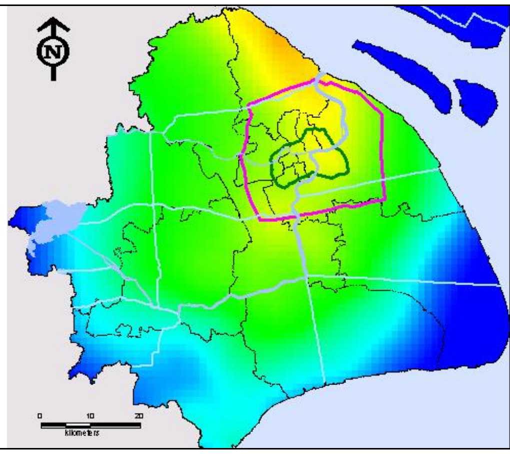




2015, EE+COAL+GAS+ELEC+WIND

2020, EE+COAL+GAS+ELEC+WIND

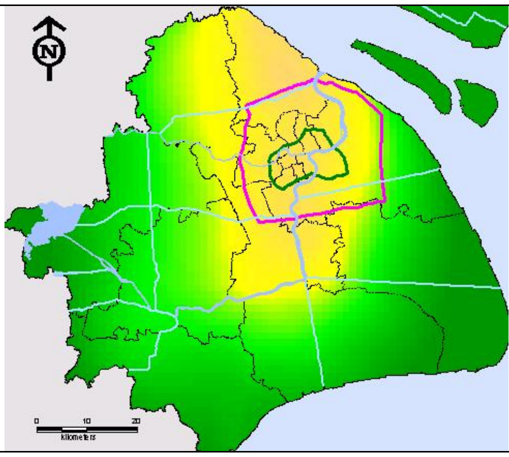




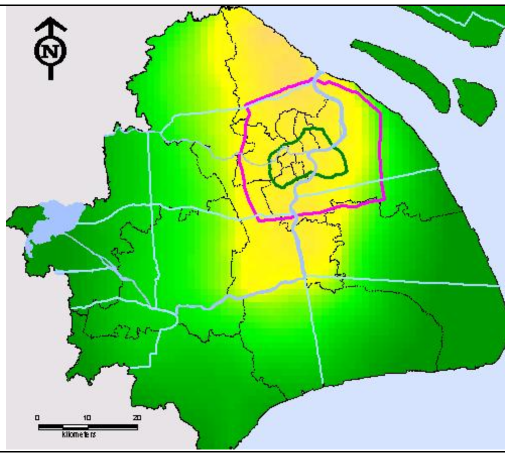
2025, EE+COAL+GAS+ELEC+WIND

2030, EE+COAL+GAS+ELEC+WIND

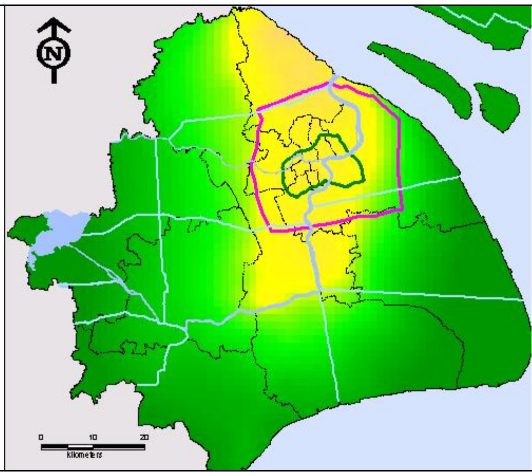
Figure 8-9 SO_2 concentration under EE+COAL+GAS+ELEC+WIND scenario



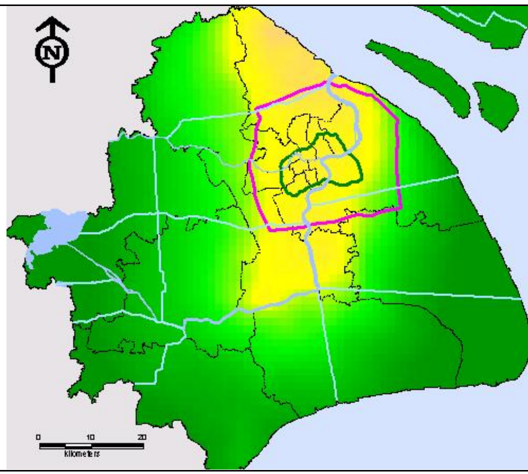
2005, EE+COAL+GAS+ELEC+WIND



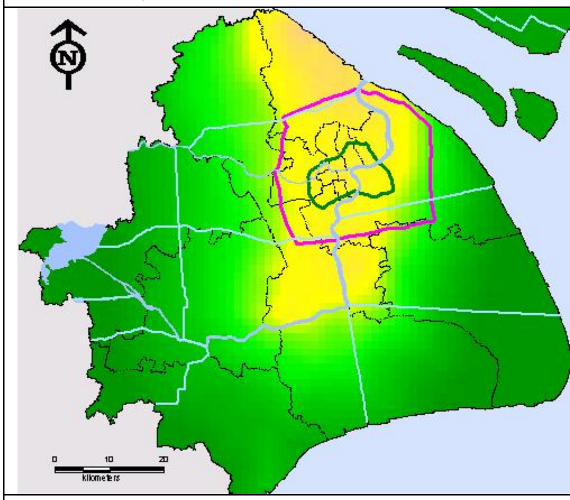
2010, EE+COAL+GAS+ELEC+WIND



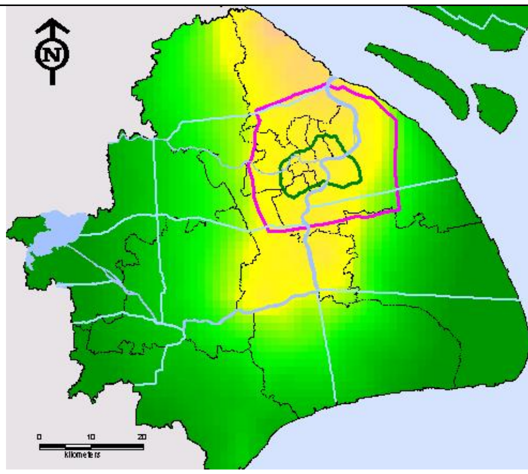
2015, EE+COAL+GAS+ELEC+WIND



2020, EE+COAL+GAS+ELEC+WIND

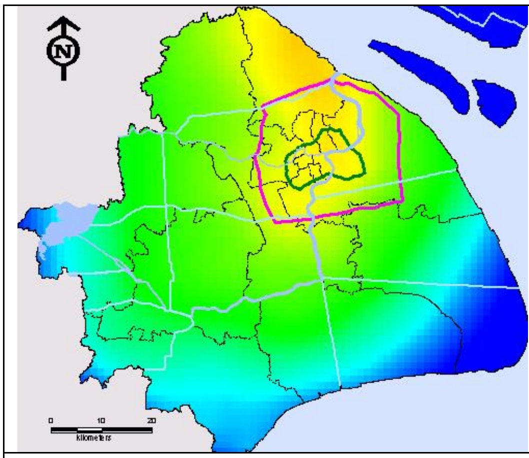


2025, EE+COAL+GAS+ELEC+WIND

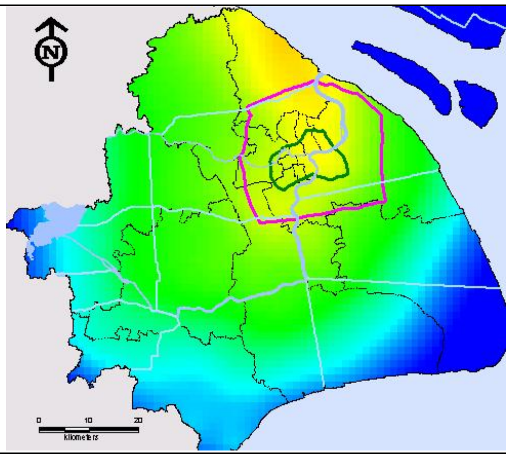


2030, EE+COAL+GAS+ELEC+WIND

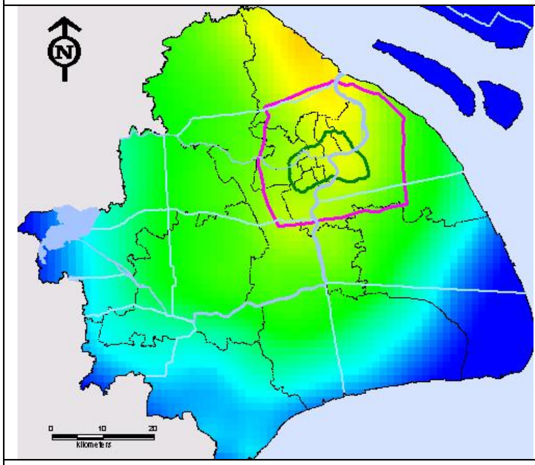
Figure 8-10 PM_{10} concentration under EE+COAL+GAS+ELEC+WIND scenario



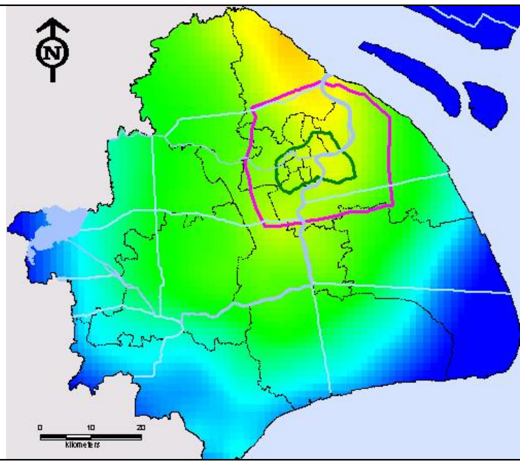
2005.EE+COAL+GAS+ELEC+WIND+SO_2b+PM



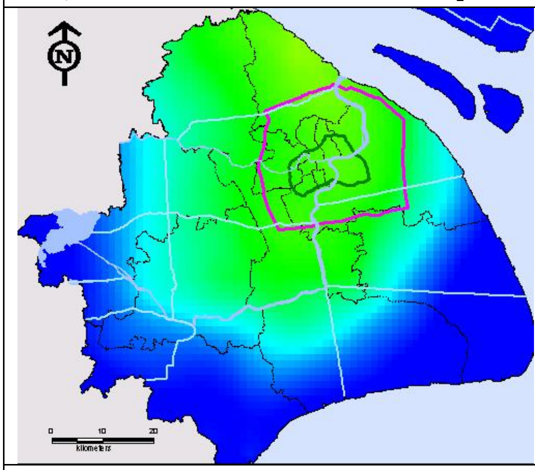
2010, EE+COAL+GAS+ELEC+WIND+SO_2b+PM



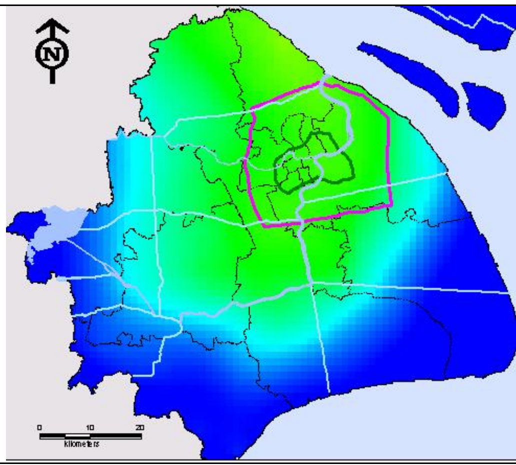
2015,EE+COAL+GAS+ELEC+WIND+SO_2b+PM



2020, EE+COAL+GAS+ELEC+WIND+SO_2b+PM

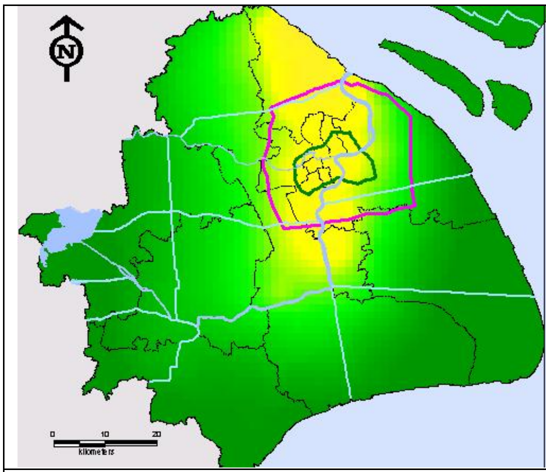


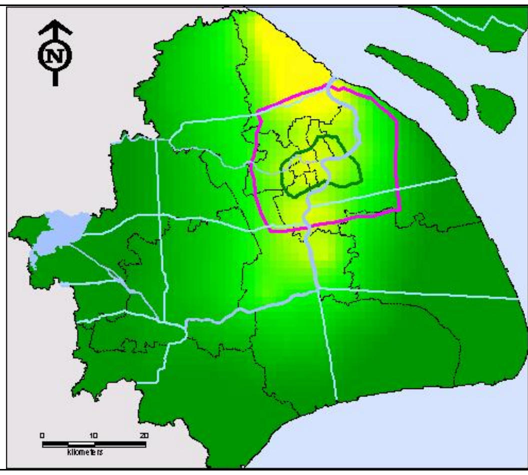
2025, EE+COAL+GAS+ELEC+WIND+SO_2b+PM



2030, EE+COAL+GAS+ELEC+WIND+SO_2b+PM

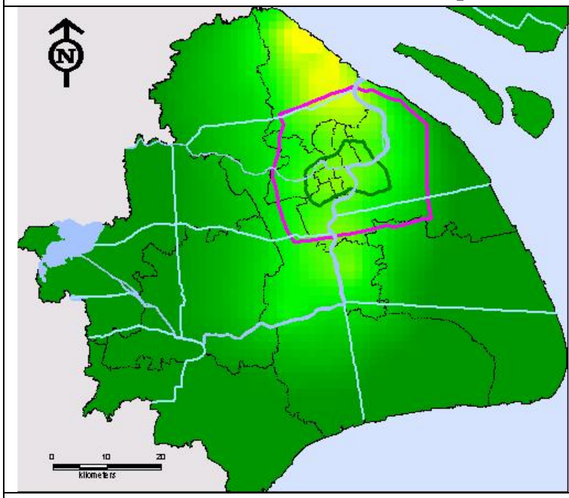
Figure 8-11 SO_2 concentration under EE+COAL+GAS+ELEC+WIND+SO_2b+PM scenario

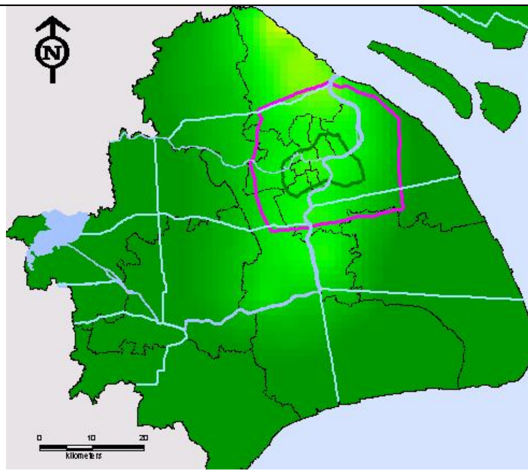




2005,EE+COAL+GAS+ELEC+WIND+SO_2b+PM

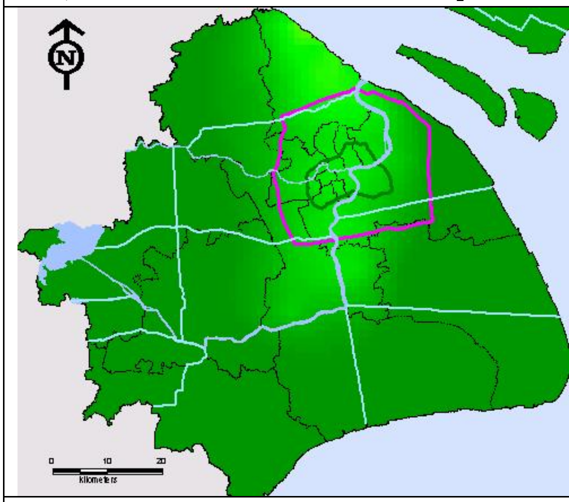
2010, EE+COAL+GAS+ELEC+WIND+SO_2b+PM

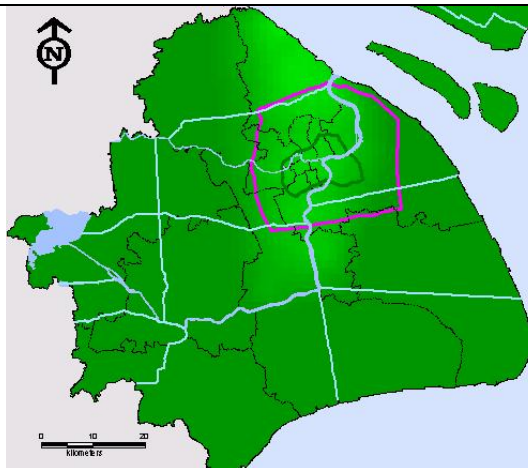




2015,EE+COAL+GAS+ELEC+WIND+SO_2b+PM

2020, EE+COAL+GAS+ELEC+WIND+SO_2b+PM





2025, EE+COAL+GAS+ELEC+WIND+SO_2b+PM

2030, EE+COAL+GAS+ELEC+WIND+SO_2b+PM

Figure 8-12 PM_{10} concentration under EE+COAL+GAS+ELEC+WIND+SO_2b+PM scenario

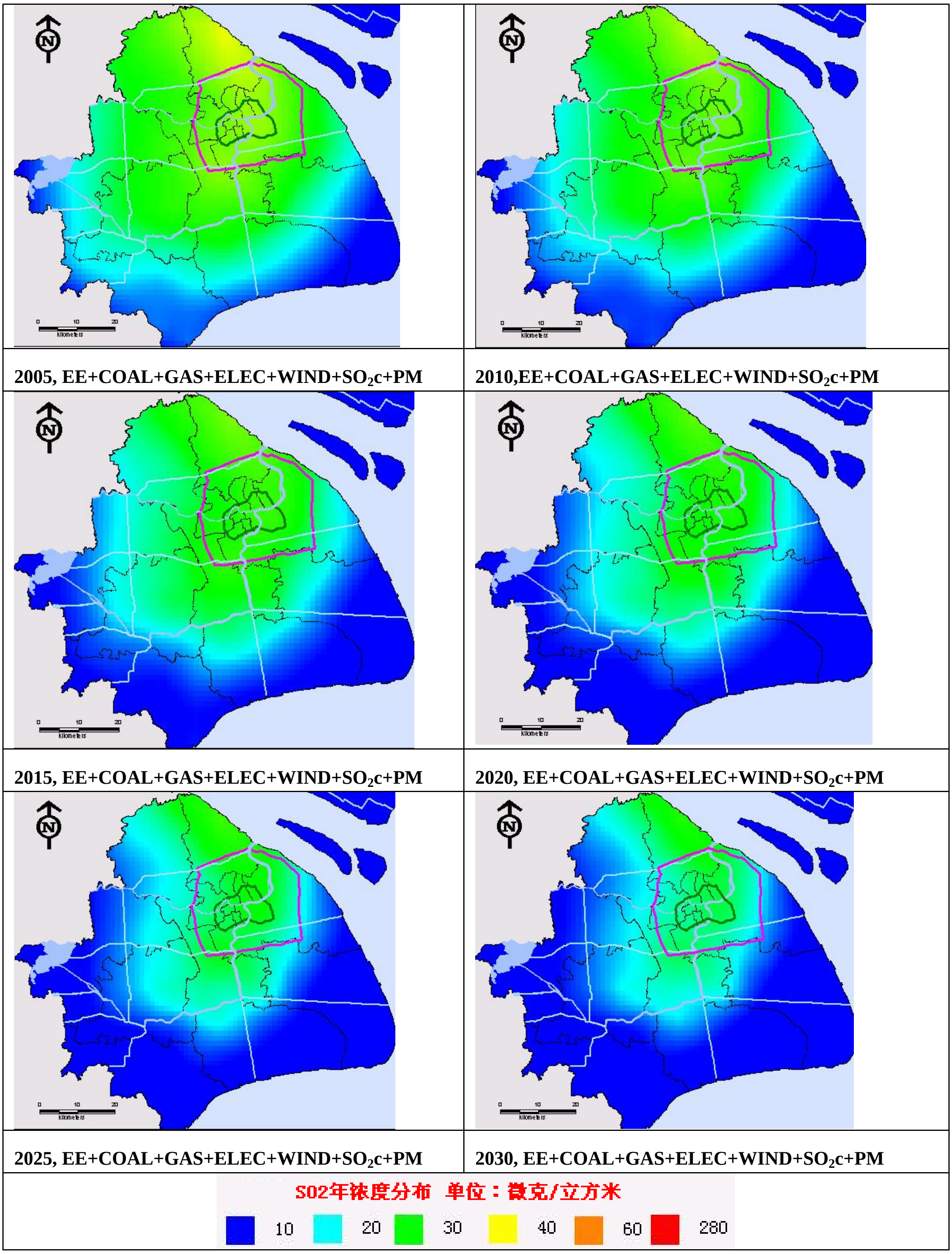


Figure 8-13 SO_2 concentration under EE+COAL+GAS+ELEC+WIND+SO_2c+PM scenario

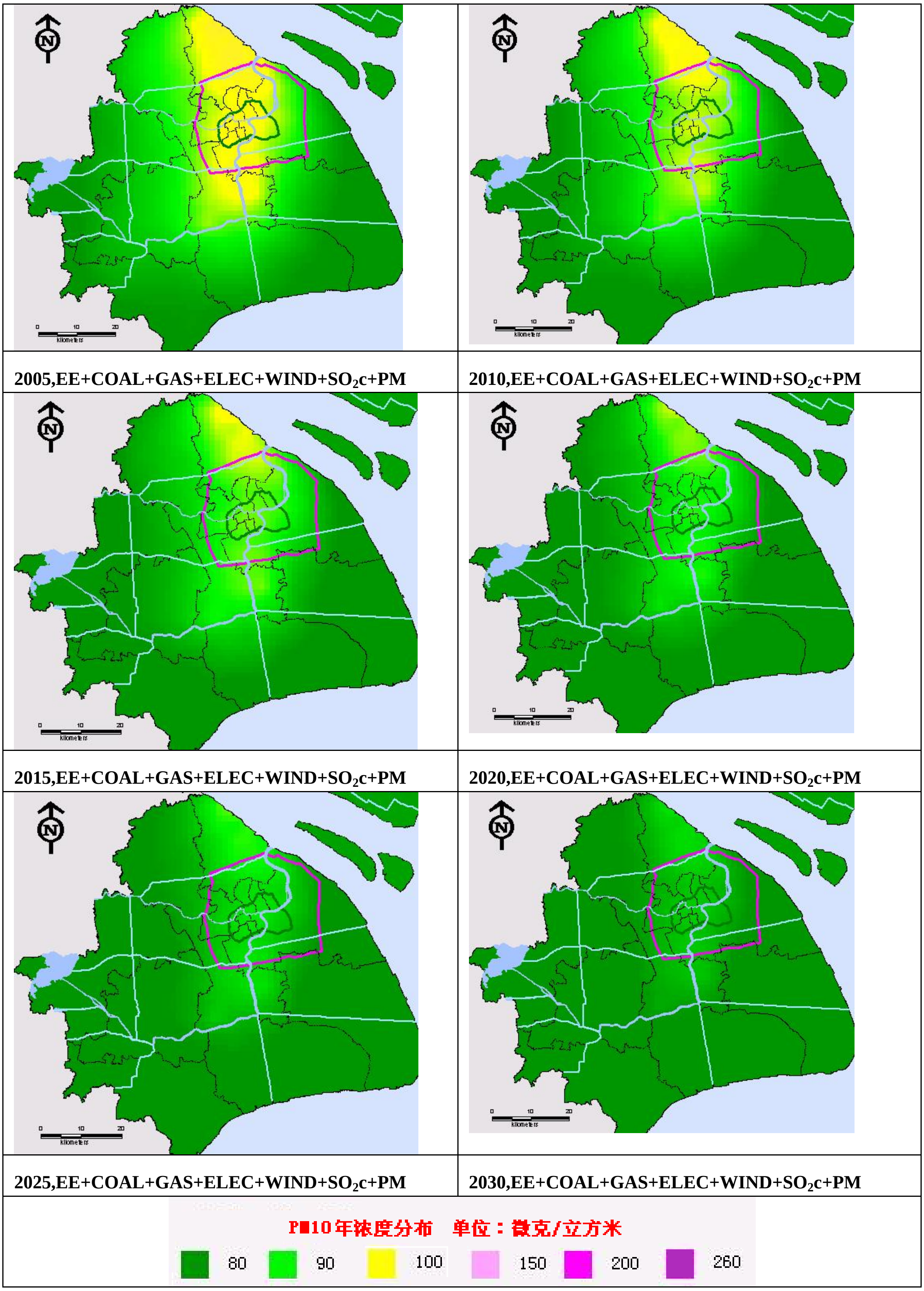


Figure 8-14 PM_{10} concentration under EE+COAL+GAS+ELEC+WIND+SO_2c+PM scenario

Chapter 9. A Meta-Analysis of Exposure-Response Functions between Air Particulate Matter and Adverse Health Outcomes

1. Introduction

Numerous epidemiological studies conducted in China and abroad over the past 10-20 years confirm that exposure to air pollution contributes to both mortality and morbidity (Xu, et al. 2000; Xu, et al. 1994; Wilson, et al. 1996; Holgate, et al. 1999). Among all air pollutants, particulate matter—measured as either TSP (total suspended particles), PM_{10} (particles less than 10 microns), $PM_{2.5}$ (particles less than 2.5 microns), or black smoke—shows the most consistent relationship with mortality.

As evidence of the adverse health effects of air pollution has been accumulated, quantification of the impact of air pollution on public health and subsequent cost-benefit analysis have increasingly become critical components in policy discussion and priority setting. Exposure-response functions link air quality changes and heath outcomes, providing key information for the health impact assessment of air pollution.

Here, we tried to make use of available epidemiological literature from both China and abroad to derive the exposure-response functions and their respective precision measures (95 percent confidence interval or standard error). With many studies providing information on the same exposure-response associations, a meta-analysis of their results was conducted to derive a common estimate.

2. Materials and Methods

2.1. Data

Using the Chinese Biomedical Literature Database and PubMed, we collected epidemiological literature on particulate air pollution and its adverse health effects published between 1990 and 2002 in China and abroad. Exposure-response coefficients and their 95% confidence intervals (CI) were obtained from this literature.

PM_{10} was selected as the particulate matter indicator because there is much PM_{10} data available for Shanghai and the rest of China. But some studies using TSP and $PM_{2.5}$ for exposure assessment were also included in the analysis. The following formulas were used for converting between different particulate matter indicators:

$$PM_{10} = TSP \times 0.65$$

$$PM_{2.5} = PM_{10} \times 0.65$$ (Teng, et al. 1999)

2.2. Literature Selection

We sought to summarize particulate-related effects by researching the health outcomes, both morbidity to mortality changes, associated with different exposure levels . The following criteria were used in selecting literature for this analysis:

- Conducted in China. When research on widely-accepted health outcomes associated with air pollution was not available in Chinese literature—e.g., long-term effects on mortality—results from international literature were used.
- Established quantitative exposure-response relationships (in the form of either slope or relative risk) between air pollutants and health outcomes.
- Excluded sub-clinical effects. We excluded sub-clinical effects, such as lung function changes, from our analysis because it is difficult measure their long-term health impact and monetary value based on current knowledge.
- Health outcomes had baseline data for either Shanghai or China as a whole. For example, restricted activity days (RADs), which is an important endpoint in many air pollution-related health impact assessments, was excluded from our analysis because of the lack of baseline RAD data for China.

Based on the above criteria, data was gathered regarding the effect of particulate exposure on the following health outcomes:

- **Long-term mortality**
- **Morbidity**
  - Chronic bronchitis
  - Hospital admission (for respiratory and cardiovascular problems)
  - Outpatient visits (in internal medicine and pediatrics)
  - Other illnesses (acute bronchitis and asthma attacks)

2.3. Meta-Analysis Method

If several studies described exposure-response functions for the same health endpoint, we obtained the mean and 95 percent confidence interval (CI) of the coefficient. This meta-analysis method was based on the variance weighted average across the results of studies with available quantitative effect estimates (coefficients or relative risks): studies with lower standard errors had more weight in the resulting joint estimate.

We used the META command in STATA to perform this process.

3. Results

3.1. Estimates of Long-Term Effects on Mortality

The exposure-response relationship between ambient particulate matter and long-term mortality was studied in two U.S. cohort studies (Dockery, et al. 1993; Pope, et al. 1995). These cohort studies give the additional number of deaths per person-year which may be directly applied to the per year impact assessment. The most up-to-date results, providing longer follow up and more data on particulate matter, were recently published for the latter study (Pope, et al. 2002). Thus, the current impact assessment was based on the results these two U.S. studies on the long-term effects on mortality rate in adult populations (Dockery, et al. 1993; Pope, et al. 2002).

The American Cancer Society (ACS) study (Pope, et al. 2002) investigated the impact of air pollution exposure in metropolitan areas throughout the United States on the survival of 500,000 people, finding that mortality risk increases 4.0 percent with each increase of 10 $\mu g/m^3$ PM_{10}. The Harvard 6 Cities Cohort study, which followed 8,111 people, found a much higher morality increase, estimating that mortality risk increases 8.5 percent with each increase of 10 $\mu g/m^3$ PM_{10} (Dockery, et al. 1993).

Our meta-analysis yielded a joint estimated relative mortality risk of 1.0430 (95% CI 1.0260, 1.0610） associated with PM_{10} pollution.

3.2. Estimates of Effects on Morbidity

3.2.1. Chronic bronchitis

Two studies conducted in China described the association between chronic bronchitis and long-term exposure to air pollution. Using an ecological cross-sectional design, the Jin, et al. study investigated the effect of ambient air pollution on the number of new cases of chronic bronchitis (incidence) in Benxi, China (Jin, et al. 2000). A similar study was conducted by Ma, et al. in Shanghai (Ma, et al. 1992). These studies estimated that the incidence rate of chronic bronchitis increases 3.0 percent in Benxi and 2.9 percent in Shanghai with each increase of 10 $\mu g/m^3$ TSP.

We calculated a joint estimated relative risk of 1.046（1.015, 1.077）per 10 $\mu g/m^3$ PM_{10}.

3.2.2. Hospital admission

The association between air pollution and hospital admission has been confirmed in North American and Europe. There have been no studies on this relationship in China, however. Therefore, we had to rely on international peer-reviewed papers for our analysis.

Hospital admission for respiratory problems. Using three European studies (Spix, et al. 1998; Wordley, et al. 1997; Prescott, et al. 1998), we calculated a joint relative risk for hospital admission for respiratory problems of 1.008 (95% CI 1.004-1.012) for each increase of 10 μg/m^3 PM_{10}. From 8 U.S. and Canadian studies (Thurston, et al. 1994; Schwartz 1994a; Schwartz 1994b; Schwartz 1994c; Schwartz, et al. 1995; Schwartz 1996; Schwartz, et al. 1996; Burnett, et al. 1997), a joint relative risk of 1.017 (95% CI 1.013-1.020) for each increase of 10 μg/m^3 PM_{10} was calculated.

Combining all these European, U.S., and Canadian studies yielded a relative risk of 1.013 (95% CI 1.010-1.015) per 10 μg/m^3 PM_{10}.

Hospital admissions for cardiovascular problems. Using four European studies (Medina, et al. 1997; Poloniecki, et al. 1997; Wordley, et al. 1997; Prescott, et al. 1998), we calculated the joint relative risk of hospital admission for cardiovascular problems to be 1.013 (95% CI 1.007-1.019) for each increase of 10 μg/m^3 PM_{10}. We derived a joint estimated relative risk of 1.008 (95% CI 1.004-1.011) per 10 μg/m^3 increase in PM_{10} using three U.S. and Canadian studies (Schwartz and Morris 1995; Schwartz 1997; Burnett, et al. 1997).

All European, U.S., and Canadian studies combined yielded an estimated relative risk of 1.009 (95% CI 1.006-1.013) per 10 μg/m^3 increase in PM_{10}.

3.2.3. Hospital outpatient visits

To date, there has been only one study in China on the association between air pollution and outpatient visits. The Xu X., et al. study conducted in Beijing reported a 3.4% (95% CI 1.9-4.9%) increase in outpatient visits to internal medicine and a 3.9%（95% CI 1.4-6.4%）increase in outpatient visits to pediatrics departments with each increase of 10μg/m^3 PM_{10} (Xu, et al. 1995).

3.2.4. Acute bronchitis

There has been one study conducted in China on the relationship between air pollution and acute bronchitis (Jin, et al. 2000). That study found that with each increase of 10 μg/m^3 PM_{10}, the incidence rate of acute bronchitis increases 4.6 percent (95% CI 0.0-9.2%).

3.2.5. Asthma

- Asthma in children（≤15 yrs）

Wei F. et al., investigated the relationship between air pollution and incidence of asthma in children in four Chinese cities, Lanzhou, Guangzhou, Wuhan, and Chongqing. He found that the incidence rate of asthma in children increases 6.95 percent[*] with each 10μg/m^3 increase of PM_{10} (Wei, et al. 2000).

[*] 95％CI were not provided in the original paper.

- Asthma in adults （>15 yrs）

Using three European panel studies on adults (Dusseldorp, et al. 1995; Hiltermann, et al. 1998; Neukirch, et al. 1998), we calculated a joint relative risk of 1.039 (95% CI 1.019-1.059) per 10 μg/m^3 increase of PM_{10}. Another estimate from two U.S. panel studies (Pope, et al. 1991; Ostro, et al. 1991) was 1.002 (95% CI 0.998-1.006) per 10 μg/m^3 increase of PM_{10}. Combining these five studies yields a joint relative risk of asthma among adults of 1.004 (95% CI 1.000-1.008) per 10 μg/m^3 increase of PM_{10}.

Table 9-1 summarizes the concentration-response coefficients described above, along with their standard error (SE).

Table 9-2 summarizes the results of our meta-analysis, expressed as the relative risk of each health endpoint associated with 10 μg/m^3 increases of PM_{10}.

Figures 9-1 through 9-7 describe the results of individual studies and give the pooled estimate for each health endpoint.

Table 9-1 Summary of concentration-response coefficients with each increase of 10 $\mu g/m^3$ PM（%）

Health endpoints	Study	Population	PM	Concentration-response functions	
				Mean	SE
Total long-term mortality	Pope, et al. (U.S.)	≥30 yrs	PM_{10}	4.00	2.0
	Dockery, et al. (U.S.)	≥30 yrs	PM_{10}	8.50	2.30
Chronic bronchitis	Jin, et al. (Benxi)	Total population	TSP	3.00	1.02
	Ma, et al. (Shanghai)	Total population	TSP	2.90	—*
Respiratory hospital admission	Spix, et al.; Wordley, et al.; Prescott, et al. (Europe)	Total population	PM_{10}	0.80	0.21
	Thurston, et al.; Schwartz J, Burnett, et al. (North America)	Total population	PM_{10}	1.70	0.18
Cardiovascular hospital admission	Medina, et al.; Poloniecki, et al.; Wordley, et al.; Prescott, et al. (Europe)	Total population	PM_{10}	1.30	0.31
	Schwartz and Morris, Schwartz, Burnett, et al. (North America)	Total population	PM_{10}	0.80	0.18
Outpatient visits (internal medicine)	Xu x, et al. (Beijing)	Total population	TSP	0.22	0.05
Outpatient visits (pediatrics)	Xu X, et al. (Beijing)	Total population	TSP	0.25	0.08
Acute bronchitis	Jin L, et al. (Benxi)	Total population	TSP	3.00	1.53
Asthma (≤15 yrs)	Wei F, et al. (Guangzhou, Lanzhou, Chongqing, Wuhan)	≤15 yrs	PM_{10}	6.95	—*
Asthma (≥15 yrs)	Dusseldorp, et al., Hiltermann, et al., Neukirch, et al. (Euorpe)	≥15 yrs	PM_{10}	3.90	1.02
	Pope, et al.; Ostro, et al. (North America)	≥15 yrs	PM_{10}	0.20	0.20

* SE were not provided in the original paper.

Table 9-2 Relative risk of each health endpoint associated with each increase of $10 \mu g/m^3$ PM_{10} (mean and 95％CI)

Health endpoints	Population	Relative risk（95％ CI）
Total mortality	adults（≥30 yrs）	1.0430（1.0260，1.0610）
Chronic bronchitis	Total population	1.0460（1.0150，1.0770）
Respiratory hospital admission	Total population	1.0130（1.0010，1.0250）
Cardiovascular hospital admission	Total population	1.0095（1.0060，1.0130）

Outpatient visits (internal medicine)	Total population	1.0034（1.0019，1.0049）
Outpatient visits (pediatrics)	Total population	1.0039（1.0014，1.0064）
Acute bronchitis	Total population	1.0460（1.0000，1.0920）
Asthma	Children (≤15 yrs.)	1.070*
Asthma	Adults (≥15 yrs.)	1.0040（1.0000，1.0080）

* 95%CI were not provided in the original paper

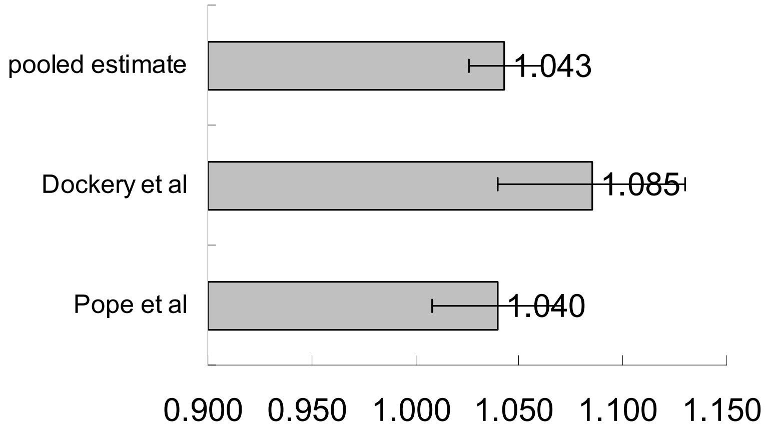


Figure 9-1 Relative risk of total long-term mortality with each increase of 10μg/m^3 PM_{10}

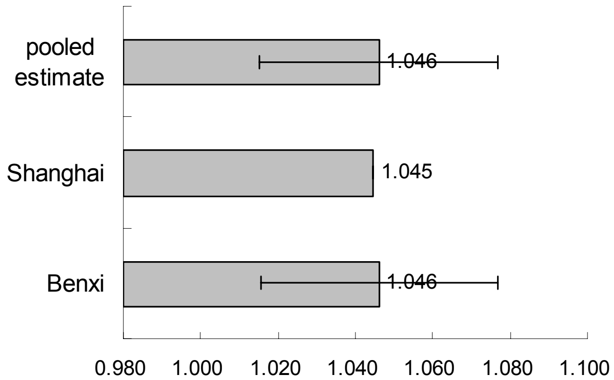


Figure 9-2 Relative risk of chronic bronchitis with each increase of 10μg/m^3 PM_{10}

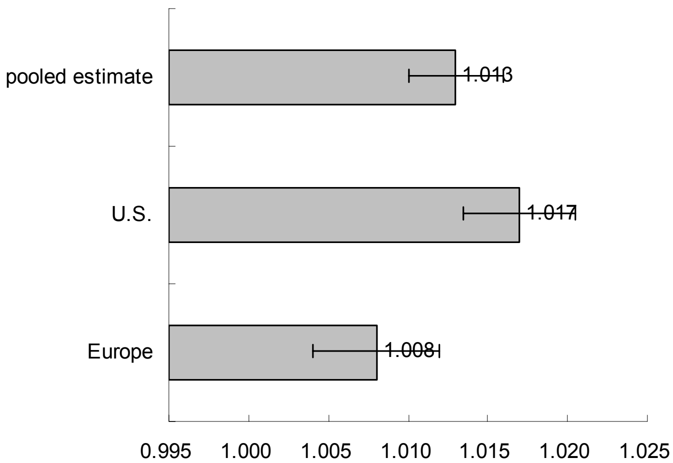


Figure 9-3 Relative risk of hospital admission for respiratory problems with each increase of 10μg/m^3 PM_{10}

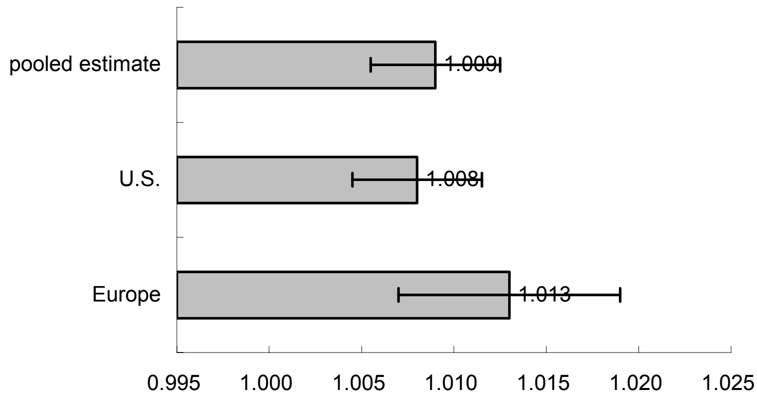


Figure 9-4 Relative risk of cardiovascular hospital admission with each increase of 10μg/m^3 PM_{10}

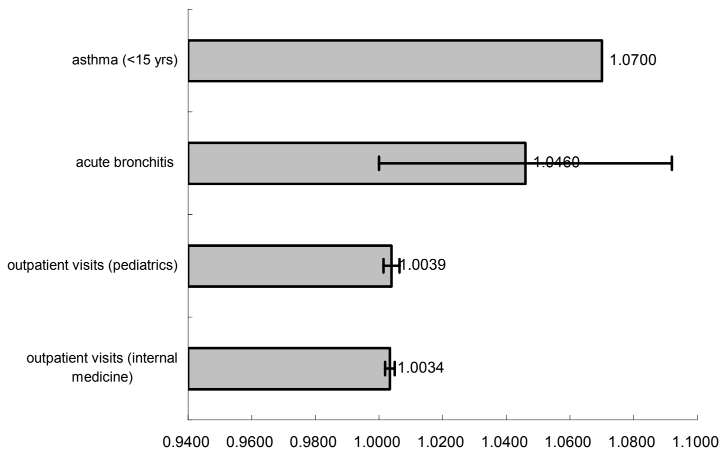


Figure 9-5 Relative risk of outpatient visits (to internal medicine and pediatrics), acute bronchitis, and asthma among children (≤15 yrs.) with each increase of 10μg/m^3 PM_{10}（We didn't conduct meta-analysis due to data limitations.）

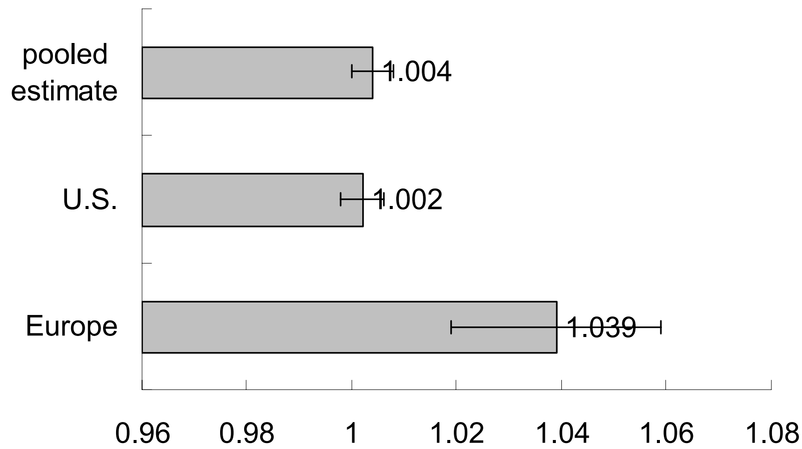


Figure 9-6 Relative risk of asthma among adults (>15 yrs.) with each increase of 10μg/m^3 PM_{10}

4. Discussion

Mortality is often considered the most important endpoint associated with air particulate exposure; scores of epidemiological studies have measured increases in mortality associated with particulate air pollution. Short-term air pollution levels on a given day or short period of days may trigger an increase in deaths within days or weeks. Most of the literature on the short-term effects of air pollution is based on time-series or case-crossover studies.

Regarding the long-term effects of air pollution on mortality, cohort studies reveal that long-term exposure to air pollution might lead to a measurable reduction in survival of the population. For the most part, these cohort studies on the long-term effects of pollution report substantially larger effects than daily time-series studies on the short-term effects of pollution.

Since the cohort studies provide a more complete assessment of the impact of exposure to air pollution than time-series studies do (Kunzli, et al. 2001), we used cohort-based exposure-response functions in our analysis. Unfortunately, we had to rely on the results of two U.S. cohort studies, because no such studies have been conducted in China. In addition, some of the exposure-response relationships we wished to analyze have not been researched in China so we had to rely on international, primarily from the U.S. and western Europe, studies.

Data from foreign studies, unfortunately, may not accurately reflect relative risks associated with air pollution in China. For example, we compared the short- and long-term relative risks of mortality associated with exposure to particulate matter in China and developed countries. The acute effects of particulate matter in western countries was calculated by conducting a meta-analysis of 109 literatures (Stieb, et al. 2002); in China, using a pooled estimate of Chinese literatures (Kan, et al. 2002). Chronic effects in western countries were estimated using two U.S. cohort studies; in China, using one Chinese cross-sectional study. Chinese studies generally reported lower relative mortality risk associated with air pollution exposure than their western counterparts (see Figure 9-8).

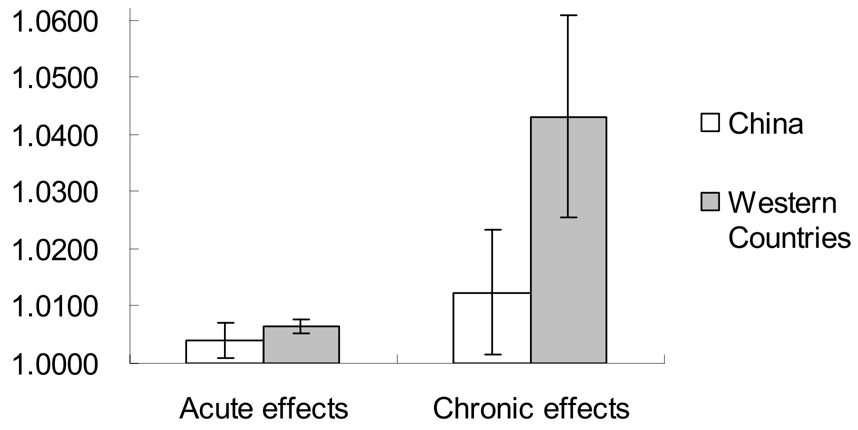


Figure 9-8 Relative risk of mortality in China and Western countries for each $10\mu g/m^3$ increase of PM_{10}

The reasons for this difference may include different air pollution levels, local population sensitivity, age distribution, and air pollutant components. For instance, the composition of motor vehicle emissions in Western Europe and the U.S., where most of the epidemiological studies were performed, differs substantially from that in China. This, together with other differences such as the predominant use of coal in China, implies that air pollution differs substantially in composition in China and the areas where most of the epidemiological studies we looked at were conducted.

Therefore, when exposure-response functions from developed countries are applied to other regions, Shanghai, for example, they should be revised to account for local conditions, such as the physical and chemical character of particulates, socio-economic status of the local population, etc. However, no such reference data currently exists.

The exposure-response coefficients looked at here, though, can at least serve as an important gauge of the health risk associated with air particulate exposure in China.

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Chapter 10. The Public Health Impact of Ambient Air Pollution Under Low-Carbon Policies

1. Introduction

The previous chapters of this report showed that low-carbon policies in Shanghai could decrease greenhouse gas (GHG) emissions, improve the local air quality, and decrease human exposure to air pollution. As part of the integrated assessment of low-carbon policies in Shanghai, this chapter will provide a quantitative estimate of the health effects of the various low-carbon policy scenarios we have been looking at.

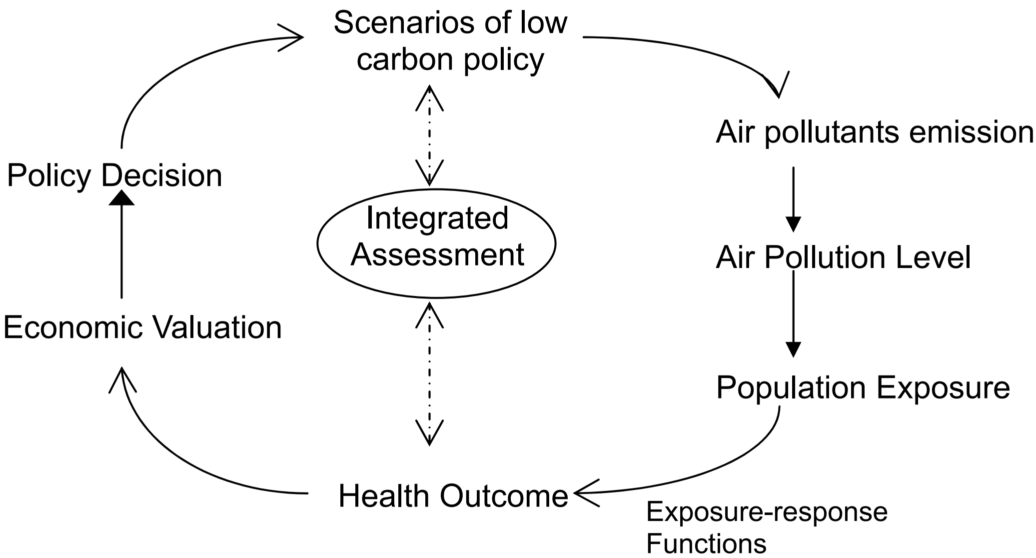

Figure 10-1 Framework Linking Low-Carbon Policies and Their Health Effects

Numerous epidemiological studies conducted over the past 20 years both in China and abroad confirm that exposure to ambient air pollution contributes to both mortality and morbidity. Some of these adverse health outcomes result from short-term exposure, others from long-term exposure. Although the underlying mechanisms have not yet been fully explained, state-of-the-art epidemiological research has consistently found that air pollution contributes to various adverse health outcomes, including reduced lung function, respiratory symptoms, chronic bronchitis, and mortality (Bate 1992).

To make a comprehensive risk assessment, it is important to quantify such health effects. Recent advances in epidemiological methods have made it possible to quantitatively assess the health impact associated with air pollution. Several studies showing the public health impact of air pollution have already been initiated and completed by local, national, and international organizations and institutions. One study, conducted by the World Health Organization (WHO), estimated that more than 2.7 million people per year throughout the world die due to air pollution, both outdoor and indoor, approximately 33 percent of whom die due to urban ambient air pollution (WHO 2003).

China is a developing country and has long relied on coal as its primary energy source. Current high speed economic growth is leading to increased energy demand. But because of the relatively poor energy technology now used in China, a great amount of pollution is emitted during energy consumption. China has been trying to save energy, optimize energy structure, and improve energy efficiency to shift to a more sustainable development path. Over the past decade, energy consumption has increased at a lower rate than gross domestic product (GDP).

Policy decisions made today in China will have a significant effect on future air pollution levels and public health. Policies in Shanghai are particularly important given that Shanghai's economic growth rate is among the highest in China. Here, we will evaluate the public health impact of ambient air pollution in Shanghai under various low-carbon policy scenarios.

2. Methods

2.1. Energy Scenarios and Air Pollutant Concentrations

For details of the low-carbon policy scenarios and the projected change in air quality resulting from them, refer to earlier chapters of the report.

2.2. Air Pollution Exposure Levels

2.2.1. Time Frame and Scenarios

The year 2000 was selected as the base period in this analysis. Air quality in 2010 and 2020 were estimated under the following scenarios:

- BAU
- EE
- EE + COAL + GAS (abbreviated "GAS" in the following part)
- EE + COAL + GAS + ELEC + WIND (abbreviated "WIND" in the following part)
- EE + COAL + GAS + ELEC + WIND + PM + SO2b (abbreviated "SO2b" in the following part)
- EE + COAL + GAS + ELEC + WIND + PM + SO2c (abbreviated "SO2c" in the following part)

2.2.2. Resolution of Exposure Assessment

In this assessment, Shanghai was divided into four kilometer by four kilometer grid cells, and changes in population exposure and adverse health effect incidence levels in each cell were estimated. The total health effect of air pollution in Shanghai is equal to the sum of all the grid-cell-specific changes in health outcomes.

2.2.3. Indicator Air Pollutants

Ambient air pollution consists of a mix of different pollutants—e.g., ozone, SO_2, NO_2, PM_{10}, total suspended particles, CO. In Shanghai, TSP, SO_2, and NO_x are major air pollutants and were routinely monitored up to July 1, 2000. Starting July 1, 2000, PM_{10} and NO_2 replaced TSP and NO_x as indicator pollutants.

The concentrations of different pollutants are correlated since they often have the same emission source, e.g., coal combustion. Therefore, in most epidemiological studies, it is impossible to attribute specific health effects to specific pollutants. A problem called the "double-counting effect" arises when the same health effects are associated more than one pollutant and then the health effects of each pollutant are aggregated for a total assessment of the effect of air pollution on public health.

For this analysis we selected PM_{10} as our air pollution indicator in calculating the impact of air pollution on health, since epidemiological evidence indicates that, among all pollutants, PM_{10} has the strongest association with adverse health effects. PM_{10} is a useful indicator for several sources of outdoor air pollution, including fossil-fuel combustion (Wilson and Spengler 1996). This choice of indicator is also in line with other similar assessments (Kunzli, et al. 2000).

2.2.4. Population Under Study

For this analysis, the exposed population comprised all people living in the Greater Shanghai area. The number of residents in each 4 km×4 km grid cell was then estimated based on population data collected by the Shanghai Bureau of Statistics. It is impossible, however, to have an accurate population number for each 4 km×4 km cell since community borders do not correspond to 4 km×4 km rectangular forms. To estimate each cell's population we calculated the population density of each community and multiplied it times the area each community occupied within a given cell. Population growth rate in each grid cell was assumed to be constant, and age distribution in each cell identical.

Then, using PM_{10} levels in and the population of each cell, we estimated the population exposure level to outdoor air pollution in 2010 and 2020 under each low-carbon policy scenario.

2.3. Estimated Health Effects

2.3.1. General Approach

Most epidemiological studies linking air pollution and health endpoints are based on a relative risk model in the form of Poisson regression (see Figure 10-2). The number of cases at a given concentration C is given by

$$E = \exp(\beta \times (C - C_0)) \times E_0 \qquad (1)$$

where C and C_0 are air pollutant concentrations under a given scenario and the baseline scenario, respectively, and E and E_0 are the number of cases of a given health outcome under concentrations C and C_0. The health effect under the scenario with respect to baseline scenario is the difference between E and E_0. To calculate this value to following data is needed: exposure-response functions (β), population exposure levels (C and C_0), and the number of cases in the baseline scenario (E_0). The following sections explain each of these components in detail.

In our analysis, we measured the health impact of each low-carbon scenario by comparing them both to the business as usual (BAU) scenario in 2010 and 2020 and to the base period of 2000.

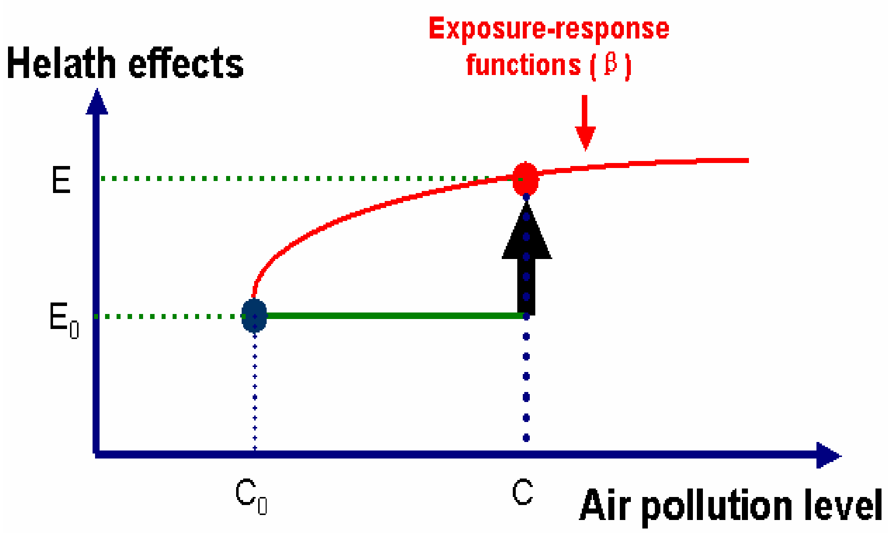

Figure 10-2 Model to derive the number of cases of a given health outcome under different scenarios

2.3.2. Health Outcome Selection

We sought to summarize particulate-related effects by researching the health outcomes, both morbidity to mortality changes, associated with different exposure levels. The following criteria were used in selecting health outcomes for this analysis:

- The health outcome has been studied in China. Only when research on widely-accepted health outcomes associated with air pollution was not available in Chinese literature—e.g., long-term effects on mortality—results from international literature were used.

- There is an established quantitative exposure-response relationship (in the form of either slope or relative risk) between air pollutants and the health outcome.
- Health outcomes excluded sub-clinical effects. We excluded sub-clinical effects, such as lung function changes, from our analysis because it is difficult measure their long-term health impact and monetary value based on current knowledge.
- Health outcomes had baseline data for either Shanghai or China as a whole. For example, restricted activity days (RADs), which is an important endpoint in many air pollution-related health impact assessments, was excluded from our analysis, because of the lack of baseline RAD data for China.

Based on the above criteria, data was gathered regarding the effect of particulate exposure on the following health outcomes:

- **Long-term mortality**
- **Morbidity**
  - Chronic bronchitis
  - Hospital admission (for respiratory and cardiovascular problems)
  - Outpatient visits (in internal medicine and pediatrics)
  - Other illnesses (acute bronchitis and asthma attacks)

2.3.3. Exposure-Response Functions

Exposure-response functions link air quality and the rate of a given health outcome. For details on the exposure-response functions used in our analysis, refer to chapter 9.

2.3.4 Baseline Incidence Data

In this analysis, the year 2000 was selected as the baseline period for our assessment. Data for various health outcomes in the year 2000 were gathered from actual data of collected in Shanghai or proxy data from other regions in China or the nation as a whole. These data were usually in the form of annual incidence rates.

3. Results

3.1. Population Exposure Assessment

According to population household registration, by the end of 2000 Shanghai's population was 13.13 million, accounting for about 1 percent of the nation's total. Population is projected to reach 14.00 million by 2010 and 14.30 million by 2020 (Shanghai Municipal Population and Family Planning Commission 2003).

Table 10-1 shows the age distribution of Shanghai residents according to the *Survey on 1 Percent Change of Population in China* conducted in 1995 (China Bureau of Statistics 1999).

Table 10-1 Percentage of population in Shanghai by age group

Age	Percent	Age	Percent
0-4	3.60	55-59	4.23
5-9	6.52	60-64	5.30
10-14	7.02	65-69	4.42
15-19	5.79	70-74	3.33
20-24	6.03	75-79	2.07
25-29	6.59	80-84	1.07
30-34	9.09	85-89	0.40
35-39	11.75	90-94	0.12
40-44	10.59	95-99	0.01
45-49	7.36	≥100	0.0027
50-54	4.71		

Combining the air quality level and population of each cell, we estimated the population exposure level to PM_{10} under different scenarios. Tables 10-2 and 10-3 summarize the proportion of the population exposed to PM_{10} in 2010 and 2020.

Table 10-2 Percentage of population exposed to PM_{10} under various scenarios, 2010

PM_{10} level (μg/m^3)	BAU	EE	GAS	WIND	SO_2b	SO_2c
0-10	0.85	1.62	3.83	5.06	13.45	12.92
10-20	8.40	10.60	18.50	19.69	19.52	20.20
20-30	11.23	12.96	9.98	9.60	63.88	64.79
30-40	7.85	6.58	19.28	33.17	3.15	2.09
40-50	5.20	6.82	46.58	32.46	—	—
50-60	6.09	24.08	1.81	0.02	—	—
60-70	23.36	37.33	0.02	—	—	—
70-80	36.41	0.02	—	—	—	—
80-90	0.62	—	—	—	—	—
TOTAL	100	100	100	100	100	100

Table 10-3 Percentage of population exposed to PM_{10} under various scenarios, 2020

PM_{10} level (mcg/m^3)	BAU	EE	GAS	WIND	SO_2b	SO_2c
0-10	0.03	0.20	5.09	6.15	22.67	22.67
10-20	2.32	5.32	19.52	20.07	37.15	42.23
20-30	5.27	9.42	10.17	11.23	40.17	35.09
30-40	6.50	9.79	41.60	58.39	0.02	0.02
40-50	7.87	4.94	21.99	4.07	—	—
50-60	5.17	3.85	1.61	0.09	—	—
60-70	3.40	5.74	0.02	—	—	—
70-80	2.96	14.84	—	—	—	—
80-90	4.79	36.72	—	—	—	—
90-100	4.31	9.16	—	—	—	—
100-110	11.48	0.02	—	—	—	—
110-120	30.25	—	—	—	—	—
120-130	15.63	—	—	—	—	—
130-140	0.02	—	—	—	—	—
TOTAL	100	100	100	100	100	100

The PM_{10} levels shown above are much lower than the actual PM_{10} concentration in Shanghai because in the present study only PM_{10} emitted in energy consumption was assessed. PM_{10} from other sources—natural sources, construction sites, etc.—were excluded.

In 2000, the population-weighted average exposure concentration of PM_{10} generated by energy consumption in Shanghai was 30.36 μg/m^3. Figure 10-3 shows the effect of various low-carbon scenarios on the population-weighted average PM_{10} concentrations in 2000, 2010 and 2020. Clearly the "SO_2b" and "SO_2c" scenarios reduce population-weighted average PM_{10} concentration most significantly.

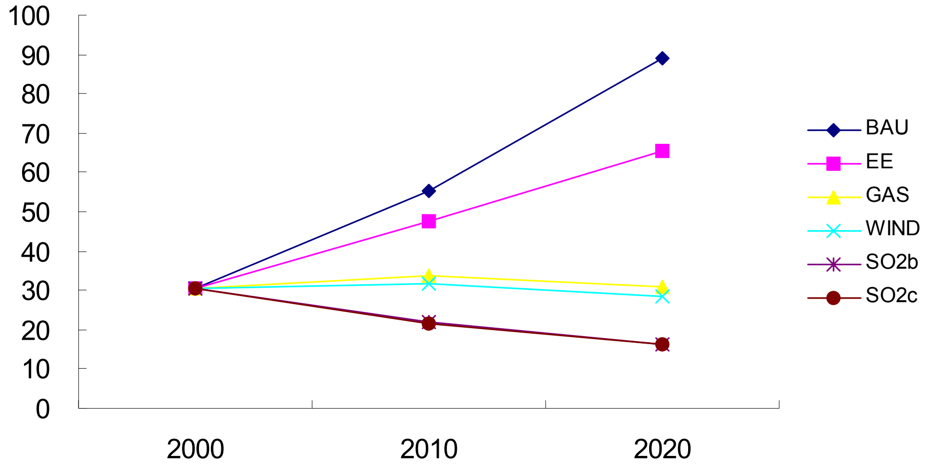

Figure 10-3 Population-weighted average PM_{10} concentrations under various scenarios

3.2. Health Effects

Tables 10-4 and Table 10-5 summarize the PM_{10} exposure-response coefficients (mean and 95% CI) and baseline rates of the health outcomes we analyzed. The public health impact of air pollution from energy consumption is computed using population PM_{10} exposure levels under each scenario, the exposure-response functions given in Table 10-4, and the baseline rates for the health outcomes shown in Table 10-5. Tables 10-6 to 10-9 show the mean and 95% CI of the public health impact results in 2010 and 2020.

Table 10-4 Summary of exposure-response coefficients used in our analysis

Health endpoints	Population	Relative risk (95% CI)
Total mortality	Adults (≥30 yrs.)	1.0430 (1.0260, 1.0610)
Chronic bronchitis	Total population	1.0460 (1.0150, 1.0770)
Respiratory hospital admission	Total population	1.0130 (1.0010, 1.0250)
Cardiovascular hospital admission	Total population	1.0095 (1.0060, 1.0130)
Outpatient visits (internal medicine)	Total population	1.0034 (1.0019, 1.0049)
Outpatient visits (pediatrics)	Total population	1.0039 (1.0014, 1.0064)
Acute bronchitis	Total population	1.0460 (1.0000, 1.0920)
Asthma	Children (≤15 yrs.)	1.070*
Asthma	Adults (≥15 yrs.)	1.0040 (1.0000, 1.0080)

**** 95%, CI were not provided in the original paper***

Table 10-5 Summary of the baseline rate for health endpoints used in our analysis (per person)

Health Outcomes	Frequency	Source
Mortality (adult ≥30)	0.01077	Shanghai Municipal Bureau of Public Health, 2000
Chronic bronchitis (all ages)	0.01390	China Department of Health, 1998
Mortality (all ages)	0.00728	Shanghai Municipal Bureau of Public Health, 2000
Respiratory hospital admission (all ages)	0.01240	Shanghai Municipal Bureau of Public Health, 2000
Cardiovascular hospital admission (all ages)	0.00850	Shanghai Municipal Bureau of Public Health, 2000
Outpatient visits- internal medicine (all ages)	3.26000	Shanghai Municipal Bureau of Public Health, 2000
Outpatient visits-pediatrics (all ages)	0.30000	Shanghai Municipal Bureau of Public Health, 2000
Acute bronchitis (all ages)	0.39000	Wang et al, 1994
Asthma attack (children <15 years)	0.06930	Ling et al, 1996
Asthma attack (adults ≥15 years)	0.05610	Ling et al, 1996

Table 10-6 Health benefits of low-carbon scenarios with respect to the BAU scenario, 2010 (mean and 95% CI)

Health endpoint	EE	GAS	WIND	SO_2b	SO_2c
Premature death	2804 (1766, 3811)	7452 (4754, 9994)	8249 (5274, 11040)	11470 (7403, 15200)	11580 (7473, 15330)
Chronic bronchitis	5828 (2048, 9069)	15450 (5558, 23500)	17100 (6175, 25900)	23740 (8722, 35360)	23960 (8805,35660)
Respiratory hospital admission	1570 (124, 2934)	4269 (341, 7906)	4745 (380, 8774)	6710 (541, 12330)	6774 (546,12440)
Cardiovascular hospital admission	796 (507, 1080)	2169 (1385, 2935)	2412 (1541, 3262)	3417 (2187, 4614)	3450 (2208, 4658)
Outpatient visits (internal medicine)	111300 (61860, 158400)	304600 (169500, 433100)	339000 (188700, 481900)	481900 (268500, 684500)	486500 (271100, 691100)
Outpatient visits (pediatrics)	11540 (4201, 18970)	31590 (11520, 51820)	35150 (12820, 57650)	49960 (18250, 81820)	50450 (18420, 82610)
Acute bronchitis	186100 (0, 334700)	493700 (0, 858500)	546400 (0, 944500)	758900 (0, 1280000)	765700 (0, 1291000)
Asthma attacks	3652 (3162, 4134)	9585 (8242, 10890)	10590 (9093, 12040)	14590 (12470, 16650)	14720 (12580, 16800)

Table 10-7 Health benefits of low-carbon scenarios with respect to the BAU scenario, 2020 (mean and 95% CI)

Endpoint	EE	GAS	WIND	SO_2b	SO_2c
Premature death	9870 (5911, 14170)	22210 (13720, 30860)	23100 (14300, 32010)	27280 (17090, 37380)	27340 (17130, 37450)
Chronic bronchitis	20700 (6636, 35400)	46330 (15730, 74980)	48160 (16410, 77610)	56770 (19760, 89720)	56890 (19810, 89880)
Respiratory hospital admission	5057 (387, 9782)	12030 （941, 22770）	12560 (985, 23730)	15150 (1197, 28380)	15190 (1200, 28450)
Cardiovascular hospital admission	2537 (1600, 3477)	6075 （3856, 8273）	6347 (4030, 8639)	7672 (4884, 10420)	7691 (4896, 10440)
Outpatient visits (internal medicine)	348600 (193000, 498300)	844200 (468700,1204000)	882700 (490200, 1258000)	1072000 (595700, 1526000)	1074000 (597200, 1530000)
Outpatient visits (pediatrics)	36210 (13090, 59950)	87620 (31810, 144400)	91620 (33270, 150900)	111200 (40450, 182800)	111500 (40550, 183300)

Acute bronchitis	659700 (0,1363000)	1478000 （0，2819000）	1537000 (0, 2913000)	1812000 (0, 3340000)	1816000 (0, 3346000)
Asthma attacks	13580 (12040,15130)	29590 （25870，33270）	30700 (26800, 34540)	35860 (31140, 40500)	35930 (31200, 40590)

Table 10-8 Increase/decrease in the incidence of health endpoints under low-carbon scenarios with respect to the base period of 2000, 2010 (mean and 95% CI)

Health endpoint	Increase in incidence					Decrease in incidence	
	BAU	EE	GAS	WIND		SO_2b	SO_2c
Premature death	8718 (5582,11650)	5914 (3816, 7836)	1266 (828, 1653)	469 (308, 610)		2754 (1821, 3553)	2858 (1891, 3686)
Chronic bronchitis	18070 (6542, 27290)	12240 (4494, 18220)	2614 (984, 3792)	967 (367, 1394)		5674 (2180, 8067)	5889 (2263, 8369)
Respiratory hospital admission	5027 (403, 9287)	3457 (278, 6353)	759 (62, 1381)	283 (23, 513)		1682 (138, 3038)	1746 (143, 3154)
Cardiovascular hospital admission	2556 (1634, 3457)	1760 (1127, 2377)	387 (249, 522)	145 (93, 195)		861 (554, 1157)	894 (575, 1201)
Outpatient visits (internal medicine)	359500 (200200, 511000)	248200 (138300, 352600)	54880 (30610, 77870)	20510 (11440, 29090)		122400 (68350, 173500)	127100 （70960，180200）
Outpatient visits (pediatrics)	37280 (13600,61120)	25730 (9397, 42150)	5688 (2081, 9298)	2125 (778, 3472)		12680 (4648, 20700)	13170 （4826，21490）
Acute bronchitis	577300 (0, 994200)	391200 (0, 659500)	83600 (0, 135600)	30940 (0, 49700)		181500 (0, 286000)	188400 （0，296700）
Asthma attacks	11170 (9589, 12710)	7520 (6427, 8581)	1588 (1346, 1821)	586 (496, 673)		3418 (2879, 3935)	3547 （2988，4083）

Table 10-9 Increase/decrease in the incidence of health endpoints under low-carbon scenarios with respect to the base period of 2000, 2020 (mean and 95% CI)

Health endpoint	Increase in incidence				Decrease in incidence		
	BAU	EE	GAS		WIND	SO_2b	SO_2c
Premature death	22710 (14050,31520)	12840 (8139, 17350)	499 (327, 651)		385 (253, 500)	4571 (3040, 5863)	4629 (3079, 5937)
Chronic bronchitis	47370 (16110,76470)	26660 (9477, 41070)	1031 (389, 1493)		793 (301, 1141)	9409 (3650, 13250)	9528 (3697, 13410)
Respiratory hospital admission	12330 (966,23310)	7274 (579, 13530)	300 (24, 545)		232 (19, 421)	2819 (232, 5073)	2855 (235, 5138)
Cardiovascular Hospital admission	6228 (3954,8479)	3691 (2354, 5002)	153 (98, 206)		119 (76, 160)	1444 (930, 1938)	1463 (942, 1963)
Outpatient visits (internal medicine)	865900 (480800,1234000)	517300 (287800, 735900)	21680 (12090, 30760)		16830 (9391, 23870)	205800 (114900, 291500)	208400 (116400, 295300)
Outpatient visits (pediatrics)	89870 (32630,148100)	53660 (19550, 88110)	2247 (822, 3672)		1744 (639, 2849)	21320 (7818, 34760)	21590 (7919, 35210)
Acute bronchitis	1511000 (0,2872000)	851600 (0, 1509000)	32960 (0, 53390)		25370 (0, 40680)	301100 (0, 467600)	304900 (0, 473400)
Asthma attacks	30220 (26400,33990)	16640 (14350, 18860)	626 (530, 718)		480 (406, 552)	5646 (4740, 6512)	5717 (4799, 6594)

4. Conclusions

Low-carbon policies would have a significant impact on Shanghai public health. Relative to the BAU scenario, implementing low-carbon policies in Shanghai could prevent 2,804-11,580 (mean value) avoidable deaths in 2010 and 9,870-27,340 deaths in 2020. They would decrease even more the incidence of several diseases.

We also estimated the health impact of air pollution under low-carbon policy scenarios relative to the incidence of health incomes in 2000. The BAU scenario would cause an increase of 8718 PM_{10}-related deaths from 2000 to 2010; the EE scenario, an increase of 5914 deaths; the GAS scenario, an increase of 1266 deaths; and the WIND scenario, an increase of 469 PM_{10}-related deaths. The SO_2b and SO_2c scenarios would decrease the number of PM_{10}-related deaths by 2,754 and 2,858 deaths, respectively.

By 2020, the increase in number of PM_{10}-related deaths from 2000 in the BAU scenario will reach 22,710; in the EE scenario, 12,840; and in the GAS scenario, 499. By 2020, the WIND, SO_2b, and SO_2c scenarios would decrease the number of PM_{10}-related deaths by 385, 4571, and 4629 deaths, respectively.

5. Discussion

Developing a sustainable energy and health future is one of the biggest challenges facing Shanghai given its rapid economic development. This study provides an opportunity for Shanghai to look into its future and decide how to shape it.

The approaches we used are similar to those employed elsewhere and widely used in heath-based risk assessments. The results illustrate that low-carbon policies can reduce air pollutant emissions, improve air quality, and meliorate public health.

Quantifying the public health impact of air pollution is an increasingly critical tool in policy decision making. Doing so, however, remains a challenge, given gaps in scientific knowledge regarding the health effects of air pollution, as well as the uncertainties characterizing several calculation steps.

Our current estimation of the public health impact of air pollution under several low-carbon scenarios is conservative for three reasons. First, PM_{10} was our lone indicator of outdoor air pollution levels, which probably caused us to omit some health effects of other air pollutants, thus underestimating the total health impact of total air pollution. Although PM_{10} is a good indictor of air pollution, there is clear evidence that other pollutants, such as ozone, nitrogen oxides, and sulfur dioxide, have independent health consequences. In addition, we did not include the synergistic effects that exist between various air pollutants or between air pollutants and co-factors such as pollen and other allergens.

Second, as stated earlier, the air pollution prediction model we used could only project primary PM_{10} and sulfur dioxide levels. Thus, we could not estimate the health effects attributable to secondary PM_{10}, such as sulfates and nitrates. Previous studies have shown that ammonium sulfate and nitrate account a substantial proportion of fine particles in Shanghai (Ye, et al. 2003).

Third, we chose only health outcomes that that can be quantitatively estimated and then assigned a monetary value for further assessment. Some endpoints, e.g. sub-clinical symptoms and declines in pulmonary function, were not included in this analysis, despite evidence linking them with air pollution exposure. Neither did we estimate the effect of exposure to ambient air pollution on cancer incidence, though a recent cohort study in the U.S. has suggested their association (Pope et al, 2002).

Dozens of epidemiological studies have measured increases in mortality, often regarded as the most important health endpoint, associated with particulate air pollution. Among them, time series studies estimated the acute effects of air pollution by examining the association between daily numbers of deaths and daily or multi-day changes in air pollution; cohort studies show that the effect of long-term exposure to air pollution on survival. Since the cohort studies provide a more complete assessment of the health impact of air pollution than time-series studies (Kunzli, et al. 2001), we used cohort-based exposure-response functions in our analysis.

Our health outcome baseline rates also strongly influence our analysis results. While the mortality data is accurate, morbidity and health-care system data are estimates with some inherent uncertainty.

In addition, these baseline rates were assumed to be the same in all cells; however, this does not exactly reflect the actual geographical distribution of health outcome incidence levels, including the obvious disparity in health status between rural and urban residents of Shanghai. For example, the incidence rate of chronic bronchitis in Shanghai's urban areas was about 18.72‰; the incidence rate in Shanghai's rural areas was only 10.94‰ (China Department of Health 1998). A more detailed study needs to be conducted using different baseline rates in different areas.

Many calculations of the impact of ambient air pollution set a threshold level of pollutant exposure or "reference exposure." This threshold level is the level below which there is no observed adverse health damage. In our analysis (using Formula 1) we used no such threshold. If we had, Formula 1 would have been replaced by

$$E = \exp(\beta \times (\max(C, Ct)-\max(C_0, C_t)))\times E_0 \qquad (2)$$

where C_t is the threshold level.

In an air pollution-related health impact assessment, there are many places in which to place this threshold level, including no threshold (or zero threshold), natural background level, the lowest observed level in epidemiological studies, and legal/policy established standards—such as the U.S. Environmental Protection Agency National Ambient Air Quality Standards (NAAQS) or China National Air Quality Standards. The possible existence of a threshold level is a very important scientific issue for air pollution-related health impact assessment. However, there is currently no scientific basis for setting a particular PM_{10} threshold. Therefore, we set none. However, we could explore the potential impact with various threshold assumptions for sensitivity analysis.

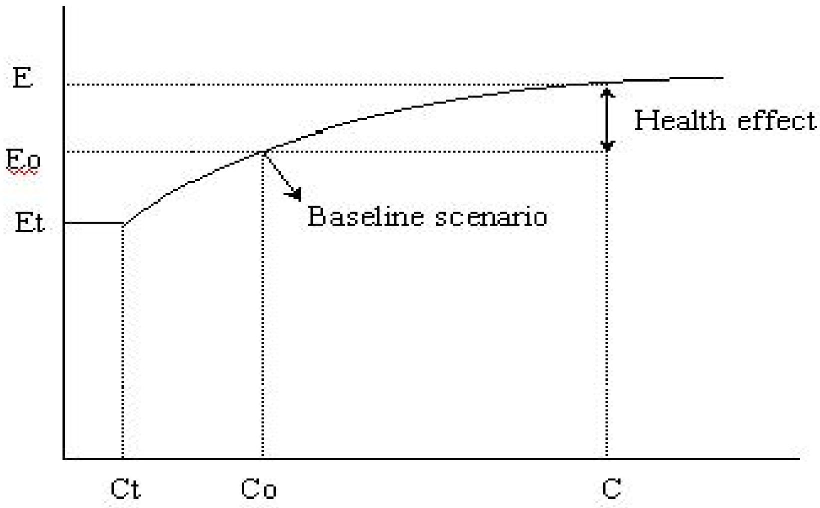

Figure 10-4 Model to derive the number of cases of a given health outcome under different scenarios with a threshold concentration

There is uncertainty in each step of any health risk assessment. For instance, parameters in our analysis, such as the exposure-response functions coefficients, are treated as distributions rather than constants. To deal with this uncertainty, we performed a Monte Carlo simulation in the Analytica® modeling environment (Lumina Decision System), and the final result was given as a range of impact rather than an exact point estimate.

Despite of the uncertainties described above, our analysis still clearly shows what a drastic effect low-carbon policies would have on public health in Shanghai. Considering public health when making energy policy will prevent thousands of deaths and tens of thousands of health problems.

Further health impact assessment method development, especially in dealing with uncertainty, transference of exposure-response functions, and health indicators such as DALYs, would yield even better policy development tools. Such development could be accomplished through close collaboration between air pollution modelers, epidemiologists, economists, and policy makers.

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Chapter 11. The Economic Valuation of Health Outcomes Associated with Air Pollution under Low Carbon Policies

1. Introduction

The valuation of health outcomes is a critical component in estimating the social cost of air pollution: it makes possible cost-benefit analyses and provides a basis deciding actions. The goal of this analysis is the valuation of the health effects of air pollution under low-carbon policy scenarios in Shanghai.

There are several methods for estimating the monetary value of health outcomes. The willingness-to-pay (WTP) approach measures how much individuals are willing to pay to improve their own security or the security of others. The main advantage of WTP is that is clearly tracks individual viewpoints and the wishes of the concerned population, meeting the requirement of welfare economics. However, it is difficult to obtain reliable and correct empirical estimations needed for WTP (Viscusi 1992).

A variety of techniques have been used to measure WTP value: labor-market (hedonic) studies, the contingent valuation method (CVM), and various types of market-based analysis. Labor-market analysis studies generally attempt to infer the compensation required for the increased risk associated with particular occupations while keeping all other attributes of the job and the worker equal. Contingent valuation methods (CVM) conduct surveys to determine what people are willing to pay to reduce the likelihood of premature death or certain diseases. Market-based approaches calculate how much people are willing to pay goods whose only purpose is to reduce the risks confronting an individual (Viscusi 1992).

Comment [KH1]:

For mortality valuation, the most commonly used approach is the value of a statistical life (VOSL). VOSL measures the value of a given reduction in risk and an individual's willingness-to-pay to reduce the risk, relying on wage and occupational risk tradeoff data or the results of CVM studies. This analysis does not yield the value of an identifiable life, but rather the value of reducing fatal risks in a population (Viscusi, 1992).

Comment [KH2]:

There is also a substantial literature on the valuation of health outcomes that relies on the human capital approach (HCA) and cost of illness (COI). The Human Capital approach considers individuals as units of human capital that produce goods and services for society; HCA assesses the costs of a premature death by counting the discounted values of future production which the "victims" could have generated if they had not died prematurely. The cost of illness (COI) approach is similar to HCA, but applies to morbidity. COI estimates the medical treatment costs plus the loss of production due to a possible incapacity to work.

The main advantage of these two approaches is their simple and transparent calculation method, resulting in higher social acceptance. However, both neglect a basic principle of welfare economics theory, each valuation of positive and negative impacts has to be based on the variations in the utility of the concerned individuals. Actually, HCA and COI are not entirely unconnected with WTP; theory shows that they provide a lower bound estimate of WTP (Cropper, et al. 1990).

This analysis for the most part used WTP values, only using COI for some morbidity endpoints for which WTP values have not been calculated.

2. Methods

2.1. General Approach

The effect of air pollution on mortality was assessed using the value of a statistical life (VOSL) measure. Literature regarding VOSL or the willingness to pay to avoid a statistical premature death comes mainly from the United States. Due to limited time and budget, we used on a contingent valuation study that was conducted in Chongqing, China to estimate VOSL for Shanghai. The effect of income on VOSL was also accounted for in the value transfer.

Since there are no Chinese WTP studies for several morbidity endpoints we inferred WTP values from U.S. Environmental Protection Agency WTP values using appropriate conversion data. We used COI approach to value hospital admission and outpatient visits endpoints due to lack of relevant WTP literature.

We calculated the annual growth in unit values for various endpoints assuming a constant 4 percent annual growth in per capita income, which was estimated using the Shanghai gross domestic product (GDP) growth scenario described by Chen Changhong, et al., and the relationship between incomes and GDP growth in China (China Development Planning Commission 2003).

The value of a change in the incidence of a given adverse health outcome was calculated by multiplying the change in incidence—e.g., the number of avoidable deaths—by the unit monetary value—i.e., the value of a single case avoided. Since both health outcomes and unit values are distributions rather than constants, we performed a Monte Carlo simulation in the Analytic® environment to calculate the economic effect.

2.2. Unit Value of Premature Death Associated with Air Pollution

Our value for premature death associated with air pollution is based primarily on a Chongqing study on the WTP value for reductions in the mortality risk related to air pollution (Wang, et al. 2001). The study reported an average WTP value for saving a statistical life of US$34,750, calculated using CVM. The study also reported that increase of $145.8 in annual income, increases the value of saving a statistical life in Chongqing by $14,550.

The 2001 average annual income in Chongqing was $495.7 (Wang et al, 2001), compared with $1234.5 in Shanghai (Shanghai Municipal Statistics Bureau, 2001). Accounting for this difference using Chongqing's coefficient between marginal WTP and income, we calculated a Shanghai VOSL of US$108,500. Note that Shanghai's annual income of $1234.5 is average annual income of all Shanghai residents, both urban and rural. The different incomes of urban and rural residents were accounted for in the conversion process.

2.3. Unit Value of Morbidity Change Associated with Air Pollution

Air pollution also affects human morbidity, and the valuation of illness and disability is important for assessing the total social cost of air pollution. WTP values for avoiding morbidity outcomes are limited and based mostly on U.S. data. Cost of illness (COI) is another method used to value morbidity. COI estimates the economic cost of health care and lost output due to morbidity, including both direct—hospital treatment, medical care, lost wages, etc.—and indirect costs. Our analysis used WTP values when they were available and COI values when they were not.

2.3.1. Valuation of Chronic Bronchitis

Chronic bronchitis is the only air pollution-related morbidity endpoint that may last for the rest of an individual's life. Two U.S. studies, Viscusi, et al. (1990) and Krupnick and Cropper, use CVM to provide estimated WTP values for avoiding chronic bronchitis. We used the approach outlined in the *The Benefits and Costs of the Clean Air Act 1990 to 2010* to establish the best estimate from these two studies. The Monte Carlo analysis then generated a mean WTP value of US$260,000 (1990 dollars) to avoid an air pollution-related case of chronic bronchitis.

Risk-risk and risk-dollar trade-off methods used by Viscusi, et al. (1990) for estimating WTP values indicated the ratio between VOSL and the WTP value of avoiding a case of chronic bronchitis should be kept constant (Lvovsky, et al. 2000). The U.S. EPA calculated a VOSL of US$4.8 million (1990 dollars), and we calculated a Shanghai VOSL of US$ 108,500. We adjusted the WTP value of avoiding a new case of chronic bronchitis accordingly, reaching a mean value of US$ 6,050 (in 2000 US$) for Shanghai.

Comment [KH3]:

2.3.2. Valuation of Acute Morbidity Outcomes

Hospital admissions and outpatient visits. Due to the lack of WTP literature on hospital admissions and outpatient visits endpoints, we used COI to value them. The direct cost of morbidity can be divided into two categories, medical expenses and lost productivity—i.e., lost wages, days missed from work, and days when activities were significantly restricted due to illness. Indirect costs, such as averting behavior, intangible costs, etc., were excluded.

The cost of medical treatment for hospital admissions was calculated based on the average duration of a hospital admission and the average daily cost of a hospital stay in Shanghai (Shanghai Municipal Bureau of Public Health 2001). Lost wages were estimated based on the duration of time away from work and average per capita income in Shanghai (Shanghai Municipal Statistics Bureau 2001).

Comment [KH4]:

Comment [KH5]:

Acute bronchitis and asthma attacks. We estimated the WTP values for acute bronchitis and asthma attacks from the U.S. EPA WTP values (U.S. EPA 1999). The average per capita incomes of U.S. and Shanghai residents were used to convert U.S. values to Shanghai values. The income elasticity was assumed to be 1.

Comment [KH6]:

3. Results

3.1. Unit Values for All Health Endpoints

Table 11-1 summarizes the mean unit values, as well as the specific approach used in their derivation, for various endpoints associated with air pollution in Shanghai in 2000.

Table 11-1 Summary of unit value for various health endpoints, 2000 (in 2000 US$)

Health endpoint	Mean (95%CI)	Approach
Premature death	108,500 (101,900, 115,100)	WTP
Chronic bronchitis	6,050 (807, 20,130)	WTP
Respiratory hospital admission	710*	COI
Cardiovascular hospital admission	1,043*	COI
Outpatient visits (internal medicine)	14*	COI
Outpatient visits (pediatrics)	14*	COI
Acute bronchitis	7.2 (2.6,11.9)	WTP
Asthma attacks	5.3 (2.3,8.3)	WTP

* The available data in Shanghai did not provide the distribution of values.

3.2. Economic Valuation of Health Outcomes

Using the unit values summarized above and the health benefit/burden values summarized in the previous chapter, we computed the total economic loss/benefits of health outcomes under different low-carbon scenarios, with respect to both the BAU scenario and the base period of 2000. Tables 11-2 to 11-5 show these results for 2010 and 2020.

Table 11-2 Economic benefits of low-carbon policy scenarios with respect to the BAU scenario, 2010 (millions of 2000 US$; mean and 95% CI)

	EE	GAS	WIND	SO_2b	SO_2c
Premature deaths	450.40 (408.90-495.60)	1197.00 (1087.00-1317.00)	1325.00 (1203.00-1458.00)	1842.00 (1672.00-2026.00)	1860.00 (1689.00-2047.00)
Chronic bronchitis	49.45 (44.89-54.41)	133.10 (120.90-146.50)	144.90 (131.50-159.40)	201.50 (182.90-221.70)	205.40 (186.50-226.00)
Respiratory hospital admissions	1.65 (1.50-1.82)	4.49 (4.07-4.94)	4.99 (4.53-5.49)	7.05 (6.40-7.76)	7.12 (6.46-7.83)
Cardiovascular hospital admissions	1.23 (1.12-1.35)	3.35 (3.04-3.69)	3.72 (3.38-4.10)	5.28 (4.79-5.81)	5.33 (4.84-5.86)
Outpatient visits (internal medicine)	2.31 (2.09-2.54)	6.31 (5.73-6.95)	7.03 (6.38-7.73)	9.99 (9.07-10.99)	10.08 (9.15-11.09)
Outpatient visits (pediatrics)	0.24 (0.22-0.26)	0.65 (0.59-0.72)	0.73 (0.66-0.80)	1.04 (0.94-1.14)	1.05 (0.95-1.15)
Acute bronchitis	2.00 (1.82-2.21)	5.32 (4.83-5.86)	5.88 (5.34-6.47)	8.17 (7.42-8.99)	8.22 (7.46-9.04)
Asthma attacks	0.03 (0.03-0.03)	0.08 (0.07-0.08)	0.08 (0.08-0.09)	0.11 (0.10-0.13)	0.12 (0.11-0.13)
TOTAL*	**507.31**	**1350.30**	**1492.33**	**2075.13**	**2097.30**

Table 11-3 Economic benefits of low-carbon policy scenarios with respect to the BAU scenario in 2020 (millions of 2000 US$; mean and 95% CI)

	EE	GAS	WIND	SO_2b	SO_2c
Premature deaths	2346.00 (1934.00-2841.00)	5280.00 (4352.00-6394.00)	5490.00 (4525.00-6648.00)	6485.00 (5346.00-7853.00)	6499.00 (5357.00-7870.00)
Chronic bronchitis	260.30 (214.50-315.20)	580.50 (478.50-702.90)	613.50 (505.70-742.90)	711.90 (586.80-862.00)	705.00 (581.10-853.70)
Respiratory hospital admission	7.87 (6.49-9.53)	18.72 (15.43-22.66)	19.54 (16.11-23.66)	23.57 (19.43-28.54)	23.63 (19.48-28.62)
Cardiovascular hospital admission	5.80 (4.78-7.02)	13.88 (11.44-16.81)	14.51 (11.96-17.56)	17.53 (14.45-21.23)	17.58 (14.49-21.28)
Outpatient visits (internal medicine)	10.69 (8.82-12.95)	25.90 (21.35-31.36)	27.08 (22.32-32.79)	32.88 (27.11-39.82)	32.95 (27.16-39.89)
Outpatient visits (pediatrics)	1.11 (0.92-1.35)	2.69 (2.22-3.26)	2.81 (2.32-3.40)	3.41 (2.81-4.13)	3.42 (2.82-4.14)
Acute bronchitis	10.53 (8.68-12.76)	23.28 (19.19-28.19)	24.31 (20.04-29.44)	28.59 (23.56-34.62)	28.66 (23.62-34.70)
Asthma attacks	0.16 (0.13-0.19)	0.34 (0.28-0.42)	0.36 (0.29-0.43)	0.42 (0.34-0.51)	0.42 (0.34-0.51)
TOTAL*	**2642.45**	**5945.31**	**6192.11**	**7303.30**	**7310.66**

Table 11-4 Economic loss/benefits under different scenarios with respect to the base period of 2000, 2010 (millions of 2000 US$; mean and 95% CI)

Health endpoints	Economic loss					Economic benefits	
	BAU	EE	GAS	WIND		SO_2b	SO_2c
Premature deaths	1400.00 (1271.00-1540.00)	949.80 862.30-1045.00	203.40 (184.60-223.80)	75.31 (68.38-82.87)		442.20 (401.40-486.60)	459.20 (416.90-505.30)
Chronic bronchitis	157.30 (142.80-173.10)	104.30 94.70-114.80	21.94 (19.92-24.14)	8.25 (7.49-9.08)		48.16 (43.73-53.00)	50.48 (45.83-55.55)
Respiratory hospital admission	5.28 (4.80-5.81)	3.63 3.30-4.00	0.80 (0.72-0.88)	0.30 (0.27-0.33)		1.77 (1.61-1.95)	1.84 (1.67-2.02)
Cardiovascular hospital admission	3.95 (3.58-4.34)	2.72 2.47-2.99	0.60 (0.54-0.66)	0.22 (0.20-0.25)		1.33 (1.21-1.46)	1.38 (1.25-1.52)
Outpatient visits (internal medicine)	7.45 (6.76-8.20)	5.14 4.67-5.66	1.14 (1.03-1.25)	0.43 (0.39-0.47)		2.54 (2.30-2.79)	2.63 (2.39-2.90)
Outpatient visits (pediatrics)	0.77 (0.70-0.85)	0.53 0.48-0.59	0.12 (0.11-0.13)	0.04 (0.04-0.05)		0.26 (0.24-0.29)	0.27 (0.25-0.30)
Acute bronchitis	6.10 (5.54-6.72)	4.17 3.78-4.58	0.89 (0.81-0.98)	0.33 (0.30-0.36)		1.95 (1.77-2.15)	2.02 (1.84-2.23)
Asthma attacks	0.09 (0.08-0.10)	0.06 0.05-0.06	0.01 (0.01-0.01)	0.00 (0.00-0.01)		0.03 (0.02-0.03)	0.03 (0.03-0.03)
TOTAL*	**1580.94**	**1070.35**	**228.89**	**84.89**		**498.24**	**517.85**

Table 11-5 Economic loss/benefits under different scenarios with respect to the base period of 2000, 2020 (millions of 2000 US$; mean and 95% CI)

Health endpoints	Economic loss				Economic benefits		
	BAU	EE	GAS		WIND	SO_2b	SO_2c
Premature deaths	5398.00 (4449.00-6537.00)	3053.00 (2517.00-3697.00)	118.60 (97.79-143.70)		91.50 75.42-110.80	1087.00 (895.70-1316.00)	1100.00 907.10-1333.00
Chronic bronchitis	601.10 (495.50-727.90)	335.90 (276.90-406.80)	13.03 (10.74-15.78)		10.09 8.32-12.22	118.00 (97.28-142.90)	118.20 97.42-143.10
Respiratory hospital admission	19.18 (15.81-23.23)	11.32 (9.33-13.70)	0.47 (0.38-0.57)		0.36 0.30-0.44	4.39 (3.62-5.31)	4.44 3.66-5.38
Cardiovascular hospital admission	14.23 (11.73-17.24)	8.44 (6.95-10.21)	0.35 (0.29-0.42)		0.27 0.22-0.33	3.30 (2.72-4.00)	3.34 2.76-4.05
Outpatient visits (internal medicine)	26.56 (21.89-32.16)	15.87 (13.08-19.22)	0.67 (0.55-0.81)		0.52 0.43-0.63	6.31 (5.20-7.65)	6.39 5.27-7.74
Outpatient visits (pediatrics)	2.76 (2.27-3.34)	1.65 (1.36-1.99)	0.07 (0.06-0.08)		0.05 0.04-0.06	0.65 (0.54-0.79)	0.66 0.55-0.80
Acute bronchitis	23.89 (19.69-28.93)	13.40 (11.04-16.22)	0.53 (0.43-0.64)		0.40 0.33-0.49	4.75 (3.92-5.75)	4.81 3.97-5.83
Asthma attacks	0.35 (0.29-0.43)	0.19 (0.16-0.23)	0.01 (0.01-0.01)		0.01 0.00-0.01	0.07 (0.05-0.08)	0.07 0.05-0.08
TOTAL*	**6086.07**	**3439.76**	**133.71**		**103.20**	**1224.47**	**1237.92**

* Summing the 5th and 95th percentile values yields a misleading 5th and 95th percentile estimates for the total health impact. Therefore, we only give the total mean.

Premature deaths dominate the value of the total benefits, accounting for about 90 percent of total benefit. Chronic bronchitis values also have an important contribution.

4. Discussion

Since there have been no valuation studies of health endpoints associated with air pollution in Shanghai, we had to estimate these values from other studies. This procedure is often called *benefit transfer* or *value transfer* in economics. Population characteristics—age distribution, income, health status, culture, etc.—may affect the valuation results. For example, local social and health insurance systems will greatly influence the risk perception of a local population, resulting in different WTP values to avoid risk.

If we converted U.S. VOSL into Shanghai VOSL by only considering the income difference between the two locations, the Shanghai VOSL would be US$ 780,000 (in 2000 US$). This figure is much higher than the one converted from Chongqing VOSL using the same conversion method. And the value would be even higher if we used purchasing power parity (PPP) as the income definition.

The economic and social situation in Shanghai is more similar to that in Chongqing than that in U.S.; thus, the Shanghai VOSL calculated from the Chongqing value is probably more suitable than that calculated from the U.S. value. Therefore, we tried to use Chinese studies whenever available, and attempted to stay on the conservative side of any range of reasonable estimates.

The total social cost of illness should include both private WTP values and the public-borne costs. In this analysis, we used COI values when WTP values were not available for certain morbidity endpoints. As a result, both WTP and COI approaches were used.

Both methods have weaknesses. COI fails to account for the disutility of illness, which is likely to be a major component of willingness to pay for reducing the risk of falling sick. Some of the cost of illness, on the other hand, may not show up in WTP estimates; costs of health care borne by the public sector, for example, will not be reflected in individual willingness to pay. Therefore, in future work, some components of COI estimates could supplement WTP estimates to better reflect the full cost of illness to society.

A solution for dealing with the paucity of WTP literature is to integrate health status index literature with the available WTP literature. Appropriate WTP values for each morbidity outcome can be obtained given the established correlation between WTP values and health index status. This approach was proposed by Johnson, Fries, and Banzhaf in 1997. However, its reliability still needs to be proved in future work.

A major complication in converting WTP estimates from study site values to target site values arises from the difference in income levels. Willingness to pay for reduction of risk clearly rises with income, but accurately determining income elasticity of the relevant WTP is difficult.

The literature on the income elasticity of WTP for reducing the risk of damage to health is, however, extremely sparse. Different studies estimated income elasticity to be anywhere from 0.26 (Loehman, et al. 1996) to 1.1 (Viscusi, et al. 1992). The calculated social costs of ill health are acutely sensitive to the value of this parameter: A change of income elasticity from 0.4 to 1.1 changes the final calculated health impact by nearly 20 times.

When data is limited, it is considered prudent to choose parameters conservatively. In the absence of conclusive data guiding elasticity estimation, we assumed a higher income elasticity of 1 for morbidity cost estimation, giving income differences a greater impact.

The double-counting effect was not completely eliminated from our analysis since some morbidity endpoints we included are actually overlapping entities. For example, chronic bronchitis and hospital admissions for respiratory problems are both related to air pollution and both used in our analysis. Respiratory hospital admissions, however, result, at least in part, from the chronic bronchitis. In this way our analysis overestimated the economic gains from the implementation of low-carbon policies. Doing so was unavoidable, though, since these two health outcomes are difficult to estimate separately.

5. Conclusions

This monetary valuation of the health benefits associated with air pollution improvement under low carbon policies in Shanghai has revealed the great social benefit of such policies. Compared with the BAU scenario, economic benefits from improved public health could reach 507.31-2097.30 million U.S. dollars by 2010 and 2642.45-7310.66 million U.S. dollars by 2020.

Compared with the base year 2000, an economic loss of 84.89-1580.94 million U.S. dollars would be incurred under the BAU, EF, GAS and WIND scenarios in 2010, while implementing the SO_2b or SO_2c scenario could yield economic benefits of 498.24 or 517.85 million U.S. dollars by 2010, respectively. By 2020, economic losses under the BAU, EF and GAS scenarios would reach 133.71-6086.07 million

U.S. dollars with respect to the base period 2000, while implementing the WIND, SO_2b, or SO_2c scenario could yield an economic benefits of 103.20- 1237.92 million U.S. dollars by 2020.

These results can be used in further cost-benefit analysis for policy-makers.

6. Recommendations for Future Research

The uncertainties in the above estimation process highlight the need for a variety of new and continued research efforts. Based on the findings of this study, the following research needs are of the highest priority:

- Because of the imprecision of adjusting health endpoint values to Shanghai from other areas (e.g., Chongqing, U.S.), studies conducted in Shanghai measuring the WTP value of avoiding air pollution-related health risks is needed, particular one measuring the WTP value of reducing the mortality risk. Also needed is research that make possible more accurate estimates of air-pollution-associated health outcome values, including research into the factors (age, income, education, pollution level, etc.) that influence WTP; the relationship between WTP and quality of life; private costs and lost output; and people’s preferences in trading off future risks.
- Due to the lack of WTP studies, domestic or international, on some morbidity endpoints, alternative methods should be developed for valuing such endpoints. Such methods include ways of calculating WTP values for avoiding some morbidity endpoints from known health status index and applying aggregate measures, such as DALYs, that do not require the direct valuing of health outcomes.

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Chapter 12. Low-Carbon Development Policy Recommendations

1. Preface

China currently has the world's fastest developing economy. China is striving to develop its economy and reduce poverty, while lowering pollution. Accompanying great economic growth and increased living standards is great energy demand growth and increased greenhouse-gas emissions. Maintaining economic growth while lowering greenhouse-gas emissions is a tremendous challenge for China.

Shanghai has one of the highest population densities, most active economies, and highest centralized energy consumption of any city in China. Per capita energy consumption in 2000 was 122 GJ, 4.1 times the national level and 1.8 times the global level. Such high energy consumption pollutes. Under BAU scenario, local air pollutant (LAP) and greenhouse gas (GHG) levels will continue to rise: by 2010, CO_2, SO_2, and PM_{10} emissions will increase to 226 Mt, 0.75 Mt and 0.25 Mt, respectively; by 2020 they will rise even further to 319 Mt, 1.11 Mt, and 0.39 Mt, respectively.

Changing energy policy can dramatically change these figures. Implementing low-carbon energy policies, such as energy efficiency (EE) improvement, low carbon energy substitution (COAL+GAS), and renewable-energy adoption (WIND), could reduce total final energy demand by 10% from BAU scenario; SO_2 emissions, by 32%; PM_{10} emissions, by 38%; and CO_2 emissions, by 12% by 2010, all while maintaining Shanghai's GDP growth. Under these scenarios, CO_2 emission growth rate will fall from 5.2% in BAU scenario to 3.9 percent, and CO_2 emission per capita will decrease 12 percent, from 4.3 t to 3.8 t. The air quality improvement resulting from low-carbon energy policies will prevent 2,804-11,580 avoidable deaths and bring 0.51-2.09 billion USD (0.29%-1.61% of GDP) of direct economic benefit.

Thus, the measures discussed in this report--including low-carbon energy substitution, energy-efficiency improvement, wind-power generation, renewable energy growth in rural areas, and end-pipe treatment--will slow CO_2 emission growth rate and lower SO_2 and PM_{10} emissions, improving urban ambient air quality from its condition in 2000 and literally saving lives, all while maintaining the rapid pace of Shanghai's economic development.

2. Main Barriers to Low-Carbon Development in Shanghai

2.1. Major Energy Carrier Has Highest Carbon Content

Coal has the highest carbon content of any energy carrier. Shanghai's coal consumption in 2002 was already 46 Mt. But it was not enough. In recent years there have been periodic electricity and gas shortages. In 2002, the electricity load was 12.35 GW, and in 2003, it exceeded 14.5 GW despite usage limits. During this time, the highest daily gas consumption was over 11.00 Mm^3, exceeding production capacity. To meet electricity and gas demand, Shanghai will increase power generation capacity and town gas production. By 2004, two 0.9 GW coal-burning power generation units will go online, and total coal consumption in Shanghai will reach 50 Mt in 2005. Before 2010, more coal-burning and gas-burning units will be needed.

According to *The Tenth Five-Year Plan for Energy Development in Shanghai*, Shanghai intends to decrease coal use to 51 percent of all primary energies used, decrease crude oil use to 39 percent, increase natural gas use to 7 percent, and maintain others at under 3 percent (see Table 12-1). While this would mark a great change in the amount of coal used, the abundance and relatively low cost of coal, virtually guarantees coal will remain the main energy carrier in future Shanghai.

Table 12-1 Comparison of Shanghai's energy structure and the world average

Energy Carriers	Shanghai		Global, 2000
	2000	2005	
Coal	65.5 %	51 %	25 %
Crude Oil	32.8 %	39 %	40 %
Natural Gas	0.6 %	7 %	25 %
Others	1.1 %	3 %	10 %
Total	100 %	100 %	100 %

2.2. Slow Utilization of New and Renewable Energies

In the 1970s, Shanghai sought to utilize solar and biomass (methane) energies, developing China's most sophisticated renewable energy technology. In the following years, lowered interest, lack of capital, and poor planning and organization inhibited further advances. However, in 1995, some universities, institutes, and enterprises began to once again research and develop new renewable energy technologies, including solar, wind, biomass, and fuel cell technologies. These organizations have made real progress, but, for the most part, the development of new and renewable energies in Shanghai is still in its early stages, and is not ready for widespread application.

2.3. Lack of Carbon Emissions Reduction Policies

Shanghai currently uses and will continue to use a lot of coal. With the implementation of end-pipe treatment measures and Shanghai's recent shift from being primarily an industrial center to being more commercial in character, SO_2 and

PM levels are improving with each passing year. Shanghai's ambient air quality is now better than most other big cities in China. But while the government is working to control SO_2, NO_x, and PM levels, there still a serious lack of focus on the emission of greenhouse gases, including CO_2.

2.4. Low Energy Efficiency

As late as the late 1990s, average energy efficiency in Shanghai was less than 40 percent. Through the increased use of energy-saving technology and equipment, energy consumption per 10,000 RMB of GDP has been decreasing, and the energy efficiency in Shanghai has risen to about 42 percent as a result. But much inefficient equipment is still in use, particularly in industry. For instance, the efficiency of many industrial boilers is only 60-80 percent, and many kilns have an efficiency of only 10 percent.

2.5. Economic Structure Necessitates Coal Use

Adjustments in industrial distribution and structure in Shanghai have eliminated some heavily-polluting industrial enterprises, expanded new-style, more energy-efficient industries, and increased the growth rate of tertiary industry. As a result, energy use has become more efficient and the proportion electricity, oil and natural gas used has increased, lowering coal consumption. Heavy and chemical industry still predominates in Shanghai, and further adjusting this structure is extremely difficult.

The use of coal is very well-established. Industry will continue to be the main component of Shanghai's economy, increasing energy demand, coal use, and carbon emissions. The need to reduce CO_2 emissions will only increase in importance.

3. Medium and Long-term Policy Recommendations for Low-Carbon Development

Besides economy growth, major factors influencing air pollutant emissions include energy intensity, energy structure, low-carbon energy usage, and end-pipe treatment. The relationship between these various factors is expressed by the Kaya formula[1]:

$$\frac{Emission}{CAP} = \frac{GDP}{CAP} \times \frac{TPES}{GDP} \times \frac{Emission}{TPES} \times (1 - ER)$$

Emission = the emission of LAP or CO_2; *CAP* = population;

GDP = gross domestic product; *TPES* = total primary energy supply;

ER = reduction rate of LAP or CO_2 emission

[1] Kaya. Y. (1990) "Impact of carbon dioxide emission control on GNP growth: interpretation of proposed scenarios" paper presented at IPCC Energy and Industry Subgroup, Response Strategies Working Group, Paris, France

In the formula, the second term (*TPES/GDP*) represents energy intensity, energy consumption per unit GDP. Energy intensity is related to energy technology levels, energy-consuming modes, and energy efficiency. The third term (*Emission/TPES*), emissions per unit energy consumption, is closely related to energy structure--the amount of low-carbon energy in use. End-pipe treatment effects energy intensity by effecting energy technology levels.

Shanghai can reduce LAP and GHG emissions while still increasing per capita GDP by implementing low-carbon development measures--increased use of low-carbon energy sources, energy efficiency improvements, energy intensity reduction, and renewable energy utilization. Such measures accord with Shanghai's desire to transition from an extensive to an intensive economic growth pattern, and promote the adjustment and optimization of Shanghai's energy structure. The implementation of such measures will produce a "win-win" situation, in which LAP and GHG emissions are reduced and fewer resources are consumed but economic growth is not disrupted. The most important aspects of such policies are energy intensity reduction, low-carbon energy switch and end-pipe treatment.

3.1. Low-Carbon Development Targets

The overall goals of low-carbon development in Shanghai should be developing in an energy-efficient and environmentally sustainable manner, achieve energy security to ensure energy supplies for residential consumption and economic development, and build a safe, clean, and efficient multiple-energy supply system.

While maintaining current "transferring natural gas from West to East" and "transporting electricity from West to the East" policies, we should strengthen take aim at the following specific development targets:

- adjust and optimize energy structure;
- develop and popularize clean and renewable energy technologies;
- limit total coal consumption;
- increase the proportion of low-carbon primary energies in use;
- optimize energy consumption structure;
- improve energy efficiency; and
- reduce LAP emissions and GHG emission growth rate

3.2. Policy Recommendations for Low-Carbon Development Strategies

Many barriers, technological, economic, political, cultural, societal, behavioral and institutional in nature, must be overcome to mitigate GHG emission levels. Moreover, the actions taken to reduce GHG emissions must be country and region specific. Developed countries have worked to achieve lower GHG emission primarily through financial incentives, technical innovation, institutional reformation, trade-barrier elimination, and energy-efficiency improvements. In developing countries like China, there is also a need for capacity building in several areas, including information gathering and evaluation, technology development, training energy managers and end-users, and financial resources use.

In order to reduce LAP and carbon emissions, we recommend Shanghai take the following six measures:

(1) Enhance Social Awareness

Global warming and climate change caused by GHG emission are global environmental issues; it behooves all countries to help lower GHG emissions.

Presently, Shanghai is focused on controlling LAP emissions, including SO_2 and PM, which directly impact the health level of urban residents. Shanghai has succeeded in reducing local air pollution and improving ambient air quality. However, there is still not enough emphasis on controlling CO_2 emissions.

Shanghai is striving to become a truly world-class metropolis and economic center. While striving for economic development, however, it is also essential to increase public awareness of regional and global environmental protection issues. We must emphasize the importance of "development meeting the need of persons at this time without endangering the needs of their offspring", and also point out that environmental protection is necessary for long-term sustainable development.

Therefore, we should increase social awareness of the gravity of carbon emission problems, ensure there are enough people who are aware of and vocal about these issues, instruct the public about contributions each individual can make toward energy conservation--by using efficient home appliances, using public facilities, etc.

It is also essential to promote more research and cooperation among researchers. Much basic research on carbon emission issues--including energy utilization and emissions, environmental effects of low-carbon energy switch, integrated decision-making about low-carbon development strategies, and application of new energy technology--is still needed

(2) Establish Local Emissions Laws and Regulations

Establish local laws and regulations that help develop a low-carbon economy in

Shanghai. At the same time, promote the research, development of energy technologies that can reduce local air pollution, and GHG emissions .

Financial measures: Shanghai's government can employ several financial measures--tax breaks, low-interest loans, direct sponsoring, etc.--to stimulate the growth and adoption of low-carbon and state-of-the-art energy technology. We suggest Shanghai devotes funds for these purposes in order to reduce CO_2 emissions.

In recent years, the funds used for environmental clean-up in Shanghai have increased yearly, reaching about 3 percent of Shanghai's total GDP by 2003. These funds have helped to greatly improve the appearance of Shanghai. Air-treatment funds are mainly put toward SO_2, NO_x and TSP reduction. A similar special fund should be established for technology and policy research regarding CO_2 emission.

Strengthen the supervision and management of energy use: The use of energy licenses has proved to be an effective means for decreasing energy usage. Heavy energy consumers must purchase an energy license, the price of which increases as energy use increases. This encourages lower energy use, reducing CO_2 emissions. Energy licenses usually can be transferred in public. We should also establish energy-efficiency standards for many products, from lighting to vehicle engines, and for buildings.

Policy building: Control total coal consumption to reduce local air pollutant and carbon emissions. In recent years, Shanghai's government has successfully employed various measures to control air pollution. The Tenth Five-Year Plan calls for energy structure adjustment policies and energy efficiency update measures to continue to improve air quality and lower CO_2 emissions. Another effective measure for developing a low-carbon economy is to set specific medium and long term goals for what proportion of total primary energy consumed in Shanghai must be low-carbon energy. For such goals to be realized, Shanghai must simultaneously develop and establish policies controlling the consumption of high-carbon, high-sulfur, and high-ash energies.

Research, development, and management: Advance low-carbon emission technology research, development, and demonstration; accelerate experimentation with and commercialization of new technology. Government support for research and development is well-justified given the grave environmental consequences of unmitigated carbon emission. We must also educate energy policy-makers regarding energy purchase and utilization.

(3) Develop and Popularize Renewable and Low or No Carbon Emissions Energy Technologies

Shanghai should research and develop renewable and low or no-carbon emission energy technologies. Development of renewable energies not only helps shift from an extensive to intensive economic growth pattern, but also accelerates the growth of energy-efficient technologies and energy-saving products throughout the world, helping China promote energy efficiency and energy structure optimization. In accordance with *The Tenth Five-Year Plan* and *2015 Perspective for New and Renewable Energy in Shanghai*, we should research solar power technology commercialization, build more solar-powered buildings, research updates in solar electric power efficiency for its commercialization, establish wind farms in Shanghai's wind-rich coastal areas, and investigate fuel cell and waste generation technologies. Over the next 5-15 years, establish a new and renewable energy framework in Shanghai.

(4) Promote Low-Carbon Energy Structure Adjustment, Ensure Energy Security, Reduce Local Air Pollution, and Mitigate Carbon Emissions

Build a demonstration project at the 2010 World Expo site and promote low-carbon energy substitution: Low-carbon energy switch and energy structure adjustment are both measures that could radically reduce air pollutant emission, improve air quality, and mitigate CO_2 emission growth. According to *The Tenth Five-Year Plan* for energy development in Shanghai, the proportion of coal consumption among total primary energy should decrease from 66 percent in 2000 to 51 percent in 2005; oil and oil derivatives should increase from 33 to 39 percent; and natural gas should increase from 0.6 to about 7 percent.

Solar, wind, and other renewable energy technology can be adopted to build a low-carbon energy supply system for 2010 EXPO exhibition. This will promote the development and use of low-carbon energy technology, decrease reliance on fossil fuels, reduce local air pollution and carbon emissions, all while making Shanghai a world-class example of renewable energy use.

Quicken the development of no-carbon energies: A no-carbon energy contains no carbon atoms and thus emits no CO_2. Increasing the proportion of no-carbon energies among primary energy consumed can remarkably reduce CO_2 emission. Shanghai is already planning to do so to some extent: 20 MW wind power plants are being built in Chongming and Nanhui, and an additional 60-80 MW wind power plant should be finished by 2010. This use of wind power should be expanded, as should the use of roof-mounted solar water heaters. Also, while constructing Chongming as an ecological island, non- or low-carbon energies should be used to decrease ecological damage.

Control coal consumption in Shanghai: Control total coal consumption in Shanghai to mitigate carbon emission. To do so, Shanghai should build gas power plants and a distributed gas fired power supply. Shanghai should also actualize an energy system combining heat, cooling, and generation in developed industrial parks to reduce the coal consumption of industrial boilers and kilns. A reasonable low-carbon energy supply system should also be constructed.

Enhance system innovation and popularize natural gas: With the recent popularization of natural gas, coal gas will be replaced by natural gas in many applications. Urban coal gas production is becoming obsolete; gas-making factories should be destroyed. The amount of natural gas consumed will soon greatly exceed the amount of coal gas used, and industry, particularly the power generation sector, will soon become the largest consumer of natural gas, exceeding residential consumption. Direct or indirect substitution of natural gas for coal will help decrease CO_2 emissions.

Focus on the introduction of liquefied natural gas in Shanghai: The proportion of natural gas used and demand for natural gas is increasing. Shanghai should also use liquefied natural gas (LNG) to ensure the energy security of gas consumption during low-carbon development. Shanghai should not only import natural gas from the East China Sea as part of the project "transferring natural gas from West to East", but also introduce LNG in Shanghai. Most important now is programming, launching, and working out the importation of LNG, so that projects can be examined and approved by Shanghai government and State Council as early as possible, making Shanghai ready to use LNG by 2008.

(5) Improve Energy Efficiency

Energy conservation and energy efficiency improvement is the most important component for Shanghai's low carbon development. In the medium and long term, both improve the environment and reduce the burden on Shanghai's limited energy supply, while strengthening economic competition.

It is particularly important to develop cleaner energy and advanced technologies with higher energy efficiency. Currently, energy efficiency in Shanghai is only around 40 percent. Increasing this figure by 0.3 percent per year, reaching almost 43 percent by 2010, and reducing energy consumption per 10,000 RMB from 1.21 tce in 2000 to 1.0 tce in 2010 are realistic goals. Energy conservation measures and energy efficiency improvements are remarkably effective in reducing carbon and LAP emissions.

Adopt advanced combined heat and power technology to increase electricity

efficiency: Combined heat and power (CHP) is an optimial and extremely economical measure to increase energy efficiency and reduction emissions, especially GHG emissions. Shanghai should rebuild heat supply units, and use trigeneration to combine heat, cooling, and electricity generation, and construct integrated gasification combined cycle (IGCC) projects to take advantage of excess heat to make electricity generation more efficient. Shanghai should also Build CHP or centralized heating supply systems in existing heavily-polluting industrial parks, such as Taopu industrial area. It could also remove industrial boilers and build decentralized heating supplies to lower coal consumption and increase energy efficiency.

Establish distributed energy supply system to improve energy efficiency: Foreign experience has shown that combined systems with large grids and distributed electricity saves investment, reduces energy consumption, and makes the energy supply system more secure and flexible. Shanghai should establish distributed energy supply systems throughout the city to reduce energy consumption and increase energy security.

(6) Develop Energy-Saving Activities in the Building and Transportation Sectors to Reduce CO_2 Emissions

Besides industry, the building and transportation sectors both have large energy-saving potential. The proportion of total energy used by the transportation sector is projected to increase from 11.1 percent in 2000 to 16.3-17.1 percent in 2020; the proportion of energy used by buildings is projected to increase from 16.2 to 25-26.7 percent in 2020. Energy-saving efforts in the building and transportation sectors have the potential to make a great impact on total energy consumption and CO_2 emissions.

In the building sector, measures to be taken include improving building insulation, using heat preservation materials, and researching, developing and demonstrating new energy-saving structures. To successfully implement energy-efficient building measures, coordinated work among many areas is necessary. Work is needed to research, develop, organize, and popularize building energy-saving technology. Work is also needed to reform heat supply system policy; open the heat market; promote energy-saving reconstruction of existing buildings; establish energy-saving regulations; enforce building energy saving policy; establish market-stimulating mechanisms for promoting the production and use of energy-saving materials and low energy consumption facilities; set aside a special fund for installing existing energy-saving technology; found a comprehensive administrative and supervisory system for energy-efficient construction; create energy-efficiency standards and energy labels for energy-using facilities.

The transportation sector also has many needs: update city planning, especially transportation planning, before the development of bus rapid transport systems and other mass transportation; establish intelligent road systems; encourage investment in and purchasing of substitution fuel cars to promote energy saving and clean energy substitution in the transportation field; levy a fuel tax; establish standards for fuel efficiency and oil quality.

Chapter 13. Epilogue

Low-carbon development utilizes advanced energy technologies and low carbon energies to reduce CO_2 emissions. Due to the grave threat unmitigated carbon emissions pose to public health and the global environment, low carbon development is a vital area for ongoing research and application.

This project adopted a Long-Range Energy Alternatives Planning (LEAP) model to analyze the environmental and health benefits of low-carbon development and low-emission measures. Policy alternatives considered include energy efficiency improvement, low-carbon energy substitution, and natural gas and wind energy generation. More than ten low-carbon and end-pipe policy scenarios were studied. The results of this scenario analysis indicate that a combination of low-carbon and low-emission policies will slow the growth rate of CO_2 emissions, reduce local air pollution (LAP), and yield extraordinary environmental and health benefits.

It is, however, inevitable that CO_2 emissions in Shanghai will continue to grow in the medium- and long-term. Several important questions remain to be answered regarding the period in which CO_2 emissions in Shanghai begin to decline. When this time comes, the following questions need to be addressed:

(1) What should Shanghai's industrial structure be?

(2) What should its configuration of energy resources be?

(3) What kind of energy-saving policies and market-stimulating mechanisms should we have?

(4) What will the costs of Shanghai's energy system be?

And all of these questions will need to be considered in future Shanghai low-carbon studies.