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Technology Assessment of Clean Coal Technologies for China:

Volume 3— Environmental Compliance in the Energy Sector: Methodological Approach and Least-Cost Strategies

Shanghai Municipality and Henan and Hunan Provinces, China

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World Bank Energy Sector Management Assistance Program (ESMAP)

Contents

Foreword

Funding for the studies was provided by a number of sources. The Shanghai and Henan case studies were funded by the Environmental Manual Program, the Dutch Trust Fund which was managed by the Energy Sector Management Assistance Program (ESMAP), the East Asia and Pacific Region's Energy Sector Unit (EASEG), and the Energy, Mining and Telecommunication Department's Energy Unit (EMTEG). The Japanese Trust Fund, as well as EASEG and ESMAP, funded the Hunan case study. The project was jointly managed by EASEG and EMTEG.

World Bank staff[1] led the project team in the development of the methodology, data analysis, and preparation of this report. The Beijing Economic Research Institute of Water Resources and Electric Power (BERI) undertook most of the data collection, analysis, and modeling work. Researchers from the Department of Environmental Engineering of Tsinghua University in Beijing performed environmental cost evaluation on sulfur deposition and ambient air pollution in the Hunan case study. The Electric Power Development Corp (EPDC) and Tokyo Electric Power Co (TEPCo) of Japan, and the Electric Power Research Institute (EPRI) in Palo Alto, California provided specific technical input in the Hunan case study. The Oeko Institute of Germany provided technical support in the use of the Environmental Manual (EM) model[2] and the estimation of emission factors for end-use energy activities.

In publishing this report, we hope to provide an insightful analysis of the long-term opportunities CCT presents for China.

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1 Mr. Noureddine Berrah of EASEG, Mr. Masaki Takahashi and Mrs. Stratos Tavoulareas of EMTEG.

2 The EM model was developed by a number of bilateral agencies from Germany (BMZ and GTZ), Netherlands (DGIS), Switzerland (BAWi) and United Kingdom (DFID) with the coordination of the World Bank.

Abstract

Economic growth has been fueled by increased coal combustion, which has serious environmental impacts. Coal is China's chief energy source, accounting for 75 percent of primary energy consumption. However, current consumption of more than 1.3 billion tons per year is China's main cause of pollution. Assessing and identifying least-cost environmental mitigation options is crucial to resolving China's air pollution problems.

The government of China recognizes the importance of improving pollution control and has tightened environmental regulations throughout the country, particularly for the power and non-power sectors, the predominant source of air emissions. Its strategy has been to exert more stringent emission control at the plant level, levy emission fees for certain pollutants, and create acid rain SO_2 control zones.

In most cases, non-power sector options are more cost-effective than power sector options in reducing environmental pollution. Key control options include:

- *Particulates:* Particulate emissions come mainly from non-power sectors. However, total particulates from the power sector are expected to decline due to the utilization of higher quality coal, the retirement of small-inefficient power plants and the utilization of high efficiency ESPs power plants.
- *SO_2 Control:* The most cost-effective options for controlling SO_2 emissions are the use of coal briquettes in the residential and industrial sector, a simplified FGD in selected existing power plants, the burning of medium-to-high sulfur coal and coal washing in all sectors.
- *NO_x Control:* NO_x emissions will become a problem in the near future. Technologies to be employed include utilization of low NO_x burners in new power plants, combustion tuning/optimization and low NO_x burners in existing power plants are cost-effective.

This study confirmed that system-level analysis is essential for evaluating alternative environmental control alternatives and policy options. Plant-level analysis is useful as a preliminary indicator of the cost-effectiveness of alternatives, but does not capture the role of each option. Scenario analysis proved to be helpful in screening the various environmental control options based on their cost-effectiveness and reducing the number of options being considered in the development of a least-cost plan.

Preface

This study is one part of the project, "Clean Coal Technologies for China". The primary objective of the overall project is to assist policy makers and environmental planners in choosing the most appropriate clean coal technologies and environmental control options. The three phases of this assistance include:

First, this report summarizes the development of an approach for conducting a system-level analysis of a province or region that yields a least-cost plan for meeting alternative environmental objectives under several energy development scenarios. This approach was first applied to Shanghai municipality, subsequently refined for the Henan province, and refined further for the Hunan province by using dispersion modeling.

Secondly, a technology assessment report on clean coal technologies was prepared by US EPRI, EPDC, and TEPCO, with contributions from NEPRI and TPRI. Two volumes were prepared, addressing the Technology Assessment of Clean Coal Technologies for China: Volume 1—Electricity Power Production and Volume 2—Environmental and Energy Efficiency Improvements for Non-power Uses of Coal.

Thirdly, a technology dissemination program for Chinese decision makers was prepared. This program improved their understanding of the various options through (1) a workshop held in China at the conclusion of this study and (2) a tour to sites in Japan that are operating CCTs.

Acknowledgments

This report summarizes the results of three separate but related studies. A core team of World Bank staff, international consultants and local (Chinese) organizations participated in all three studies. Additional consultants contributed to some of the studies. All studies were supervised and led by Mr. Noureddine Berrah of EASEG and Mr. Takahashi Masaki of EWDEN. Also, Dr. Zhao Jianping at World Bank Beijing Office (EASEG) provided useful guidance and insight, as well as coordinated meetings with the Government of China and other Chinese organizations. In addition to Messrs. Berrah, Takahashi and Zhao, the core team consisted of Mr. Stratos Tavoulareas, Energy Consultant, who provided technical support and the State Power Economic Research Center (SPERC) formerly known as the Beijing Economic Research Institute of Water Resources and Electric Power (BERI) which undertook most of the data collection, analysis, and modeling work. Members of BERI included: Mr. Ge Zhengxiang, Mr. Wang Leiping, Mr. Zhou Jianglong, Mr. Hu Ming, Mr. Wang Lei, Mr. Peng Ximing, Mr.Chen Libin, Mr. Bai Jianhua, Mr. Fu Zhikui, Mr. Chen Qiuxin and Ms. Wang Wenjie

The Shanghai and Henan studies were carried out mainly by the core team. The contribution of Mr. Uwe Fritsche of Oeko-Institut of Germany should be acknowledged who assisted in the development of emission factors for end-use energy activities and the utilization of the Environmental Manual (EM) model[3].

Key contributions to the Henan study were made by:

- Prof. Hao Jiming, Prof. He Kebin, Mr. Li Ji, Mr. Lei Duan and Mr. Dai Wennan of Tsinghua University who evaluated the environmental damage costs in the Province of Hunan
- Mr. Nishino Toshiro, Mr. Ozono Katsuhisa, and Mr. Kikuchi Tetsuo of Electric Power Development Co. (EPDC) of Japan and Mr. Murata Hajime and Mr. Hatano Yoshihiro of Tokyo Electric Power Co (TEPCo) of Japan who coordinated the study
- Dr. George Offen and Mr. Neville Holt of the Electric Power Research Institute (EPRI) who provided useful data and insights on the use of clean coal technologies in China
- Mr. Horii Nobuhiro of the Institute of Developing Economies in Japan
- Dr. Zhu Fahua of The Nanjing Environmental Protection Research Institute (NEPRI) for his insights on the present status of clean coal technologies in China, as well as the translation of documents from English to Chinese.

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[3] The EM model was developed by a number of bilateral agencies from Germany (BMZ and GTZ), Netherlands (DGIS), Switzerland (BAWi) and United Kingdom (DFID) with the coordination of the World Bank.

Also, the team would like to acknowledge the contributions of Mr. Charles Feinstein of the World Bank who provided technical guidance throughout the project and Mr. Dean Girdis, Energy Consultant who assisted in editing this report.

Abbreviations and Acronyms

ADB	Asian Development Bank
AFBC	Atmospheric Fluidized Bed Combustion
BAU	Business-as-usual
BAW	Bilateral Agency of Switzerland
BCM	Burner Component Modification
BERI	Beijing Economic Research Institute
BMZ	Bilateral Agency of Germany
CCT	Clean Coal Technology
CFB	Circulating Fluidized Bed
CFBC	Circulating Fluidized Bed Combustion
CO_2	Carbon Dioxide
DFID	Bilateral Agency of the United Kingdom
DGIS	Bilateral Agency of the Netherlands
EASG	East Asia and Pacific Region's Energy Sector Unit
EM	Environmental Manual for Power Development
EMTEG	Energy, Mining and Telecommunications Department's Energy Unit
EPDC	The Electric Power Development Corporation
ESMAP	Energy Sector Management Assistance
ESP	Program
	Electrostatic Precipitators
FGD	Flue Gas Desulfurization
FSI	Furnace Sorbent Injection
GESP-II	Generator of Electric System Planning
GDP	Gross Domestic Product
GTZ	Deutsche Gesellschaft fur Technische Zusammenarbeit GmbH
IGCC	Integrated Gasification Combined Cycle
LPG	Liquefied Petroleum Gas
LNB-I	Low-NO_x Burner type-I
LNB-II	Low-NO_x Burner type-II
LNG	Liquefied Natural Gas
LSFO	Low Sulfur Fuel Oil
MAED	Model for Analysis of Energy Demand
MEDEE	Modele de Demande en Energie pour l'Europe
MW	Megawatts
NEPA	National Environmental Protection Against

NEPRI	Nanjing Environmental Protection Research Institute
NO_x	Nitrous Oxide
NPV	Net Present Value
OECD	Organization for Economic Cooperation and Development
O&M	Operating and Maintenance
PC	Pulverized Coal
PFBC	Pressurized Fluidized Bed Combustion
PM^{10}	Particulate Matter
PV	Present Value
RMB	Renminbi
SCR	Selective Catalytic Reduction
SEPA	State Environmental Protection
SNCR	Administration
SO_2	Selective Non-catalytic Reduction
SWS	Sulfur Dioxide
	Simplified Wet Scrubbing
TAC	Total Amount Control
TEPCO	Tokyo Electric Power Company
TCE	Tons of Coal Equivalent
T/O	Tuning/Optimization
TPRI	Thermal Power Research Institute
TPC	Total Plant Cost
TAG	Technical Assessment Guide
TPRI	Thermal Power Research Institute
TSP	Total Suspended Particulates
TWh	Terawatt Hours
US EPRI	US Electric Power Research Institute
VAT	Value Added Taxes
VOCs	Volatile Organic Compounds
WASP	Wien Automatic System Planning Package
WB	World Bank
WHO	World Health Organization
WTP	Willingness to Pay

Units of Measure

Energy & Power:
1 KWh= 3,412 BTU= 860 Kcal
1,000 KWh= 3.412 mm BTU
1 MW = 1,000 KW

Currency Equivalents

8.3 Yuan RMB = 1 US$

Executive Summary

1. China's rapid economic growth during the last 15 years has brought significant benefits to the Chinese people. Incomes have increased; poverty has fallen; and health indicators have improved. However, the same economic growth, with its accompanying industrialization, urbanization and increased automobile ownership, has generated enormous pollution, lowering air and water quality.

2. Although the level of pollution in China has been well documented, only recent studies have focused on the significant damage of this pollution on humans and the environment. For example, a study completed in 1998 under the auspices of the Chinese Academy of Science (CAS), "Forestry Towards the 21st Century," estimates that 2.8 million square kilometers or 29.2% of China's land area was affected by acid deposition by 1993. By 1998, the affected land area had increased to 40%.

3. The same study estimates that acid rain has caused direct economic losses of 44 billion yuan (US$ 5.3 billion) because of the reduction of timber growth and 54 billion Yuan (US$ 6.5 billion) because of the crop reduction in southeast China (which includes the provinces of Anhui, Fujian, Guangdong, Guangxi, Guizhou, Hubei, Hunan, Jiansu, Jiangxi, Sichuan and Zhejiang).

4. Similar studies by the World Bank estimate the following:

- Air and water pollution damage on human health is as high as $544 billion per year—nearly 8% of GDP in 1995[4].
- Indoor air pollution, created primarily from burning coal and biomass for cooking and heating, causes 111,000 premature deaths each year, mainly in rural areas.
- Chronic obstructive pulmonary disease, linked to particulate pollution, is the number one cause of all adult deaths in China, at 26% of the total, five times the rate of the US.[5]

5. Faced with steadily worsening environmental conditions, the Chinese government recognized that limited natural resources could eventually constrain economic growth. The government began enacting laws that created environmental standards as well as a legal and administrative framework to protect the environment. In addition to a revised Emission Standard for Air Pollutants for Thermal-fired Power Plants which went into effect on January 1, 1997, recent initiatives of the government include:

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[4] World Bank, *China 2020: China's Environment in the New Century: Clean Water Blue Skies*, 1997.

[5] World Bank, *China: Renewable Energy for Electric Power*, September 1996.

- The requirement of SO_2 removal equipment, such as flue gas desulfurization (FGD)
- The limitation of the total volume of particulates and sulfur emissions in certain areas (acid rain and SO_2 control zones)
- The use of pollution fees (0.20 Yuan/Kg SO_2 emissions)

6. Considering these changes in China, the World Bank carried out three studies to assess the cost-effectiveness of environmental control options and develop least-cost plans which satisfy environmental goals, as well as economic growth requirements, for the Municipality of Shanghai and the provinces of Henan and Hunan.

Objectives

7. The objectives of the studies were:

- To develop a basic methodology and approach to assess the cost-effectiveness of alternative environmental control that could be adaptive and flexible to varying conditions within China
- To identify least-cost environmental compliance strategies for the four energy-based pollutants (particulates, SO_2, NO_x and CO_2) from the power and non-power sectors
- To apply the methodology in selected provinces to demonstrate its effectiveness and refine it for further application throughout China
- To develop conclusions for Shanghai, Henan and Hunan regarding least-cost pollution control options and environmental compliance strategies, and to engage local organizations and build the indigenous capacity to carry out similar assessments in the future.

Methodology

8. The methodology utilized was based upon three case studies of increasing complexity and comprehensiveness. Beginning in 1997, the *Shanghai case study* included: (1) an estimation of emissions from the power and non-power sectors; (2) an assessment of the cost-effectiveness of environmental control options; and (3) an attempt to estimate the environmental damages (externalities). Indicative environmental externality values were developed by using values from the *New York State study* (Asian Development Bank, 1996) and adjusting them to reflect the GDP and population density of the Shanghai area.

9. The *Henan case study*, carried out in 1998, was more comprehensive and included a detailed assessment of the energy demand forecast to develop a better basis for predicting future emission patterns especially from the non-power sectors. Least-cost plans were developed for the power sector with emission limitations and environmental externalities by using an enhanced GESP II to accept emission constraints and environmental externalities.

10. The *Hunan case study*, initiated in 1999 and completed in mid 2000, includes a detailed assessment of environmental externalities carried out by Tsinghua University. Dispersion models are used to simulate the impact of SO_2 emissions, and a similar analysis is carried out to assess the impact of particulates and NO_x emissions. Finally, the environmental damage from these pollutants is estimated.

11. The methodology is designed to address the issues noted above and includes the following four general steps (Figure 1):

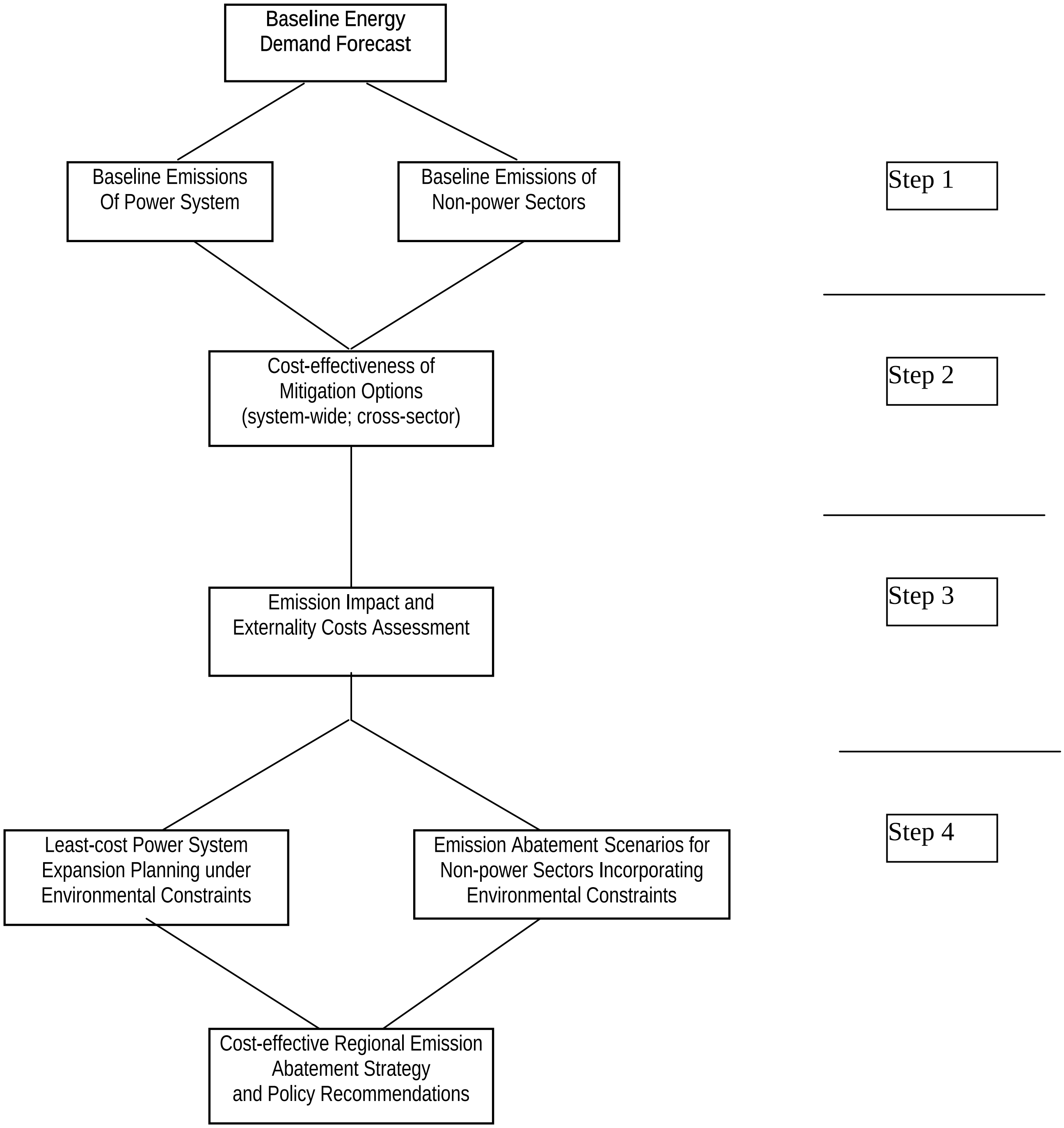
- The development of baseline energy demand and emissions forecasts
- The evaluation of environmental control options and strategies based on their cost-effectiveness (a cross-sectoral perspective approach is followed to compare options across sectors)
- An assessment of emission impacts and environmental damages (externality costs)
- The incorporation of environmental constraints into energy planning, including power system least-cost expansion planning and emission abatement strategies for non-power sectors

12. A brief description of each step in the methodology is provided in the following paragraphs.

<u>Step 1. Establishing Baseline Energy Demand and Emissions Scenarios</u>

13. Within this step, a baseline energy demand scenario is first developed for the period under evaluation (usually 20 years). Then, a bottom-up approach is developed by aggregating the energy demand of end users in each sector. This bottom-up approach helps explain future changes in energy use patterns which may impact the emission release rates and their environmental damage. There are many models available for such analyses. In two out of the three case studies carried out in China (Henan and Hunan Provinces), the Model for Analysis of Energy Demand (MAED) is used (Annex 6). In the third case (Shanghai), an existing energy demand forecast is adapted without further analysis.

Figure 1
Analyzing Emissions Mitigation Policies for Power and Non-Power Sectors



The model projects future energy demand by reconstructing the energy consumption at sector, subsector and end-use levels in the base year and by generating forecasts based on scenarios that reflect:

- International, domestic energy sources and the energy market
- Population growth, lifestyle and standard of living
- GDP growth pattern
- Changes in energy efficiency and technologies

14. Following the development of the energy demand forecast, baseline emissions are estimated from the power generation and energy use in non-power sectors. For the power sector, the emission release rates are estimated using the EM model (Environmental Manual for Power Development) in conjunction with the generation expansion planning models (WASP for Shanghai and GESP II for Henan and Hunan). This estimation is based on the features of the existing and new energy facilities including their typical design, fuel characteristics, operating practices and energy conversion efficiency. The most commonly estimated pollutants are total particulates (TSP), SO_2, NO_x, and CO_2. In addition to the pollutants released by the power generation facilities, the pollution *rates* occurring throughout the fuel chain are also estimated, including those from fuel extraction (e.g., coal mining), processing (e.g., coal cleaning or oil refining) and transportation.

Step 2. Screening Environmental Control Options

15. In this step, all alternatives for emission control options are identified. These include:

- Specific options which can be applied on existing power plants
- The retirement of smaller inefficient plants and their replacement with larger and more efficient ones
- Advanced coal utilization
- Emission reduction options for non-power sectors

16. After the emission mitigation options are identified, their costs in reducing specific pollutants are estimated at the system level. The cost-effectiveness of each environmental control option is estimated using the discounted value of costs divided by the discounted tons of pollutant reduction, assuming the utilization of the environmental control option wherever applicable throughout the sector.

17. Generation expansion planning models (e.g., WASP or GESP II) are used to estimate system-wide costs and emissions from the power sector. To estimate emissions with a reasonable level of accuracy and consistency, the capability of these models to dispatch the existing power plants' abilities to meet the projected demand for electricity is essential.

18. The costs of environmental control options are not spread (allocated) to more than one pollutant. For example, for most options the cost-effectiveness for each pollutant is calculated assuming all the incremental costs (over the base case option) associated with this pollutant. The synergistic effect of controlling multiple pollutants is considered in the optimization (least-cost planning) where environmental externalities are utilized (Step 4). The cost-effectiveness is used as a screening criterion to identify the most cost-effective options so that they can be subjected to a more detailed analysis.

Step 3. Conducting an Environmental Externality Analysis

19. Evaluating pollution impacts and damage costs involves an assessment of the following:

- The effect of emissions on ambient concentrations and/or other pollution level indicators
- The damage caused by pollution, often represented by the dose-response relationship between the affected population (human or other types of victims) and the pollution levels of the concerned pollutant
- The economic value of the damage

20. With regard to environmental externalities, the methodology is designed to address two main questions:

- What are some indicative externality values for each case (site or province or country)?
- How can externality analysis be used in policy-making?

21. Environmental externalities are usually controversial because they depend on the perspective of each stakeholder and a very site-specific setting including the present inventory of pollutants, prevailing weather patterns, topography, population density and economic conditions. While the development of site-specific externality values was outside the scope of this study, an attempt was made to identify some indicative values for Shanghai Municipality, Henan, and Hunan Provinces.

Environmental Externalities

22. Two approaches are utilized to estimate environmental externalities. In the first, externality values from the New York State study[6] are used as a reference point but are adjusted to reflect the GDP per capita and population density of Shanghai and Henan. A second, more detailed, approach is taken for Hunan. The externality cost for each pollutant is estimated based upon an optimum control option for each pollutant, and then, collectively, an externality cost for all pollutants and control options is obtained.

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6 Ref: Rowe et al., *New York Externality Model*, 1994

23. The damages are estimated for Shanghai and Henan based upon a formula that accounts for the distance between the pollution's source and the population density. The environmental damage was approximately two times as high for all the pollutants (TSP, SO_2 or No_x) in Shanghai than in Henan because of the former's higher population density.

24. The Hunan case study takes a methodological approach and seeks to determine the externality cost for each pollutant—TSP, SO_2 and NO_x. This system-oriented approach uses dispersion modeling and is based upon the implementation of a clear planning process that uses a step-by step approach.

25. The externality cost of each pollutant (SO_2, NO_x and TSP) is completed independently using a dispersion modeling and damage-cost valuation approach. Based on these results, an optimal analysis of the externality cost for all pollutants is performed collectively. For power generation expansion, the final analysis yields an optimum system-level solution that accounts for the externality costs for each pollutant.

26. Table 1 presents the results.

Table 1: Externality Values

	Shanghai	*Henan*	*Hunan*
	($1996/ton)		*($2000/ton)*
TSP/PM10	1903	940	801
SO_2	390	217	364
NO_x	454	252	201

Step 4. Developing Least-cost Plans Under Environmental Constraints

27. Beginning with a business-as-usual case, a least-cost integrated power system expansion plan considered the following:

- A pollutant emissions limitation (including an annual reduction goal);
- A pollutant emissions externality cost; and
- A combination of the two prior factors.

28. Environmental constraints were incorporated in least-cost planning in a number of different forms:

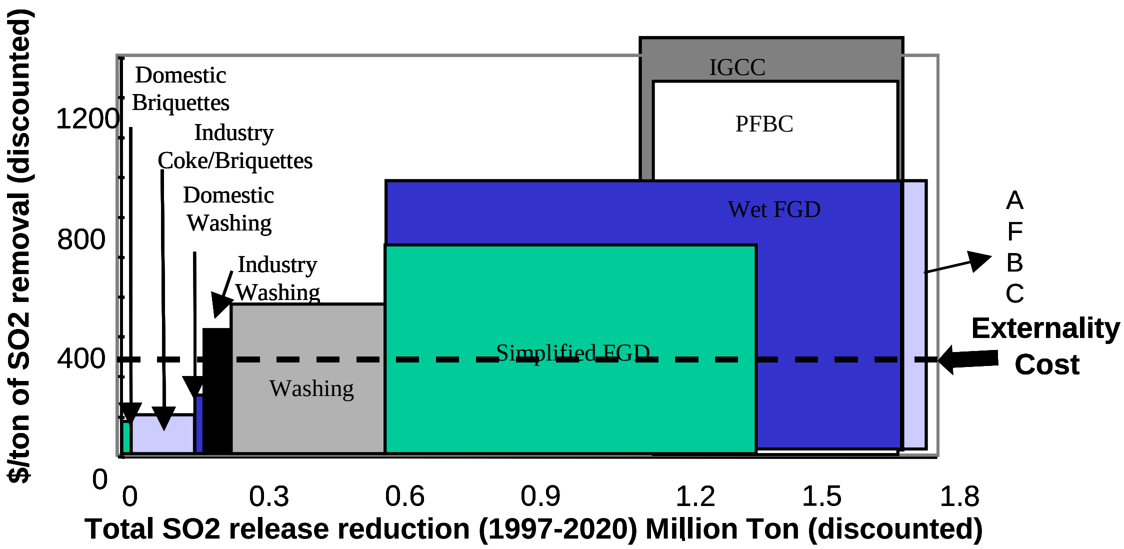
- All options under consideration were selected so that they could satisfy China's most recent environmental regulations;
- Total emissions from the Sector could be limited to a specific level each year; and
- Environmental externality values could be included.

29. Power and non-power sectors were handled separately primarily because planning tools for the power sector are well-established, while no such tools exist for the non-power sectors. For the power sector, a least-cost plant was developed using WASP in the case of Shanghai and GESP II in the case of Henan. In Hunan, the GESP II model was also used to develop the least-cost business-as-usual (BAU) case, taking into account the primary energy situation, load forecast, existing system, and expansion candidates. In addition, GESP II was used to simulate and analyze alternative technology options and their corresponding pollutant emission.

Key Findings Regarding Environmental Control Options

30. In most cases, non-power sector options are more cost-effective than power sector options in reducing environmental pollution, as shown for example by the SO_2 control options for Shanghai in Figure 2. However, the achievable reduction (total tons of pollutant) by non-power applications is limited and may not be adequate to achieve certain levels of environmental control. Also, the enforcement of non-power sector policies is more difficult than that of power sector policies. The following paragraphs summarize the key findings for the main pollutants (particulates, SO_2, NO_x and CO_2).

Figure 2: Cost Effectiveness of SO_2 Control Options (Shanghai)



31. *Particulates:* In Shanghai, Henan, and Hunan, particulate emissions come mainly from non-power sectors (78%, 84% and 87%, respectively). Total particulates from the power sector are expected to decline due to actions already taken by the central and local governments including the utilization of a higher quality coal (lower ash content), the retirement of small-inefficient power plants and the utilization of high efficiency ESPs in new and some existing coal-fired power plants. An evaluation of alternative particulate control options indicates that the use of gas and briquettes in households, coal washing, and the installation of ESPs in existing small power plants, are the most cost-effective options for the further reduction of particulates.

32. Such options should be pursued because their costs (per ton of TSP removed) are lower than their estimated environmental damage (measured in externality values). Furthermore, the cost of an increased control of particulates is relatively small. For example, particulates can be reduced 20% from their 1997 levels in Henan by the year 2020 by utilizing high efficiency ESPs in both new and existing power plants (including small to medium size, 50-200 Mws). The average cost of electricity will increase from 0.262 Yuan/kWh to 0.264 Yuan/kWh.

33. *SO_2 Control:* The non-power sector is again the largest contributor to SO_2 emissions. In Shanghai, the most cost-effective options for controlling SO_2 emissions include the following (see Figure 2): the use of coal briquettes in the residential and industrial sector, coal washing in all sectors, and simplified FGD installed in those selected existing power plants that burn medium-to-high sulfur coal.

34. In Henan, the most cost-effective options for controlling SO_2 emissions are the use of briquettes in rural households and simplified FGD installed in all units that burn medium-to-high sulfur coal. In Hunan, the use of rural household and industrial briquettes, boiler retrofit, industrial and household coal washing, and industry coal screening are the most effective control options. However, the costs of all SO_2 control options seem to be higher than the environmental damage cost.

35. A least-cost plan for Henan that included the stabilization of SO_2 emissions to 1997 levels by the year 2001 identified a combination of simplified and wet FGDs on existing and new coal-fired power plants as key SO_2 control options. The impact of SO_2 stabilization on the cost of electricity was significant. The average cost of electricity increased about 10%, from 0.262 Yuan/kWh to 0.289 Yuan/kWh.

36. The plan suggests that the stabilization of particulates and SO_2 in non-power sectors can also be accomplished as a result of the introduction of gas in urban households, and briquettes in industry and rural households. The study recommends an implementation schedule that addresses the introduction of non-power sector environmental control options.

37. *NO_x Control:* Although the control of NO_x emissions in existing plants is not currently required, there is an understanding that NO_x emissions will become a problem, especially in urban areas where a rapidly expanding transportation sector emitting volatile organic compounds is setting the stage for a smog problem. To prevent this problem by reducing the growth rate of NO_x emissions, combustion NO_x controls should be applied to the largest extent possible. These should be implemented not only in new plants, but in existing plants as well, many of which are being rehabilitated. In addition to the utilization of low NO_x burners in new power plants, combustion tuning/optimization and low NO_x burners in existing power plants are cost-effective options (costing less than $ 100 per ton, which is lower than the estimated externality value of $ 250 per ton).

38. The stabilization of NO_x to 1997 levels by the year 2001 can be achieved using combustion tuning/optimization and low NO_x burners up to the year 2010. After

2010, the installation of SCR in some power plants would be necessary. The impact of the NO_x emission constraint on the cost of electricity was relatively small (the average cost increased from 0.262 Yuan/kWh to 0.265 Yuan/kWh).

Least Cost Optimization Analysis

39. While the cost-effectiveness of each environmental control option is useful as a screening device, eventually a least-cost abatement plan needs to be developed that satisfies system-level requirements including environmental goals and standards. Least-cost emission abatement plans for the power sector may be derived from least-cost expansion modeling but with the inclusion of environmental compliance requirements and constraints. For non-power sectors, alternative scenarios are developed based on the cost-effectiveness of the various options. Both the Henan and Hunan case studies embody this approach.

40. Figure 3 and Table 2 offer evidence. They describe emission abatement for the SO_2 limitation case as it compares to the Base Case (BAU). From the year 2003 to the year 2005, the SO_2 emission decreases significantly due to the retirement of a large number of small-size power plants. There are no new technologies competing for the SO_2 reduction for the Hunan electric power system, and as such, other emission reductions should be considered as well.

Figure 3: SO_2 Emission Abatement for Hunan Power Sector

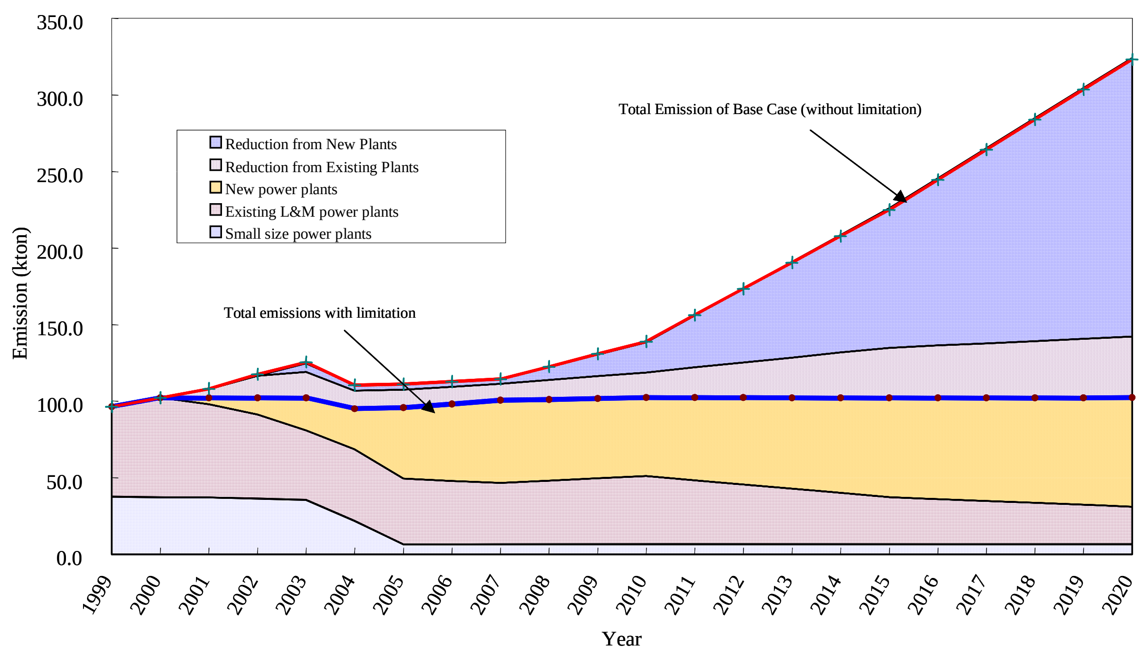


Table 2: Emission Reduction: Optimal Integrated Planning of Generating Capacity Expansion (SO2-2000 Case), (000 tons)

	1996	*2000*	*2005*	*2010*	*2015*	*2020*
SO_2	96.5	102.3	95.8	102.3	102.3	102.3
TSP	180.1	183.3	49.2	51.2	51.7	52.9
NO_x	79.9	84.2	85.8	116.0	151.9	192.3
CO_2	17425	18414	19795	25903	41178	58751
SO_2 reduction vs. BAU Case	0.0	0.0	15.3	36.7	122.6	220.8

Recommendation

41. This study confirms that system level analysis is essential for evaluating alternative environmental control alternatives and policy options. Plant-level analysis is useful as a preliminary indicator of the cost-effectiveness of alternatives, but does not capture the role of each option in an integrated power system, which is being dispatched based on economic considerations.

42. Scenario analysis proves to be helpful in screening the various environmental control options based on their cost-effectiveness and reducing the number of options being considered in the development of a least-cost plan.

43. An assessment of non-power sector environmental control options was carried out satisfactorily, but the level of detail and the quality of the analysis was not the same with the power sector. In future studies, further improvement is needed in:

- The level of detail of the data being collected;
- The methodology for developing a least-cost plan for non-power sector applications (currently, the identification of the best options is done solely based on their cost-effectiveness and expert judgment); and
- The level of environmental damage being caused by each pollutant for each setting.

44. Future studies will benefit greatly from information about the environmental damages caused by each pollutant on the environment. For example, the impact of particulates in households (indoor air quality) is different than the impact of particulates from industrial facilities in an urban or rural setting. Of course, the quantification of such damages is a very subjective and controversial activity, but even an indicative range of values would be helpful in evaluating the various options. The approach followed in this study (to identify the break-even point at which environmental control options become more cost-effective than the baseline option) has proven useful for policy-making, but the availability of environmental damage costs will make it even more useful.

45. More detail assessments, which would be beneficial in the future, include:

- A simplified dispersion analysis to assess the impact of increased pollution in air quality;
- The tracing of the costs of environmental control options over time, following the change from their introduction in China to their cost reduction due to less expensive local manufacturing and better knowledge of the technology; examples of technologies that fit this “learning curve” paradigm are ultrasupercritical pulverized coal, PFBC, IGCC and SCR; and
- An improvement in methodology, so that it distinguishes between marginal and average cost-effectiveness in developing a least-cost plan to meet a set of environmental goals.

1

Introduction

1.1 China is the third largest energy producer and the second largest electricity producer in the world. Coal is the most important source of energy and accounts for 75 percent of total energy production. Coal-fired power plants provide more than 90 percent of thermal power generation, which provide around 80 percent of the total electric power production. However, current consumption of more than 1.3 billion tons per year is China's main cause of pollution and acid deposition. Assessing and identifying least-cost environmental mitigation options is thus crucial to resolving China's air pollution problems.

1.2 This report summarizes the results of three studies on the cost-effectiveness of environmental control options and strategies in Shanghai Municipality and Henan and Hunan Provinces of China. The studies were funded by ESMAP and carried out jointly by World Bank staff, the State Power Corp. of China and the Beijing Economic Research Institute (BERI) utilizing software models such as WASP, GESP-II and the Environmental Manual for Power Development (EM[7] model). While the focus of the three case studies was on the power sector, the analyses included both the power and non-power sectors.

1.3 The rapid growth of the Chinese economy and the concurrent use of coal to meet the ever-increasing demand for energy have led to increased levels of both local and regional air pollution damage. This damage has been estimated to be nearly 8% of China's GDP in 1995 (China 2020, World Bank). The failure to address these issues will only cause greater damage to the economy, jeopardizing China's long-term growth prospects.

1.4 The government of China recognizes the importance of these issues and has tightened environmental regulations throughout the country, particularly for the power and non-power sectors, the predominant source of air emissions. Its strategy has been to exert more stringent emission control at the plant level, levy emission fees for certain pollutants, and create acid rain SO_2 control zones.

1.5 China's efforts are shifting to emphasize the regulation of the pollution load (emission release rates) at local and regional levels. Specifically, it seeks to assist power

[7] Developed by Deutsche Gesellschaft fur Technische Zusemmenarbeit (GTZ) GmbH.

companies and provincial authorities in adjusting abatement plans and strategies. Since 1996, provinces have been asked by the State Environmental Protection Administration (SEPA) to keep their particulate and sulfur dioxide emissions at 1995 levels. While these are not strict requirements, they are targets used as environmental constraints for provincial energy planning. Also, policy makers continue to look at alternative environmental control strategies to improve regulatory requirements.

1.6 These requirements create the need to approach the cost-effective abatement of local and regional emissions at sector and multi-sector levels to reduce compliance costs and improve regulatory efficiency. The sectoral and cross-sectoral perspectives are especially important in dealing with the growing impact of sulfur dioxide (SO_2) emissions as China moves to limit the total SO_2 pollution at the provincial level or within acid rain and SO_2 control zones.

Objectives

1.7 The four objectives of the studies were to:

1. Develop a basic methodology and approach to assess the cost-effectiveness of alternative environmental control that could be adaptive and flexible to varying conditions within China.
2. Identify the least-cost environmental compliance strategies for the four energy based pollutants (particulates, SO_2, NO_x and CO_2) from the power and non-power sectors.
3. Apply the methodology in selected provinces to demonstrate its effectiveness and refine it for further application throughout China;
4. Develop conclusions for Shanghai, Henan and Hunan regarding least-cost pollution control options, and environmental compliance strategies, as well as to engage local organizations to build the indigenous capacity to carry out similar assessments in the future.

1.8 Included in the development of the methodological framework and the local capacity building was the enhancement of the GESP II power system planning model, which is being used extensively in China for power system planning. Because this capability was not available when the Shanghai study was carried out, this study focused only on the assessment of cost-effectiveness of alternative strategies. The Henan case study includes development of least-cost plans with and without environmental externalities. Finally, the Hunan case study employed a detailed three-level analysis architecture to evaluate clean coal technologies in the power sector: a technology analysis of each pollutant control option at the plant level; an assessment of each option from a system perspective; and a system-oriented least-cost analysis for the entire power system.

Report Organization

1.9 The report is organized in five sections and nine Annexes covering the following topics:

- Section 1: Introduction
- Section 2: Methodology
- Section 3: Key Findings
- Section 4: Results and Conclusions
- Annex 1: Environmental Regulations of China
- Annex 2: Description of GESP Model

2

Background

2.1 The Shanghai Municipality and Henan and Hunan Provinces were selected for their different attributes and because they represent distinct regions within China. The former is a densely populated and industrialized coastal area, and the latter two are more rural, less-developed in-land provinces. Comparing these areas from the energy development and environment point of view provides important insights regarding the most appropriate (cost-effective) environmental control options.

Overview

2.2 By the end of 1996, Shanghai Municipality had a population of 13 million and an area of 6,340 km^2 (see Table 2.1) and a population density of 2,060 people/ km^2. Henan is a populous province (nearly 92 million by the end of 1996) that extends over a larger area (167,000 km^2). Its population density is 550 people/km^2. Hunan province has a population of 65 million, an area of 212,000 km^2 and a population density of about 305/ km^2.

Table 2.1: Statistics on Shanghai, Henan Hunan, and China

		Shanghai	*Henan*	*Hunan*	*China*
Population, 1998	million	14.64	93.15	49.39	1248.1
Area	km^2	6,340	167,000	212,000	9,600,000
Population Density	People/km^2	2,309	558	307	130
Population Growth Rate, 1998	%	0.48	0.78	0.57	0.96
Percent of Rural Population, 1997	%	2.7	74.8	43.5	70.1

2.3 In addition to the population density, other key differences between the dense Shanghai and less dense Henan and Hunan are:

- Most of the population of Henan (80%) and Hunan (75%) lives in rapidly developing rural areas, while Shanghai's population is mostly urban (only 14% is rural).

- The annual population growth rate in Henan and Hunan is similar to the national average (0.9% and 1.1%, respectively), while Shanghai's population grows at a much slower rate (0.03%).

Economy

2.4 Shanghai's GDP and income per capita are much higher than Henan's and Hunan's, while the growth rate is similar. Table 2.2 provides the key economic data. In the 1980s, the GDP of the provinces and the country in general grew at an annual average of 5-7%. In the 1990s, the annual growth rate increased to 10-13%.

Table 2.2: Economic Data of Shanghai, Henan, Hunan and China (1998)

		Shanghai	*Henan*	*Hunan*	*China*
Economic Indicators					
GDP	Billion Yuan	368.82	435.66	321.14	7,939.57
GDP per Capita	Yuan	25,193	4,677	4,939	6,361
GDP	Billion $	44.44	52.49	38.69	956.57
GDP per Capita	$	3,035	563	595	766
Percent of China's GDP(%)		4.6	5.5	4.0	-
Growth Rate					
GDP, 1980-1998	%	9.7	10.8	9.2	9.9
GDP, 1990-1998	%	12.6	12.2	11.2	10.8
GDP per Capita, 1980-1998	%	9.3	9.3	8.0	8.5
GDP per Capita, 1990-1998	%	11.2	11.2	10.1	9.6
Output by Sector (% of total)					
Agriculture	%	2.1	24.6	35.8	18.4
Industry	%	50.1	46.2	40.3	48.7
Services	%	47.8	29.2	33.9	32.9

2.5 As Table 2.2 shows, Henan's economic output has a substantial agricultural component (25%), while Shanghai's agricultural output is only 2%. Industrial output is similar for both Henan and Shanghai, while the output of the service sector is higher in Shanghai (43% vs. 28% in Henan and 32% in Hunan).

Energy

2.6 Energy statistics (shown in Table 2.3) indicate that energy per capita in Shanghai is 3-4 times higher than in Henan and in greater China. The industrial sector consumes 60-70% of the energy in both Shanghai and Henan, while the residential is a significant contributor (17-19%) in Shanghai.

Table 2.3: Energy Consumption for Shanghai, Henan and China (1996)

		Shanghai	*Henan*	*Hunan*	*China*
Energy Consumption					
Energy Consumption	M tce	47.82	66.54	43.29	1389.48
% of China's Energy		3.4%	4.8%	3.1%	-
Energy Intensity	kgce/yuan	0.165	0.182	0.164	0.205
Energy per capita	tce/person	3.666	0.725	0.673	1.135
Energy Consumption by Sector					
Agriculture	M tce	1.05	3.39	3.20	56.97
Industry	M tce	36.58	47.84	30.65	1019.88
Service	M tce	7.08	4.59	2.55	134.78
Residential	M tce	3.11	10.71	6.88	177.85
Total	M tce	47.82	66.54	43.29	1389.48

2.7 Coal is the main source of energy for both Shanghai and Henan (see Table 2.4). Oil and gas represent 11-13% of the total energy consumption, mainly from the transportation sector.

Table 2.4: Consumption by Energy Source (1996)

		Shanghai	*Henan*	*Hunan*
Coal	M tce	11.57	29.34	32.50
Oil and Gas	M tce	9.63	8.32	6.84
Electricity	M tce	14.04	24.35	3.94
Total		47.82	66.54	43.29

Power Subsector

2.8 Installed power generating capacity of Shanghai and Henan represents 3.7% and 5.0% of the total installed capacity of China and is also dominated by coal. Oil-fired generation represents approximately 7% of the total power generated in Shanghai, while there is no oil- or gas-fired capacity in Henan. Instead, Henan has a small percentage (approximately 3%) of hydroelectric power. This limited availability of energy resources is a major constraint for both economic development and environmental protection.

Table 2.5: Power Sector (1998)

		Shanghai	*Henan*	*Hunan*	*China*
Install Capacity	MW	9,527	13,784	9,920	277,289
% of China's Power	%	3.44%	4.97%	3.58%	-
Power Generation	TWh	48.29	62.62	35.00	1,157.7
% of China's Generation	%	4.17%	5.41%	3.02%	-
Installed Capacity					
Coal	MW	8,000	13,156	4,757	190,538
Oil and Gas	MW	1,527	0	60	17,245
Hydro	MW	0	628	5,103	65,065
Nuclear	MW	0	0	0	2,100
Total	MW	9.527	13,784	9,920	277,289
Power Generation					
Coal	TWh	45.00	60.94	15.30	893.39
Oil and Gas	TWh	3.28	0	0.11	45.43
Hydro	TWh	0	1.68	19.59	204.30
Nuclear	TWh	0	0	0	14.10
Total	TWh	48.29	62.62	35.00	1,157.7

Environmental Issues

2.9 Shanghai and most of the cities in Henan Province suffer from excessive levels of air pollution. The average concentration of SO_2 in Shanghai is close to the National Air Quality Standard and the limit recommended by WHO, 60 $\mu g/m^3$, but the concentration of TSP in both urban and rural areas (241 and 203 $\mu g/m^3$, respectively) exceeds by far the WHO standard (60 $\mu g/m^3$). In Shanghai, acid rain is common, as indicated by the average pH of the precipitation, which reached 5.42 in 1994 and 5.38 in 1996. Acid rain occurrence frequency was 15.2%, 1.9% higher than in 1995.

2.10 One key difference lies between Henan and Hunan, as compared to Shanghai. The industrial and residential sectors in Henan and Hunan continue to rely almost exclusively on coal. In Shanghai, they have started making the transition to cleaner fuels such as oil, LPG and gas.

Shanghai

2.11 Because the Shanghai power and non-power sectors were not studied in detail, the resulting analysis was relatively simple. The sources of pollution vary with the types of pollutant (TSP versus SO_2) and are as follows:

- Industrial and residential sources contribute approximately 78% of particulates, while power plants contribute only 22%; within the power sector, 90% of particulates (20% of the total) come from small power plants less than 125 MW.

- The power sector emits approximately 72% of the total SO_2 emissions; in 1994, the total coal consumed in Shanghai was 35.13 million tons, which produced 451.9 thousand tons of SO_2, 325.5 thousand tons of which were emitted from power plants.

Henan

2.12 The Henan Province faces similar environmental problems. Pollution is concentrated in urban areas, but it is rapidly expanding to rural areas too. TSP and SO_2 concentrations (see Table 2.6) in most cities are above the WHO limit. While NO_x concentrations have not yet reached the WHO limit (150 $\mu g/m^3$), release of NO_x emissions is increasing rapidly, mainly because of the growth of the number of automobiles in urban areas. As a result, NO_x is expected to become a serious concern soon both in terms of its contribution to acid rain and urban smog. The degree of ecological damage is becoming a constraint to economic development and is receiving increased public attention.

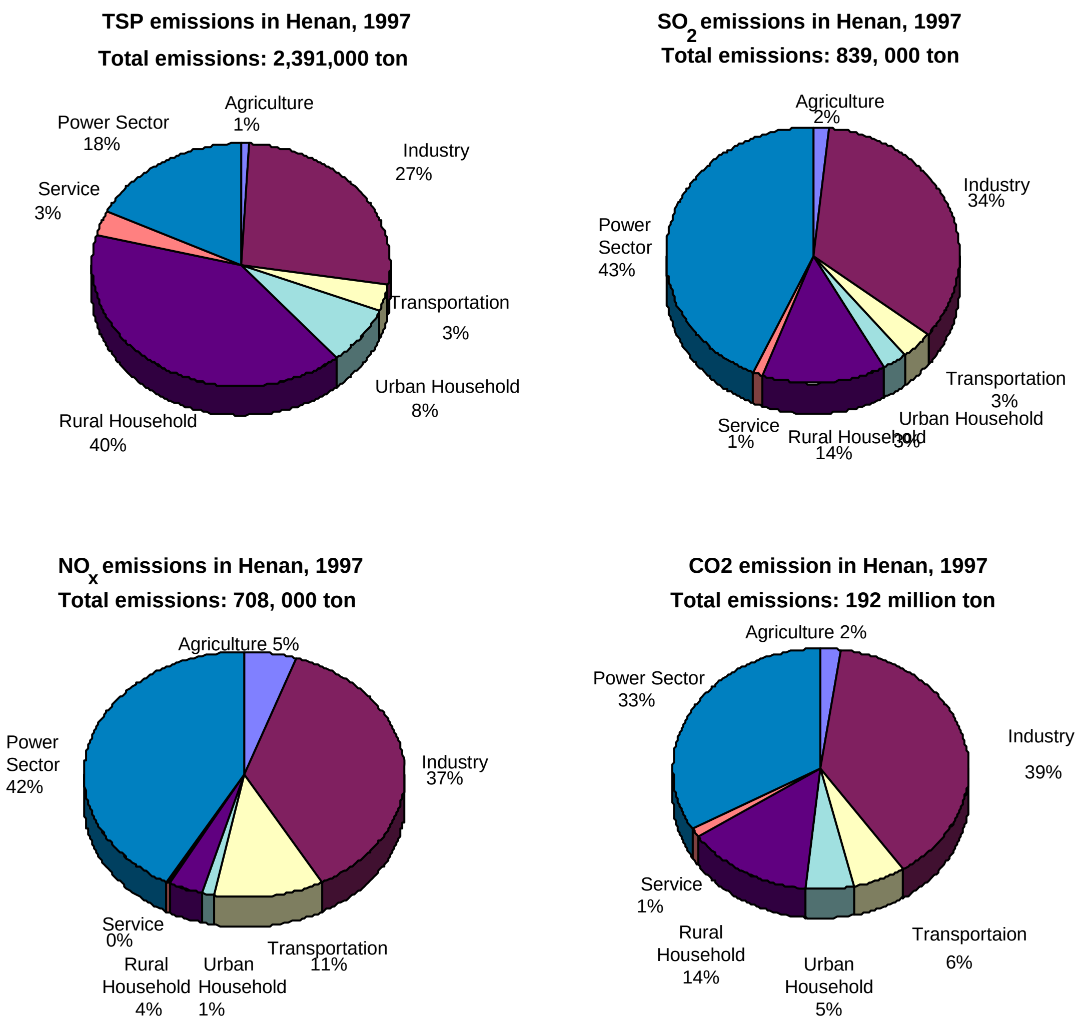
Table 2.6 The Annual Mean Value of Ambient Concentration of SO_2, TSP and NO_x Emissions In Major Cities of Henan Province ($\mu g/m^3$)

	1993			*1998*		
Name of City	*SO_2*	*TSP*	*NO_x*	*SO_2*	*TSP*	*NO_x*
Luoyang	155	365	56	82	401	49
Anyang	095	403	65	40	452	74
Zhengzhou	67	418	71	51	424	61

Source:NEPA, China Environment Yearbook 1996

2.13 Figure 2.1 shows the major contributors of air pollution in Henan. Rural households burning coal and biomass are the main contributors of particulates (contributing 40% of the total), followed by industry (27%) and power (18%). The main contributors of SO_2 include the power sector (43%), industrial sector (34%), and rural households (14%). Power and industry are also the main contributors of NO_x and CO_2.

Figure 2.1: Contributors to Air Pollution in Henan



Hunan

2.14 In 1997, the emission of SO_2 in Hunan was 821,000 tons, the emission of smoke dust was 510,000 tons, and emission of industrial dust was 945,000 tons.

2.15 In 1997, coal-fired plants owned by Hunan power electric company consumed 5.13 million tons of coals, in which average dust content reached 32.28% and average sulfur content reached 0.71%. Plants discharged 53,320 tons of SO_2, 74,880 tons of smoke dust and 45,000 tons of NOx.

Initiatives to Improve the Environment

2.16 Both the central and provincial governments have made efforts to improve the environment through policies and regulations. In 1995, China promulgated *The Environmental Protection Law* and a number of additional laws affecting the environment and natural resource utilization. The environmental regulations that apply to thermal power plants are described in Annex 1.

2.17 Local governments promulgated similar environmental protection regulations. In particular, the Shanghai municipality issued stringent environmental regulations and increased efforts to enforce existing regulations by imposing fines on industrial units and power plants which do not comply with emission standards. The municipality also imposed the use of flue gas desulfurization for all new plants. It is also cooperating with the World Bank to apply the bubble concept to control sulfur dioxide emissions while minimizing costs.

2.18 However, more remains to be done to bring air pollution to acceptable levels. Balancing economic development and environmental control through the utilization of cost-effective options is a critical issue. The methodology developed and applied in this project is a first attempt to develop cost-effective strategies for environmental control.

3

Methodology

Overview

3.1 The methodology utilized was based upon three case studies of increasing complexity and comprehensiveness. As a result, the approach was progressively refined and improved with each subsequent case study. By the commencement of the third study, Hunan, a comprehensive framework had been developed for evaluating the cost-effectiveness of alternative environmental control strategies and for creating least-cost compliance plans. Existing tools were used, some of which had been enhanced, but the most important aspect of the work was the integration of various analyses into one methodological framework.

3.2 Beginning in 1997, the Shanghai case study included: (1) an estimation of emissions from the power and non-power sectors; (2) an assessment of cost-effectiveness of environmental control options; and (3) an attempt to estimate the environmental damages (externalities). A power subsector study completed in 1997 for the Waigaoqiao thermal power was used to build upon existing data (emission rates and factors) and models without modifications.

3.3 Indicative environmental externality values were developed by utilizing values for the New York State study (Asian Development Bank, 1996) and adjusting them to reflect the GDP and population density of the Shanghai area. To adjust for the uncertainty of such estimates, a sensitivity analysis was carried out to identify the externality ranges within which various environmental control policies became cost-effective.

3.4 The Henan case study, carried out in 1998, was more comprehensive. It included a detailed assessment of the energy demand forecast to develop a better basis for predicting future emission patterns especially from the non-power sectors using a GESP II model (Annex 2). The demand forecast was developed using the MAED (Model for Analysis of Energy Demand) model. Also, least-cost plans were developed for the power sector with emission limitations and environmental externalities. To do so, the GESP II model had to be enhanced to accept emission constraints, as well as environmental externalities.

3.5 Last, the Hunan case study, initiated in 1999 and completed in mid 2000, represents the culmination of analytical efforts. In addition to the analyses carried out in the Henan study, the Hunan case included a detailed assessment of environmental externalities carried out by Tsinghua University. Dispersion models were used to simulate the impact of SO_2 emissions on ambient air quality and acid rain deposition. Similar analysis was carried out to assess the impact of particulates and NOx emissions. Finally, the environmental damage from these pollutants was estimated.

3.6 The methodology applied in the Shanghai, Henan and Hunan case studies involves the assessment of the cost-effectiveness of alternative environmental control options at the system level and the development of least-cost compliance strategies that satisfy sector-wide environmental requirements and limitations. Key principles followed were:

- A comprehensive approach for better use of resources;
- An internalization of environmental externalities in the planning process;
- The assessment of all significant sources of pollution; not only the power generation facilities, but non-power sources such as industrial, residential and transportation;
- The cost-effectiveness of key environmental control options (alternative strategies) based on a sector-wide analysis and assessment of system-level effects; and
- The optimum mix of development and environmental control options taking into account:
  - System-wide costs;
  - Synergistic characteristics of options (some options control more than one pollutant); and
  - Emission constraints (i.e., keeping emissions below a certain level).

The Methodology

3.7 The methodology is designed to address the issues noted above and includes four general steps (see Figure 3.1):

1. Developing baseline energy demand and emissions forecasts;
2. Evaluating environmental control options and strategies based on their cost-effectiveness (a cross-sectoral perspective approach is followed to compare options across sectors);
3. Assessing emission impacts and environmental damages (externality costs); and
4. Incorporating environmental constraints into energy planning, including:
   - A power system least-cost expansion plan

- An emission abatement strategy for non-power sectors

3.8 These steps provide a structured approach to address the needs of power companies (usually the development of least-cost plans under environment constraints), as well as policy-makers, who are interested in assessing the cost-effectiveness of alternative policies or technological options. Because the power system and the non-power sectors have quite different technical and institutional structures, they are analyzed in parallel using different models. However, the results are brought together whenever possible, especially in the screening of options based on cost-effectiveness, environmental externalities, and the final cross-sector assessment of emission mitigation strategy.

3.9 A brief description of the methodology is provided in the following paragraphs.

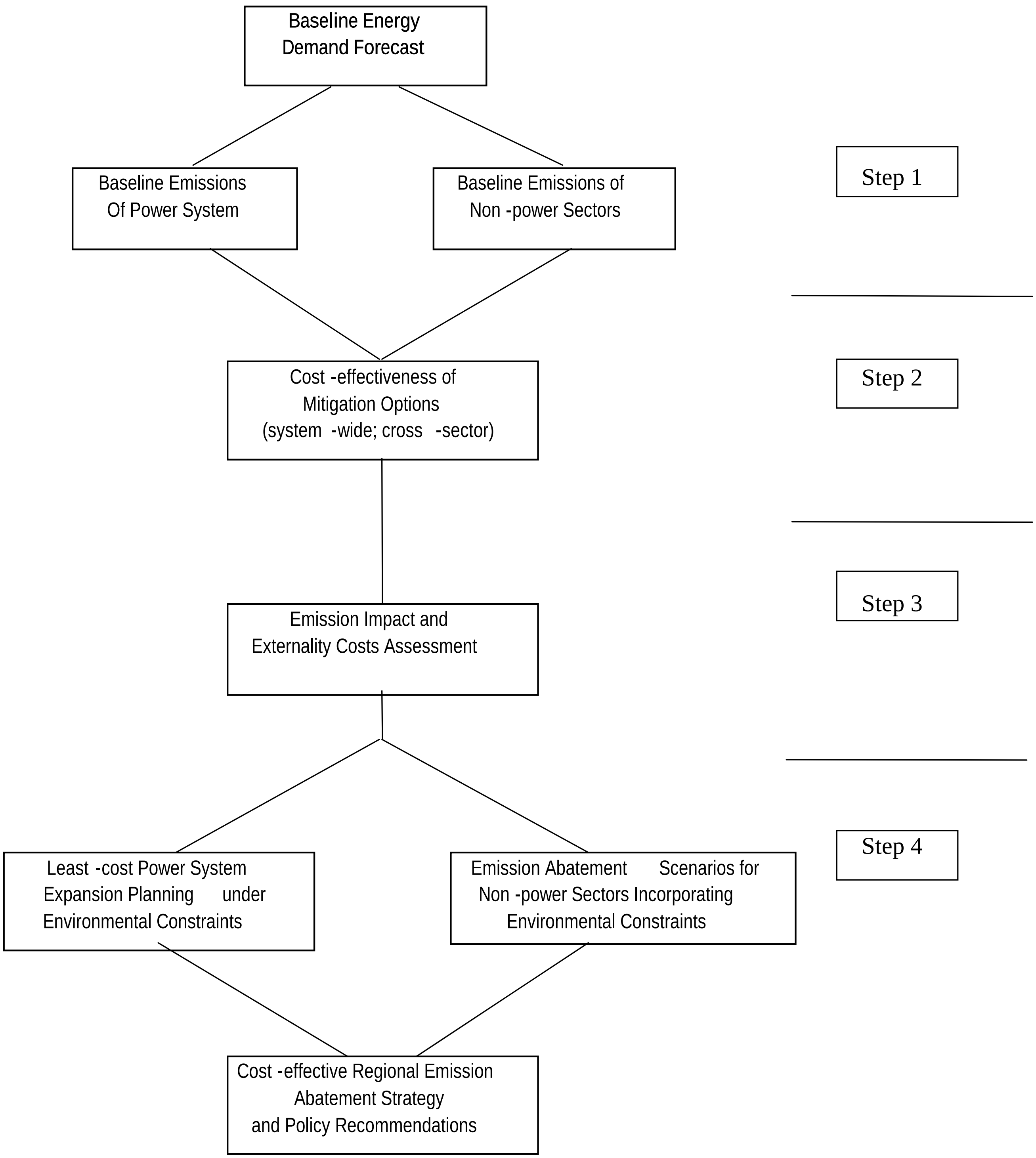
Step 1. Establishing Baseline Energy Demand and Emissions Scenarios

3.10 A baseline energy demand scenario is developed for the period under evaluation (usually 20 years). A bottom-up approach (which aggregates the energy demand of end users in each sector) then follows to understand future changes in energy use patterns which may impact the emission release rates and their environmental damage.

3.11 There are many models available for such analyses. In two out of the three case studies carried out in China (Henan and Hunan), the Model for Analysis of Energy Demand (MAED) was used (Annex 6). In the third case (Shanghai), an existing energy demand forecast was adapted without further analysis.

3.12 MAED is a simulation model designed to evaluate medium- and long-term demand for energy in a country or region. The model was developed by, and was originally based upon work done at the University of Grenoble in France (MEDEE model). MAED consists of three modules:

Figure 3.1: Analyzing Emissions Mitigation Policies for Power and Non-Power Sectors



- Module 1 (energy demand) calculates the final energy demand by energy form and economic sector for each reference year according to the various parameters describing each socio-economic and technical development scenario.
- Module 2 (hourly electric power demand) converts the total annual demand for electricity in each sector to the hourly demand, (i.e., the hourly demand imposed on the grid by the respective sector).
- Module 3 (load duration curve) ranks the hourly demands imposed on the grid in decreasing order of magnitude and provides the load duration curve. The curve forms a basic input to least-cost planning models (Step 4).

3.13 The model projects future energy demand by reconstructing the energy consumption at sector, subsector and end-use levels in the base year, and generating forecasts based on scenarios that reflect:

- international, domestic energy sources and the energy market;
- population growth, life style and standard of living;
- GDP growth pattern; and
- changes in energy efficiency and technologies.

3.14 The output of the MAED model consists of detailed estimates of alternative energy forms used in each subsector for each year selected. The breakdown of demand by energy form and economic sector is an important result of the analysis, which can serve as input information for detailed studies of the various sectors and can help optimize the supply of the various energy forms.

3.15 Following the development of the energy demand forecast, baseline emissions are estimated from power generation and energy use in non-power sectors. For the power sector, the emission release rates are estimated using the EM model[8] (Environmental Manual for Power Development) in conjunction with the generation expansion planning models (WASP for Shanghai and GESP II for Henan and Hunan). This is based on the existing and new energy facilities including their typical design, fuel characteristics, operating practices and energy conversion efficiency. The most common pollutants estimated are: total particulates (TSP), SO_2, NO_x, and CO_2. In addition to the pollutants released by the power generation facilities, an attempt is made to estimate the pollution rates throughout the fuel chain, including the rates for fuel extraction (e.g., coal mining), processing (e.g., coal cleaning or oil refining) and transportation.

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8 The EM model was developed by a number of bilateral agencies from Germany (BMZ and GTZ), the Netherlands (DGIS), Switzerland (BAWi) and the United Kingdom (DFID) with the coordination of the World Bank.

3.16 For the non-power sectors, the emission release rates were estimated using the energy demand from the MAED model and the emission factors for each end-use application which were derived from the EM model.

Step 2. Screening Environmental Control Options

3.17 Under this step, all alternatives for emission control options were identified. These included:

- Specific options which can be applied to existing power plants such as the use of cleaned (washed) coal, retrofit control technologies such as the upgrading of electrostatic precipitators (ESP), combustion tuning, low NO_x burners, selective catalytic reduction (SCR), flue gas desulfurization (FGD);
- The retirement of smaller inefficient plants and their replacement with larger and more efficient ones;
- Advanced coal utilization technologies such as atmospheric fluidized-bed combustion (AFBC), pressurized fluidized-bed combustion (PFBC), and integrated gasification combined cycle (IGCC); and
- Emission reduction options for non-power sectors, such as industrial, residential and transportation-related included:
    - The use of washed coal instead of raw coal;
    - The use of briquettes;
    - The switching of urban households from coal to gas or LPG; and
    - Three-way catalysts (for CO, NO_x and hydrocarbon control) considered for automobiles.

3.18 These options, each one separately and in combination with each other, form the basis for scenario analysis.

3.19 After the identification of emission mitigation options, their costs in reducing specific pollutants are estimated at the system level. The cost-effectiveness of each environmental control option is estimated using the discounted value of costs divided by the discounted tons of pollutant reduction, assuming the utilization of the environmental control option wherever applicable throughout the sector. For example, FGDs are installed only in medium and large size units (above 125 MWs), because smaller units are either expected to retire or are judged uneconomical to retrofit. If an existing power plant does not have adequate space, it is assumed that no FGD will be installed. Similarly, gas (LPG or natural gas) is used in urban areas as an alternative to coal, but coal briquetting is used in rural households where gas is not readily available.

3.20 Table 3.1 provides a list of options being considered in the various case studies.

Table 3.1: Emission Abatement Options

Options	*Power Generation*			*Industry/ Agriculture*			*Household/Service*		
	TSP	**SO_2**	**NO_x**	**TSP**	**SO_2**	**NO_x**	**TSP**	**SO_2**	**NO_x**
Supply of sized coals				x	x	x	x	x	x
Coal washing	x	x		x	x	x	x	x	x
Briquettes				x	x	x	x	x	x
Gaseous fuels							x	x	x
Boiler renovation				x	x	x	x	x	x
Boiler retirement	x	x	x	x	x	x	x	x	x
Combustion tuning/optimization			x	**Not Applicable**					
ESP rehabilitation	x								
Low NO_x burner			x						
Selective catalytic reduction (SCR)			x						
Sorbent injection		x							
Simplified FGD	x	x							
Wet FGD	x	x							
AFBC	x	x	x						
PFBC	x	x	x						
IGCC	x	x	x						

3.21 With regard to models, generation expansion planning models (e.g., WASP or GESP II) are used for estimating system-wide costs and emissions from the power sector. The capability of these models to ensure that the existing power plants meet the projected demand for electricity is essential for estimating emissions with a reasonable level of accuracy and consistency.

3.22 The costs of environmental control options for the non-power sectors are estimated, in most cases, using a spreadsheet. Key inputs include: the costs of the environmental control options (in RMB/unit energy output or facility) and the corresponding emission factors. For example, the cost of catalytic converters on automobiles and the resulting emission reduction per automobile are inputs in the sectoral spreadsheet model that calculates the cost-effectiveness (e.g., RMB/ton of NO_x).

3.23 The costs of environmental control options are not spread (allocated) to more than one pollutant. For example, for options such as PFBC and IGCC, which reduce particulates, sulfur dioxide, NO_x and CO_2 emissions, the cost-effectiveness of each pollutant is calculated with the assumption that all the incremental costs (over the base case option) were associated with this pollutant. The synergistic effect of controlling multiple pollutants is considered in the optimization (least-cost planning) where environmental externalities are utilized (Step 4).

3.24 The cost-effectiveness is used as a screening criterion to identify the most cost-effective options, which can then be subjected to a more detailed analysis. Ideally, only the options which have a cost-effectiveness value below the environmental externality should be considered further. However, this criterion should be applied in a flexible way considering that frequently the externality costs are not available with any certainty, so a range may be used instead of a specific number. Also, environmental externalities (damages) may vary from sector to sector. For example, indoor air quality throughout China is much worse than outdoor suggesting that the damage from residential applications is higher than from the average of other applications. Therefore, the costs of environmental control options which reduce indoor air pollution should be compared to a higher environmental externality.

Step 3. Environmental Externality Analysis

3.25 Evaluating pollution impacts and damage costs involves an assessment of:

- The effect of emissions on ambient concentrations or other pollution level indicators;
- The damage caused by pollution, often represented by the dose-response relationship between affected population (human or other types of victims) and the pollution levels of the applicable pollutant; and
- The economic value of the damage.

3.26 The methodology with regard to environmental externalities is designed to address two main questions:

1. What are some indicative externality values for each case (site or province or country)?
2. How can the externality analysis be used in policy-making?

3.27 Environmental externalities are usually controversial. They depend on the perspective of each stakeholder and the site-specific setting including the present inventory of pollutants, prevailing weather patterns and topography, population density and economic conditions. While the development of site-specific externality values is outside the scope of this study, an attempt was made to identify some indicative values for Shanghai Municipality, Henan, and Hunan Provinces.

3.28 Two approaches were utilized. First, for Shanghai and Henan, externality values from the New York State study[9] were used as a reference point and were adjusted to reflect the GDP per capita and population density of each (see Table 3.2). Secondly, for Hunan, a more detailed approach was taken. The externality cost for each pollutant was estimated based upon a first an optimum control option for each, and then collectively, an externality cost for all pollutants and control options was obtained.

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[9] Ref: Rowe et al., New York Externality Model, 1994.

Approach One: New York State Externality Values

3.29 For the first approach, the value of per capita GDP is taken from the World Development Report 1996 (From Plan to Market) using purchasing power parity. The values are multiplied by the number of affected individuals to obtain total values for the impacts per unit of time. The individuals affected are equivalent to the population in related areas. The population of the different areas is estimated based on statistics of related regions. Based on emissions and their unit economic cost and population, the economic externality costs of the emissions at present and future are calculated.

3.30 The damages were estimated for the three regions based on the distance from the source and the population density. Table 3.2 presents the results. For all pollutants (TSP, SO_2 or NO_x), the environmental damage is approximately twice in Shanghai than in Henan, mainly because of higher population density.

Table 3.2: Externality Values (*$ 1996/ton)*

	Shanghai	*Henan*
TSP/PM10	1903	940
SO_2	390	217
NO_x	454	252

3.31 These results are not based on detail site-specific considerations, but they capture the key impacts and are indicative of the level of environmental damage. More importantly, they highlight the need for site-specific studies that can address the nuances of each situation and provide a more realistic externality cost based on actual site conditions.

3.32 To address the uncertainty associated with externality costs, a sensitivity analysis can be carried out to assess the impact of varying environmental externalities on the total cost of the power system. Such analysis identifies the breakeven points where certain control options become more cost-effective than the base-case scenario.

3.33 Figure 3.2 summarizes this analysis and presents the externality value (at the intersection of the two lines) above which the environmental control option becomes more cost-effective than the baseline plan. Such information is useful to policy-makers because it identifies the value of environmental externality which needs to be assigned to a pollutant to make an environmental control option cost-effective relative to the conventional option (the baseline plan or business as usual scenario).

3.34 Figure 3.3 provides an example of such analysis for SO_2 control in Shanghai. In this case, one would conclude that when the externality cost of SO_2 emissions reaches 6000 RMB/ton-emission ($720), coal washing would become cost-effective for the Shanghai power system, compared to the base case (no-control) scenario. Such thresholds provide useful information to energy planners and policy makers to assess the level of environmental externalities above which certain policies or technological options become cost-effective.

3.35 In each of these case studies, externality analysis was used (1) to assess the impact of environmental externalities on the cost-effectiveness of specific environmental control options or scenarios and (2) to incorporate the results into the creation of a least-cost development plan.

Figure 3.2: Externality Values in a Power System

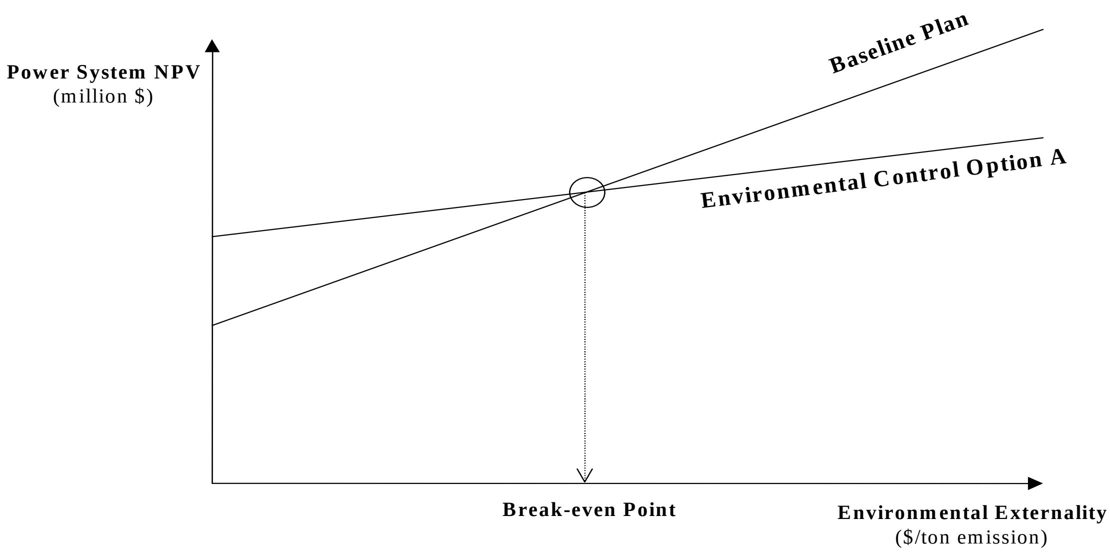
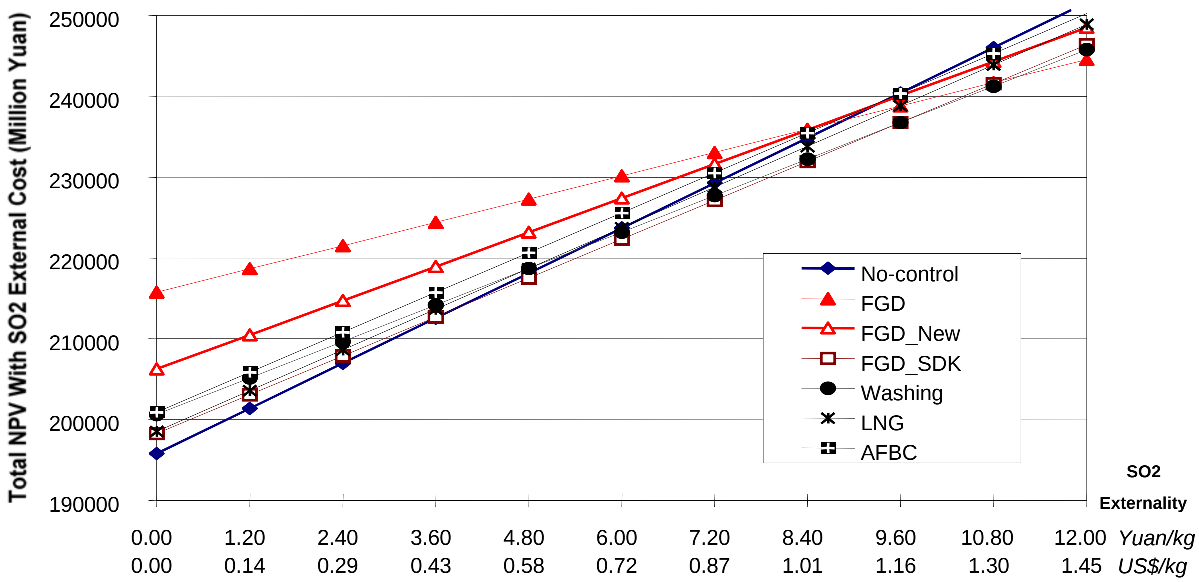


Figure 3.3: Shanghai Power System When SO_2 Externality Is Included



Approach Two: Dispersion Modeling and Damage Cost Estimation Approach

Overview

3.36 The Hunan case study took a methodological approach and sought to determine the externality cost for each pollutant – TSP, SO_2 and NOx. This system-oriented approach used dispersion modeling and was based upon the implementation of a clear planning process using a systematic approach.

3.37 The externality cost of each pollutant (SO_2, NO_x and TSP) was completed independently using dispersion modeling and a damage cost valuation approach. Based on these results, an optimal analysis on the externality cost for all pollutants was performed. The final analysis yielded the optimum system-level solution for power generation expansion with a consideration of the externality costs for each pollutant.

3.38 The detailed dispersion modeling exercise included three steps:

- The modeling of pollutants' dispersion to determine the pollution level;
- The determination of the impact on receptors such as crops, forest, and human health; and
- The evaluation of the environmental damage under the modeled pollution level in economic terms.

3.39 The project estimated the impact of and the damage caused by alternative energy development scenarios on air quality (TSP, SO_2 and NOx). For SO_2, the entire province was taken into account, and three major kinds of damage were considered: on crops, forest, and human health. Since TSP and NOx dispersion are of urban scale, Changsha City, the capital of Hunan province, was selected for the case study, and the damage on human health caused by TSP was taken into consideration. Hunan province was also assessed and the scope of work is summarized in Table 3.3 as follows:

Table 3.3: Scope of Externality Cost Analysis for Hunan

	SO_2	*TSP*	*NOx*
Geographical region	Hunan	Changsha City	Hunan
Base Year	1995	1998	1998
Period of analysis	2000 – 2020	2000 – 2020	2000 - 2020
Increments	5 years	5 years	5 years
Damage Considered	Crops Forest Human Health	Human Health (TSP only)	Health Material Visibility

Damage Cost Valuation

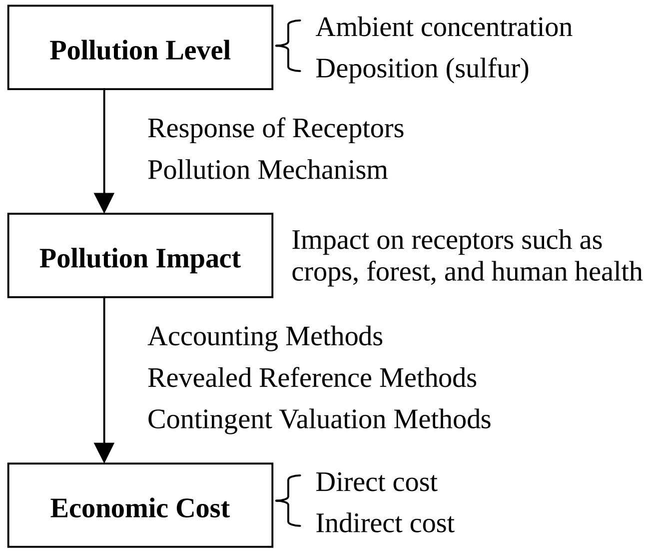
3.40 There are two means of valuing environmental damage, primary and secondary economic methods. Primary methods require a collection and analysis of field data, while secondary methods rely on the findings of previously conducted research. Figure 3.4 provides a summary of this process. Once the pollution level is determined, the impact of the pollution on various receptors and its economic cost is calculated.

3.41 The first step to determine economic cost is to calculate the pollution impact. For example, sulfur deposition is of great harm to the forest. As a result, the kind of damages and the extent caused by sulfur deposition must be estimated. Based on studies, sulfur deposition can cause timber loss, soil erosion, a decrease in the ability of a forest to purify air, etc. Regarding timber loss, the relationship between the volume of timber loss and sulfur deposition must be established. The second step is to make a monetary valuation of the respective impacts.

3.42 Economic cost can be divided into two parts: direct damage cost and indirect damage cost:

- *Direct Impacts:* These impacts have directly measurable productivity changes and can be valued using market prices.
- *Indirect Impacts:* These impacts (such as ecological impacts) cannot be measured by market prices. A project that impinges only on one or a small number of markets can have indirect effects which are much more widespread.

Figure 3.4: Scheme of Damage Cost Valuation Process



3.43 Lastly, three major methods for calculating the economic value of environmental damage are typically employed : 1) accounting methods, 2) revealed preference methods, and 3) contingent valuation methods.

3.44 The impact of SO_2 deposition was measured by assessing the damage to crops, forests, and human health. Forest damage was measured by its impact on timber loss, soil erosion, and the decrease in the forest's ability to purify air. Crop damage was measured using a dose response technique where levels of pollutant were used to determine the resulting decrease in crop yields. The impact on crop damage was measured by the market value of the decrease in crop yield. Lastly, for human health, the impact of pollutants was measured based on increased morbidity, hospitalization, and mortality. Health impacts were valued using a human capital approach, cost of actual treatment, and a willingness-to-pay approach for improved health.

3.45 TSP damage was also measured by its impact on human health based on statistics derived from increased morbidity, hospitalization, and mortality. Using dose-response results and other data the economic cost was measured by using the human capital and willingness to pay approaches.

3.46 Table 3.4 below presents a summary of the SO_2 emissions and externality cost in Hunan for both power and non-power emissions. As is noted, total emissions of SO_2 continue to increase until 2020, the majority of which is from the non-power sector. A dose-response technique, an accounting method, was used to estimate crop and forest damage due to decreased yield. In addition, an indirect ecological benefit of forests was also calculated, estimated to be eight times that of the direct benefit of forest yields. Lastly, human health cost was estimated based upon existing studies that employed both the human capital approach and the willingness to pay approach, generating a linear relationship between damages and SO_2 concentration.

3.47 Total damage cost per ton of SO_2 is estimated to be 3,022 RMB/ton in 2000, increasing to 4,884 RMB/ton in 2010, then decreasing slightly to 6,595 RMB/ton in 2020.

Table 3.4: SO_2 Emission Damage Cost (1995-2020)

Year		***1995***	***2000***	***2005***	***2010***	***2015***	***2020***
				Emission (10^6 ton)			
Non-power		0.80	0.88	1.06	1.24	1.43	1.63
Power		0.09	0.10	0.11	0.14	0.22	0.32
Total		0.89	0.99	1.17	1.38	1.65	1.95
Damage Cost (billion RMB)	Crops	0.54	0.60	0.74	0.93	1.16	1.42
	Health	0.38	0.84	1.46	2.32	3.43	4.98
	Forest	1.20	1.55	2.38	3.47	4.92	6.50
	Total	2.12	2.99	4.58	6.72	9.51	12.90
				Damage Cost			
(RMB/ton)		2,384	3,022	3,912	4,884	5,736	6,595
(US$/ton)			364	471	588	691	795

Note: Assume exchange rate of 8.3 RMB/US$

3.48 In Table 3.5, TSP emission results and damage costs are presented for Changsha City and for Hunan Province. Because TSP can be transported over only short distances most TSP deposition and damage occurs in urban areas. Moreover, although the vast majority of emissions are released outside of the city, more damage is correspondingly borne by the city as a result of the density of the impacted population. In Changsha, road dust accounts for 65% of TSP concentration.

3.49 To calculate TSP-related damage, dose-response functions were used based upon recent research on the effects of TSP on human health in Chongqing. This was in turn based upon three kinds of effect: mortality, hospitalization, and hospital visits. An average of the damage costs was made using the Human capital approach and the WTP approach.

3.50 For Hunan, a variant of the New York State model was used. Based upon the annual emission level for TSP and the estimated population by local, regional and distant, the deposition of TSP was estimated. By using the Per capita GDP purchasing power parity, the damage cost from the US was converted to Hunan Province. Thus, the incremental cost is larger in Changsha City by a factor of two over that of Hunan Province.

Table 3.5: TSP Emission Damage Cost in Changsha City and Hunan Province

	1998	*2000*	*2010*	*2020*
Emissions, ton/year (000)				
Changsha City	20	20.7	24.5	30.9
Hunan Province	1,342	1,417	1,677	2,113
Total Damage Cost (M RMB)				
Changsha City	196	271	631	1,177
Hunan Province	6,810	9,420	21,930	40,900
Incremental Cost (RMB/ton)				
Changsha City	9,991	13,098	25,756	38,125
Hunan Province	5,073	6,651	13,078	19,358
Incremental Cost (US$/ton)				
Changsha City	1,204	1,578	3,103	4,593
Hunan Province	**611**	**801**	**1,576**	**2,332**

3.51 In Table 3.6, NOx emission results and damage costs are presented for Changsha City and for Hunan Province. For NOx, there are two major resources: coal combustion and vehicle exhaust. The method and assumptions to calculate NOx emission from coal combustion is the same employed as in the TSP calculation. For valuation of damage cost, an emissions-based valuation method and the New York methodology was used.

Table 3.6: NOx Emission Damage Cost in Changsha City and Hunan Province

	1998	*2000*	*2010*	*2020*
Emissions, ton/year (000)				
Changsha City				
Hunan Province	433	362	256	247
Total Damage Cost (M RMB)				
Changsha City				
Hunan Province	552	605	842	1,195
Incremental Cost (RMB/ton)				
Changsha City				
Hunan Province	1,275	1,671	3,286	4,865
Incremental Cost (US$/ton)				
Changsha City				
Hunan Province	**154**	**201**	**396**	**586**

Step 4. Least-cost Plans Under Environmental Constraints

3.52 Beginning with a business-as-usual case, a least-cost integrated power system expansion plan is undertaken, with consideration for the following:

- Pollutant emissions limitation (including annual reduction goal)
- Pollutant emissions externality cost[10]
- Combination of the two prior factors

3.53 Environmental constraints are incorporated in least-cost planning in a number of different forms:

- All options under consideration are selected so they satisfy China's most recent environmental regulations. For example, a coal-fired power plant burning coal with higher than 1% sulfur content is equipped with FGD.
- Total emissions from the Sector could be limited to a specific level each year. For example, annual SO_2 emissions (tons/year) from the power sector could be limited below a certain level after year 2000.
- Environmental externality values can be included.

3.54 Power and non-power sectors are handled separately mainly because planning tools for the power sector are well-established, while no such tools exist for non-power sectors. In the case of emission limitations, the objective is to select a combination of the available options which minimizes the costs while achieving the emission targets. For the power sector, a least-cost plant was developed using WASP in the case of Shanghai and GESP II in the case of Henan. In the latter case, in addition to the typical power system constraints and requirements (e.g., compliance with plant-level environmental requirements), system-wide emission goals were set and satisfied. For example, alternative plans were developed with limitations of the total particulates and SO_2 emissions released by the power sector after year 2000.

3.55 In Hunan, the GESP II model was also used to develop the least-cost business-as-usual (BAU) case, taking into account the primary energy situation, load forecast, existing system, and expansion candidates. In addition, GESP II is used to simulate and analyze alternative technology options and the corresponding pollutant emission. Using this approach, a system-level analysis was completed to determine what control technologies to employ to achieve the most cost-effective solution for the power system development plan.

3.56 The environmental protection goal is the reduction of air pollution from the three main power generation air pollutants: SO_2, NO_x and TSP. First, each single pollutant

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[10] The externality cost of pollutants was completed by the Environment Science Research Institute of Tsinghua University for pollutants (SO_2, NO_x and TSP).

reduction target is considered independently. Based on the information from these independent results, an optimization analysis on combined-pollutant reductions is then performed. In the last analysis, the optimal system-level solution of power generating with combined-pollutant reduction (SO_2, NO_x and TSP) strategy is presented.

3.57 For the non-power sectors, a spreadsheet is used to estimate the costs and emissions of alternative strategies. From this spreadsheet, a low-cost strategy can be identified which meets emission limitations.

3.58 Environmental externalities are incorporated in both power and non-power sector planning by adding a cost component equal to the externality ($/ton or RMB/ton) multiplied by the emission release rate (tons/year).

Least-Cost Plans for the Power Sector

3.59 Least-cost development plans for the power sector utilize models such as WASP and GESP, which usually require the following types of inputs:

- An electricity demand forecast (see Step 1);
- An existing power system including actual performance parameters, fuels burned and planned retirements;
- New power plants for which key procurement decisions have been made or construction has started (these along with the existing plants constitute the "fixed system");
- The availability and costs of fuels;
- Key technologies which should be considered for future expansion; and
- Environmental constraints

3.60 Most of the above elements are typical in all least-cost planning activities. The unique element in this study is the incorporation of sector-level environmental constraints and environmental externalities, in addition to the requirements that each thermal power plant complies with the applicable environmental regulations.

3.61 The tool used in least-cost planning was the Wien Automatic System Planning Package (WASP), part of ENPEP and the Generator of Electric System Planning (GESP). WASP is a generation expansion planning model developed and distributed by the International Atomic Energy Agency (IAEA), which is widely used in developing countries. It uses probabilistic simulation to estimate generating system production costs and dynamic programming to determine the optimal expansion pathway. WASP was used in the Shanghai case study, mainly because it was available with the power system data already in place from the Waigaoqiao power project. GESP was selected for Henan and Hunan case studies, because it allows the user to specify emission constraints (total pollutant per year), a capability which was added by BERI with World Bank funding under this project.

3.62 GESP is a multi-region planning model using mixed integer programming to determine the optimal generation mix for system expansion within the planning period. The GESP model was modified to enable it to handle emission limits (in which the total emissions of pollutants of the power system are fixed) and environmental externalities (in which the damage of emissions is imposed on the power system just like other traditional cost items, such variable operating and maintenance costs). Other GESP modifications included: modules for calculating emissions, increased the number of environmental control options and data associated with them, and a more detailed description of fuel quality. The new version, called GESP2, is used in the Henan and Hunan case studies.

Optimum Development Plans for Non-Power Sectors

3.63 Optimization for the non-power sectors as a whole is impractical because of the wide differences of energy activities and technologies among these sectors. Moreover, there is a lack of models for optimum expansion planning. For this reason, the project team used a spreadsheet model to analyze scenarios, which were developed based on the cost-effectiveness ranking of the mitigation options (Step 2). The alternative scenarios adapt first the lower cost options until the emission reduction target is achieved. The user selects the scenario which best satisfies the emission requirements (i.e., the total emission from non-power sectors) at the lowest or relatively low cost.

3.64 The spreadsheet is structured to allow input of environmental externalities, which are added to the operating costs of each option. The evaluation of alternative scenarios with externalities is similar to the analysis without externalities.

4

Key Findings

4.1 The key findings of the report are presented first with regard to the cost-effectiveness for the control of various pollutants (particulates, SO_2, NO_x and CO_2) and their integration into a least-cost plan. The impact of environmental externalities on both the cost-effectiveness of environmental control options and the least-cost plan is then considered. The results of the exercise are illustrative and serve as a basis for further work in the sector and to improve future methodologies.

Particulate Control

4.2 Particulates are a major health concern, especially in urban areas. Industrial and residential (household) sectors in Henan are the main contributors of particulates, with approximately 80% of the total. The power sector contributes only 16% of the total. 73% (11.7% of the total particulates) comes from small power plants (less than 125 MW). The larger size plants emit only 4.4% of the total particulates.

4.3 The situation in Shanghai is similar. A total of 78% of particulate emission is from the industrial and residential sectors. The power sector contributes 22%. 90% of the power sector's contribution comes from small power plants.

4.4 In Hunan, the situation is somewhat similar to both Henan and Shanghai. The non-power sector contributes 87% of total particulate emission; the remaining 13% constitutes the power sector's contribution. Within the non-power sector, the industrial sector is by far the largest contributor with a total 83% of emissions.

4.5 In Henan, a major contributor to the continuing decline of particulates after year 2001 is the retirement of small power plants, which are not equipped with ESPs. They are being replaced with large power plants that are more efficient and utilize modern ESPs. If further reduction of particulates is desirable, the residential and industrial sectors provide the most cost-effective options with the greatest potential impact on improved health quality. As Figure 4.1 shows, over the planning period of 1997-2020, the following options should be pursued:

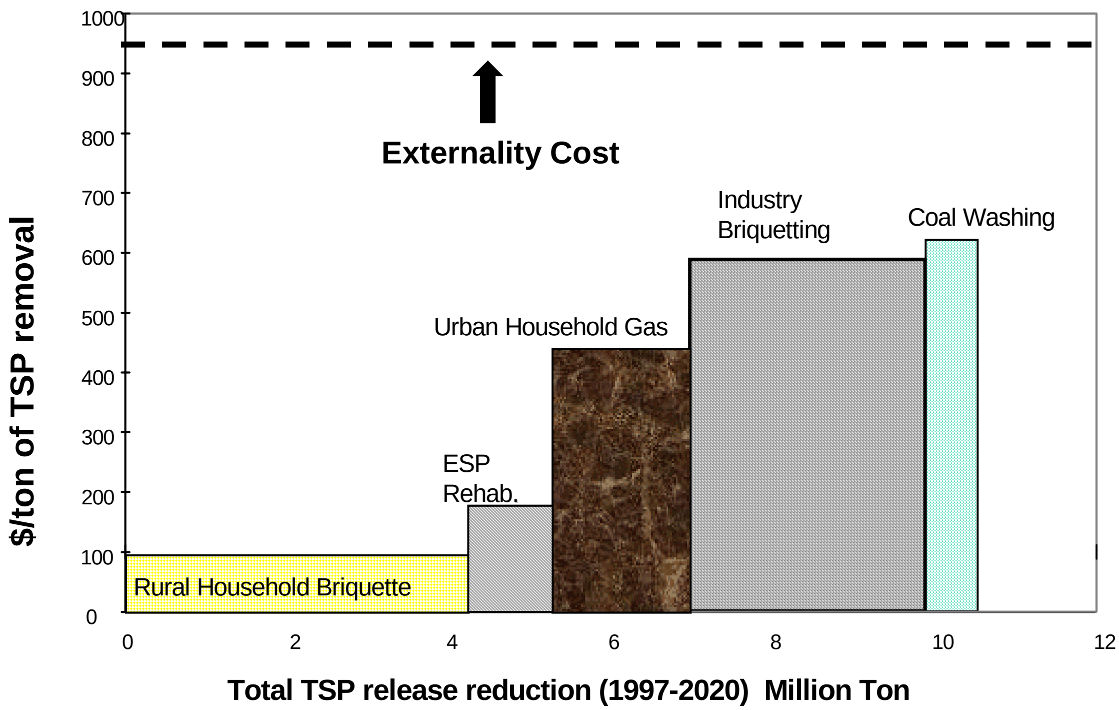
a. Switching from raw coal to briquettes in the households has the potential to reduce particulates by a total of 6 million tons at a cost of only 100 $/ton.

b. The rehabilitation/upgrading of ESPs in small and medium size power plants has a cost of approximately 180 $/ton.

c. Switching urban households from raw coal to gas has a cost-effectiveness of approximately 430 $/ton.

d. Switching industrial facilities from raw coal to briquettes or to washed coal (10-15% ash instead of the commonly used coal with 30-35% ash) has a cost of approximately 600 $/ton.

Figure 4.1: Cost Effectiveness of TSP Control Options (Henan)



4.6 All the above options have a cost below the projected environmental externality cost in Henan (approximately $940/ton), which suggests that there is an economic justification for implementing all of them because the cost of particulate is high.

4.7 Although the analysis of non-power sector options in Shanghai were not assessed at the same level of detail as in Henan, similar trends are expected in terms of cost-effectiveness. In the power sector, the reduction of particulates will require the installation of new electrostatic precipitators (ESP) or the upgrading of ESPs in existing power plants. As it is shown in Figure 4.2, for the period 1997-2020:

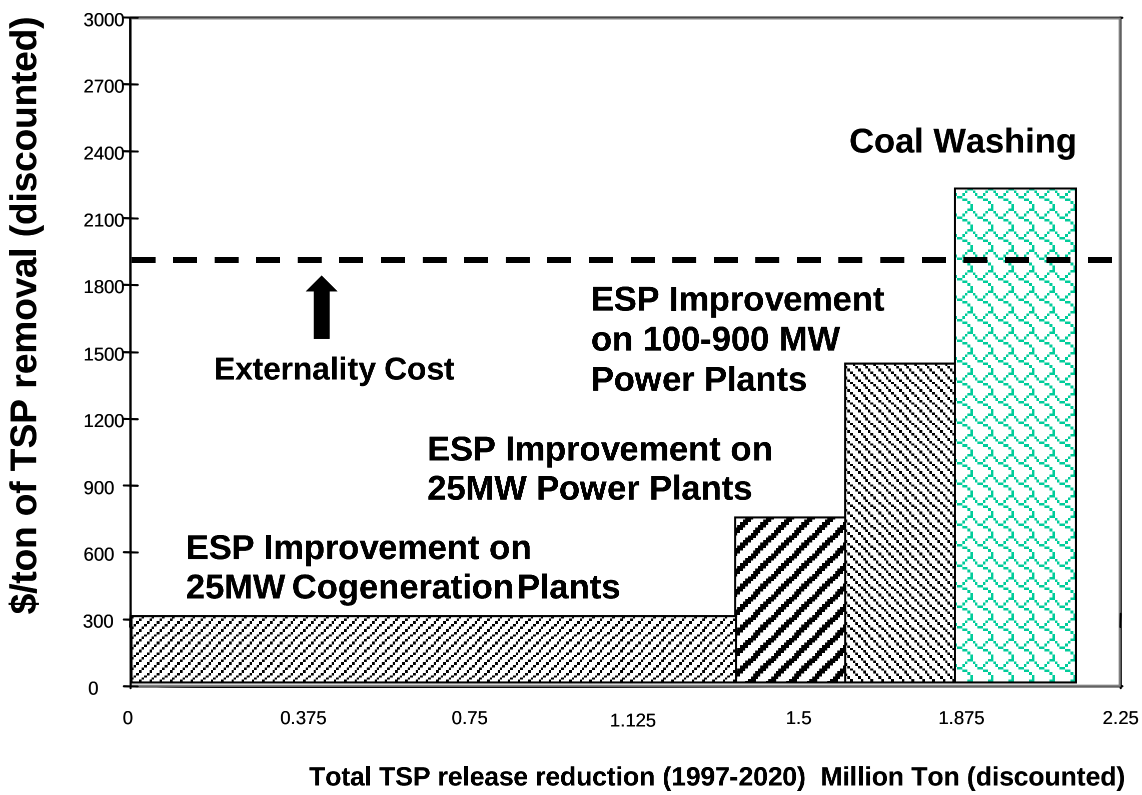
- Approximately 1.4 million tons of particulates can be removed at a cost of $300/ton, by improving the efficiency of ESPs of existing cogeneration plants from 92% to 99.9%.
- An additional 250,000 tons of TSP can be removed during the same period (1997-2020) at $750/ton through similar ESP efficiency improvements of five

25 MW power plants with ESP collection efficiency projected to increase from 96.25% to 99.9%.

- The cost of retrofitting ESPs on existing power plants of 100 - 125 MW averages $1,500/ton, while coal washing reduces particulates $2,200/ton. These two options have the potential to reduce particulates by approximately 400,000 tons each during the planning period.

4.8 Considering that the environmental externality cost of TSPs in Shanghai is projected to be approximately $1,900/ton, most of the above options should be pursued.

Figure 4.2: Cost Effectiveness of TSP Control Options (Shanghai)



4.9 In Hunan, from 2000-2020, particulate emissions are expected to fall about 17% to about 1.2 million tons from 1.4 million tons. The greatest potential percent gain is achieved within the power sector with a 71% reduction to 53,000 tons from a high of 183,000 tons in 2000. Within the non-power sector, there is projected to be only a 9% reduction in total emissions during the same period.

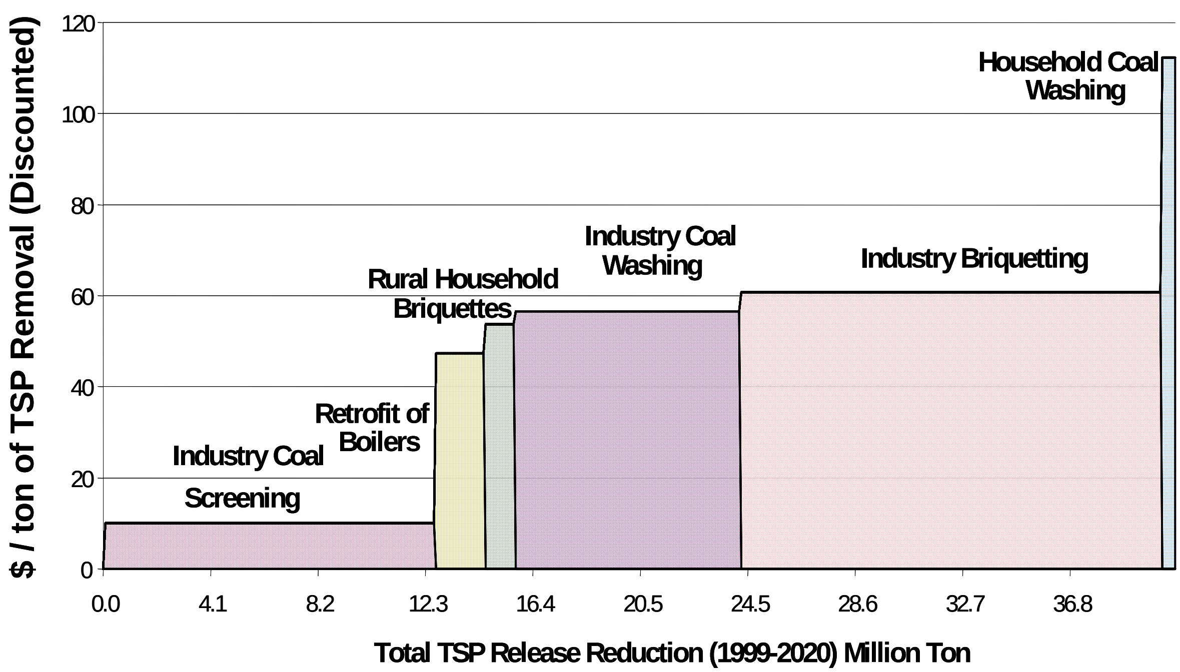
4.10 In Hunan, the cost effectiveness of abatement technologies for TSP was evaluated in depth for both the power sector and the non power sector (Figure 4.3). Within the power sector, the most significant reductions can be achieved with interventions in the industrial sector. For the period of 1999-2020, the greatest gains can be achieved as follows:

- 12.7 million tons of TSP can be removed at a cost of approximately $10/ton, through the use of coal screening by industry;
- An additional 10 million tons of TSP can be removed at a cost of about $55/ton through industry coal washing; and
- An additional 16.1 million tons of TSP can be removed at a cost of about $500/ton through industry briquetting.

4.11 In addition, boiler retrofit will remove 1.9 million tons of TSP at a cost of about $50/ton; household briquettes will remove 1.1 million tons of TSP at a cost of about $55/ton; and household coal washing will remove 0.6 million tons of TSP at a cost of about $110/ton.

4.12 Other abatement options, such as town gas and LPG were not presented because their abatement costs are too costly, $850/ton and $140/ton, respectively. Further, a system-level analysis was not undertaken because TSP is no longer viewed as much as a significant problem as the principal polluters in the power sector, which are small thermal units that will be retired in 2003-2004 as mandated by government.

Figure 4.3: Cost Effectiveness of TSP Control Options (Hunan)



SO_2 control

4.13 The power sector is the major contributor of SO_2 emissions in both Shanghai and Henan; in Hunan, the non-power sector is the largest contributor. In Shanghai, power contributes approximately 72% of SO_2, in Henan only 43%, and in Hunan only about 10%. Already, in Shanghai, some industrial and residential users have switched from coal to gas or LPG, considerably reducing emissions in the non-power sector. The same users in Henan and Hunan continue to rely on coal. As these users in Henan switch to LPG, oil and gas in the future, the contribution of power sector in terms of SO_2 emissions will increase to 53% of the total by year 2020. In Hunan, the majority of power is generated from hydro sources or coal plants burning low sulfur coal, while the non-power sector uses almost no gas.

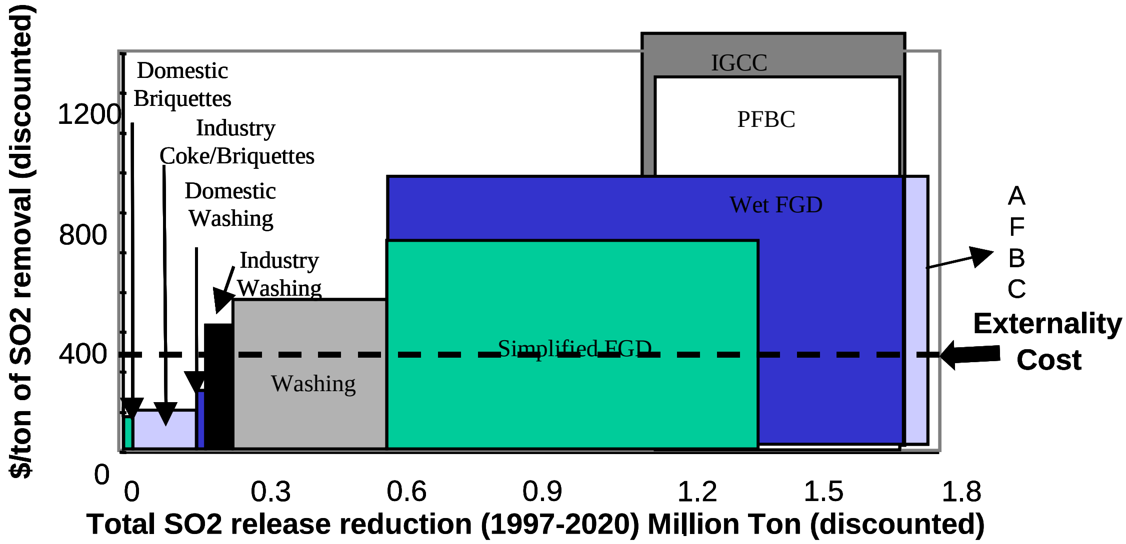
4.14 To assess the effectiveness of controlling SO_2 emissions from the power sector, a number of alternatives were introduced in Shanghai, and subsequently used in Henan and Hunan, including:

- Wet FGD in all large existing and new power plants (FGD-All)
- Simplified FGD in all large existing and new power plants (simplified FGD)
- Coal washing
- Atmospheric fluidized bed combustion (AFBC)
- Pressurized fluidized-fed combustion (PFBC)
- Integrated gasification combined cycle (IGCC)
- Liquefied natural gas (LNG)

4.15 For Shanghai, the cost effectiveness of these options, as well as some industry and residential sector options, are shown in Figure 4.4. The conclusions drawn from this figure are:

- The most cost effective options for SO_2 control are in non-power sectors such as the industrial and residential. One option is the use of briquettes instead of raw coal at a cost of less than \$100/ton for both industrial and residential applications.
- The total amount of SO_2 reduction from non-power sectors is limited to a total of 275,000 tons over the period 1997-2020. Significant SO_2 reduction can only be achieved through SO_2 control measures in the power sector.

Figure 4.4: Cost Effectiveness of SO_2 Control Options (Shanghai)



4.16 Based on the cost-effectiveness, the following options should be pursued in order of priority (cost-effectiveness in parenthesis):

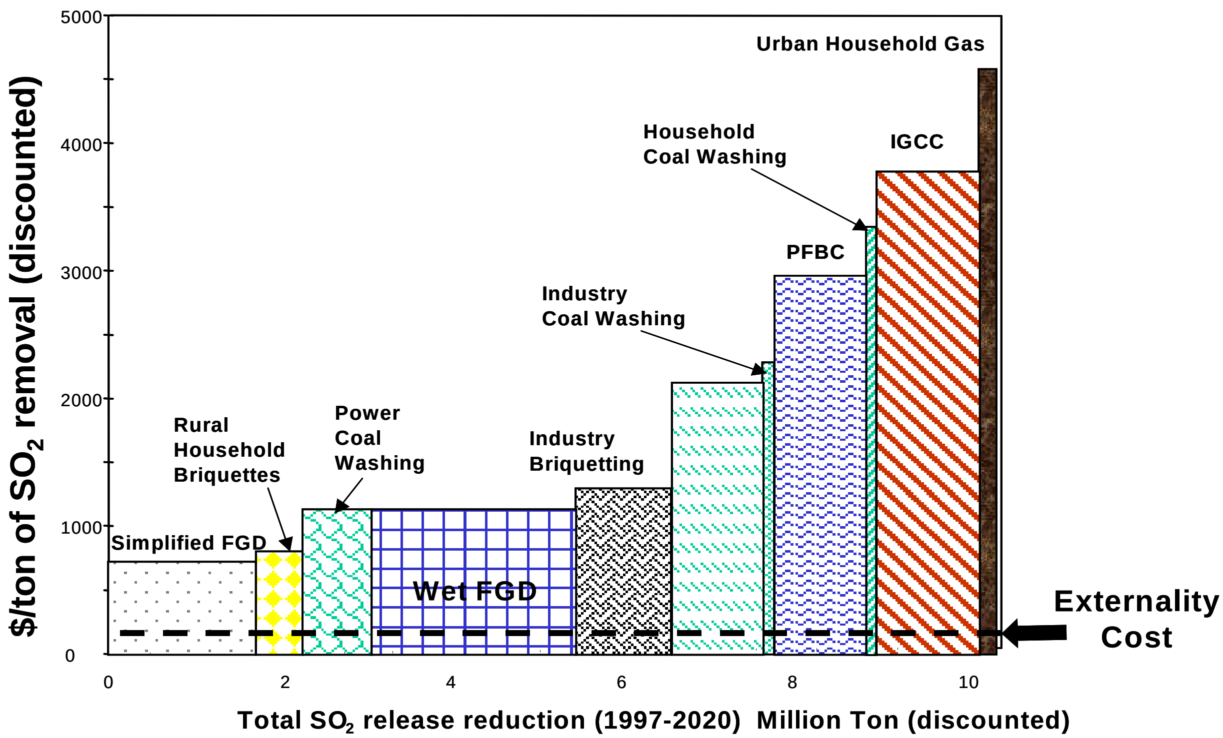
- Coal briquettes in the industrial and domestic sectors (\$150/ton of SO_2)
- The use of washed coal in industry and existing power plants (\$400 - 500/ton of SO_2)
- Simplified FGD in existing power plants which burn medium-to-high-sulfur coal, such as 2% sulfur and 30% ash (\$700/ton of SO_2)
- Wet FGD and AFBC, which have similar cost-effectiveness (approximately \$900/ton), but FGD could remove more SO_2
- Advanced technologies, such as IGCC and PFBC, which have higher cost of SO_2 removal, but they reduce other emissions (TSP, NO_x and CO_2) for which they need to be credited

4.17 A similar level of analysis was undertaken in Henan, using the same control options as presented in Shanghai. As Figure 4.5 shows, the most cost effective options to control SO_2 emissions in Henan are:

- Simplified FGD to all units which burn medium-to-high sulfur coal can remove 1.7 million tons of SO_2 for the period of 1997 - 2000 at a cost of \$800/ton of SO_2 removed
- The use of briquettes in rural households can remove 500,000 tons of SO_2 at a cost of \$800/ton
- Wet FGD to all units which burn medium-to-high sulfur coal can remove over 2.2 million tons at a cost of \$1,150/ton

4.18 In general, non-power sector options are not as cost-effective in Henan as they are in Shanghai, because there is a large cost increase switching from raw coal to the alternatives, briquettes, washed coal or gas.

Figure 4.5: Cost Effectiveness of SO_2 Control Options (Henan)



4.19 Coal washing in Henan is not as cost effective as it is in Shanghai. The use of washed coal in power plants can remove 800,000 tons of SO_2 at a cost of $1,300/ton. Washed coal in industry and household sectors can remove only 100,000 tons and 30,000 tons, respectively, at relatively higher costs ($2,300/ton and $3,300/ton, respectively).

4.20 It was assumed that advanced Clean Coal Technology such as AFBC, PFBC and IGCC can be applied only to the new units. Each of the three options can remove approximately 1 million tons of SO_2 throughout the 1997 - 2020 period at costs of $2,300/ton, $3,200/ton and $4,000/ton, respectively.

4.21 Natural gas use in urban households appears to be a high cost option, but its costs need to be evaluated against the benefits, which are also high (indoor air quality is the number one cause of premature death and respiratory problems). In the case of Henan, natural gas is limited, and the widespread use of gas by households would depend on gas that was derived from coal. In the latter case, the beneficial impacts on the households should be compared to the potential adverse effect the gas production facilities could have on the local environment.

4.22 In Hunan, the non-power sector is the major contributor of SO_2 emissions with about 90% of total emissions, as compared to the only 10% that is being contributed by the non-power sector. The breakdown is quite different than in Henan and Shanghai mostly because of two reasons. First, the power sector in Hunan is dominated by hydropower and the use of low sulfur coal. Secondly, with the development of the Hunan economy, the use of industrial boilers grew rapidly, meeting industrial energy demand in the textile, petroleum and chemical, and building material sectors.

4.23 Even though the majority of the coal consumed by the industrial sector (about 87%) was anthracite and bituminous coal with a sulfur content of about 1%, the remaining coal consumed had a very high sulfur content of >3%, emitting as much as four times the level of pollutants. As in the case of Henan, with the future transition to LPG, oil and gas, the contribution of the power sector in terms of SO_2 emissions will increase to 53% of the total by the year 2020.

4.24 As Figures 4.6 show, for the period of 1999-2020, the most cost effective options to control SO_2 emissions in Hunan are non-power investments in the industrial and household sectors. For non-power, these include:

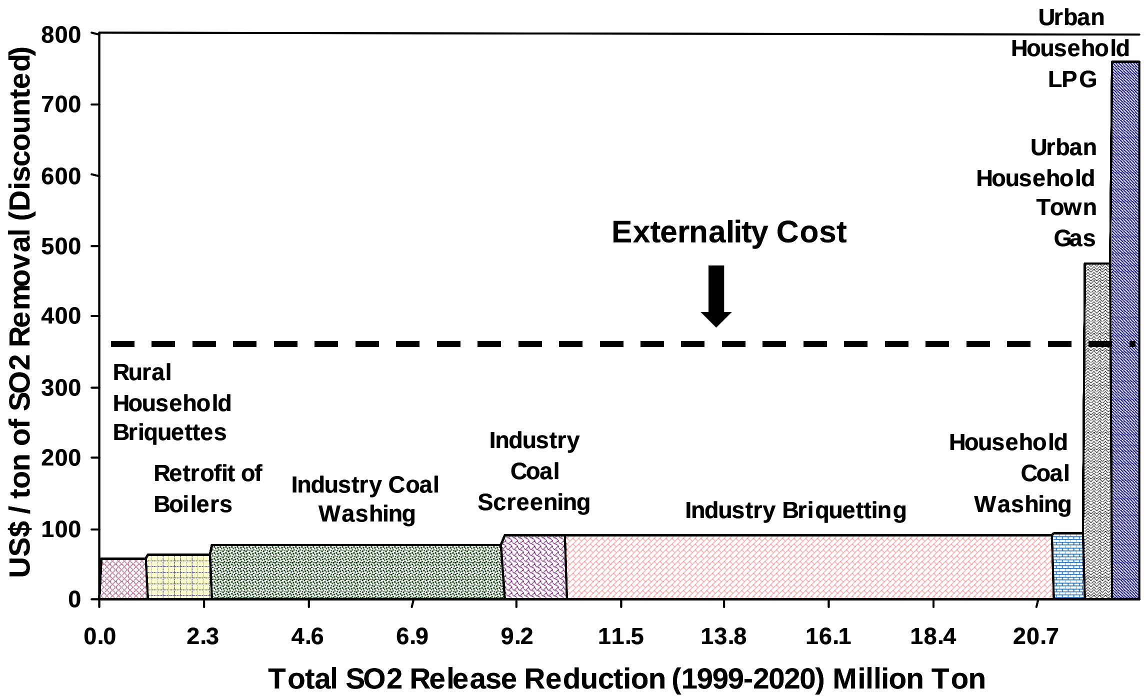
- Rural household briquettes which can remove 1 million tons of SO_2 at a cost of only $58/ton
- Industrial briquettes, the most effective in terms of abatement, which can remove 10.8 million tons of SO_2 at a cost of about $90/ton
- Industrial coal washing which can remove 6.5 million tons of SO_2 at a cost of $75/ton
- LPG, the most expensive option at a cost of $760/ton, which can remove 0.65 million tons of SO_2

4.25 For the power sector, the abatement options for SO_2 removal cost considerably more, at a cost of between $660 to $5,200/ton. They include:

- Conventional wet scrubbing (LSFO) in all new power plants would remove 1.8 million tons of SO_2 at a cost of $660/ton, the most economic abatement option in the power sector.
- Conventional wet scrubbing (LSFO) in all existing power plants would remove 3.1 million tons of SO_2 at a cost of $762/ton, the largest single reduction for the power sector.
- Simplified wet scrubbing (SWS) in all available power plants would reduce SO_2 emissions by 2.6 million tons at a cost of $772/ton.
- Furnace sorbent injection (FSI) in existing plants is the most expensive option at a cost of $2,600 per ton.

4.26 In general, non-power sector options are not as cost-effective in Henan and Hunan as they are in Shanghai because there is a large cost associated with switching from raw coal to the alternative fuels.

Figure 4.6: Cost Effectiveness of SO_2 Control Options for Non-power (Hunan)



NO_x control

4.27 Even though NO_x emissions are not perceived to be a problem, NO_x concentrations are increasing rapidly above internationally acceptable levels, especially in urban areas. The rapid growth in the transportation sector in combination with increasing NO_x emissions from other sources suggest a serious urban pollution problem could arise in the near future.

4.28 The power and industrial sectors continue to be major contributors of NO_x In 1997, the power sector in Henan contributed 42% of the total NO_x emissions, while industry contributed 37% as compared to Hunan in 2000, where the power sector contributed only about 18% and industry contributed 54%. The contribution of these sectors is expected to increase because NO_x control standards are not as strict as those for SO_2.

4.29 In this study, a number of NO_x control options were evaluated for Henan, including:

- Boiler tuning and optimization, which involves tuning the combustion system (i.e., the burner) settings and utilizing the power plant optimization software to reduce NO_x emissions
- Low NO_x burner retrofits of existing boilers

- Selective catalytic reduction (SCR) on both existing and new boilers

4.30 In addition, other options, which are not primarily for NO_x control but reduce NO_x, were considered. Such options include AFBC, PFBC, IGCC, LNG and the retirement of small boilers. Furthermore, installation of three-way catalysts in automobiles was considered.

4.31 In Henan, abatement options include:

- Combustion tuning/optimization can be applied to all new and existing plants, which can remove 500,000 tons of NO_x for the period of 1997 - 2000 at a cost of $20/ton.
- Low NO_x burner (LNB) is already incorporated in the design of the new boiler in business-as-usual cases, but if LNB is retrofitted to existing plants, it can remove an additional 300,000 tons of NO_x at a cost of $100/ton.
- If further NO_x reduction is required, SCR installation to new power plants can remove an additional 400,000 ton of NO_x at a cost of $1,200/ton.

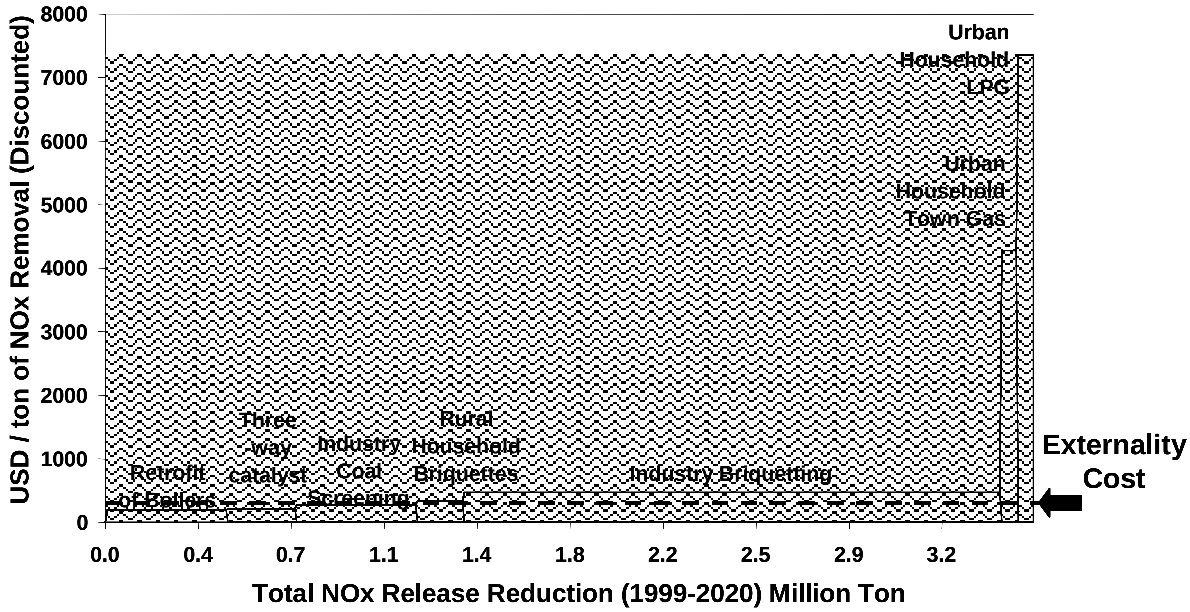
4.32 These results suggest that combustion tuning/optimization and low NO_x burner retrofits are cost-effective (considering the projected environmental externality of approximately $250/ton of NO_x). The cost of SCR and automobile catalysts exceeds, by far, the projected externality cost for NO_x emissions.

4.33 The three-way catalysts to be used in new cars after the year 2000 reduces 70,000 tons of NO_x at a cost of $7,600/ton. While this is high, it should be noted that the catalyst reduces not only NO_x, but also hydrocarbons and CO emissions.

4.34 A similar assessment of the effectiveness of NO_x control options was not carried out for Shanghai, but the results would most likely be similar. Potentially, one option which may be cost-effective for Shanghai is the addition of overfire air in addition to low NO_x burners in existing boilers.

4.35 In Hunan, many NO_x control options were reviewed for both the power and non-power sectors and are presented in Figures 4.7 and 4.8. In general, non-power options are the most effective NO_x control options as compared to power sector options.

Figure 4.7: Cost Effectiveness of NO_x Control Options for Non-Power Sector (Hunan)

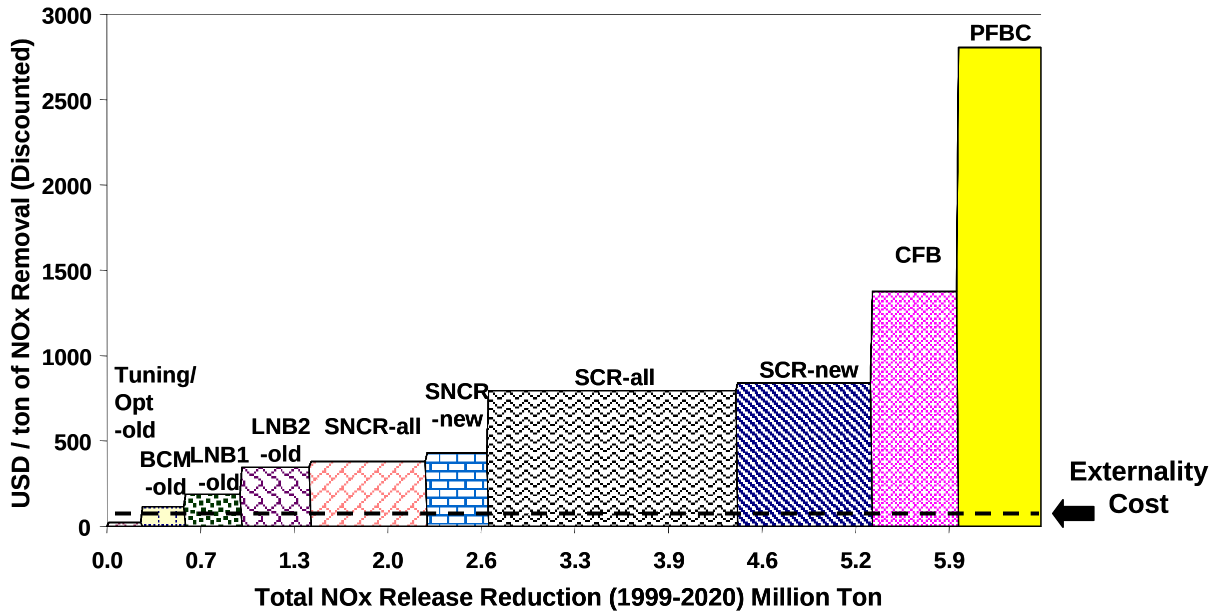


4.36 Most non-power sector NO_x control options are very cost effective at removing harmful emissions. For the 1999-2000 planning period, they include the following:

- Boiler retrofit, the most cost-effective control option, can remove almost 0.5 million tons at a cost of $190/ton.
- Industry coal screening can remove 0.5 million tons at a cost of $270/ton.
- Industry briquetting, the most effective option in terms of total abatement, can remove 2.1 million tons at a cost of $470/ton.

4.37 However, several control options are not that effective at removing NO_x including urban household town gas and urban household LPG, with costs above $4,200 and $7,300/ton.

Figure: 4.8: Cost Effectiveness of NO_x Control Options for Power Sector (Hunan)



4.38 For the power sector in Hunan, there are numerous control options that are available to reduce NO_x emissions with a relatively wide range of cost effectiveness. These include tuning, BCM, LNB1, LNB2, SNCR-all, SNCR-new, SCR-new, CFB and PFBC, in ascending order of cost effectiveness. NO_x control options include:

- Tuning, which can abate 0.25 million tons with a cost effectiveness of $22/ton, is the only option that is cost effective when compared to the estimated externality cost of NO_x emissions.
- SNCR can abate 1.25 million tons with a cost effectiveness of $400/ton.
- SCR can abate 2.7 million tons with a cost effectiveness of $800/ton.
- PFBC is not cost effective at a cost of $2,800/ton.

Least-Cost Optimization Analysis

4.39 Even though cost-effectiveness is a useful screening device for each environmental control option, eventually a least-cost abatement plan must be developed which satisfies system-level requirements including environmental goals and standards. Least-cost emission abatement plans for the power sector may be derived from least-cost expansion modeling, given environmental compliance requirements and constraints. For non-power sectors, alternative scenarios are developed based on the cost-effectiveness of the various options. Such an approach was completed for both the Henan and Hunan case studies.

Henan

4.40 For the Henan power sector, a least-cost plan was developed using the GESP II model, expanded to include the stabilization of emissions to a certain level or the reduction by a certain percentage.

4.41 A number of alternative scenarios were developed for Henan based on the most urgent environmental issues and the most likely constraints:

- Reduction of particulates by 20% from the 1997 level by year 2020;
- Stabilization of SO_2 to 1997 levels by year 2001;
- Stabilization of NO_x to 1997 levels by year 2001; and
- Stabilization of particulates, SO_2 and NO_x, to 1997 levels by year 2001.

4.42 For SO_2 emission control, a cap at the 1997 emission level will have a major impact on the power system investment planning. In Henan's case, the emission cap implies a 60% reduction of the baseline emissions in year 2020, which will increase the cost of electricity from an average of 0.262 RMB/kWh to 0.289 RMB/kWh, a 10% increase.

4.43 As shown in Figure 4.9, the optimum mix of power-sector SO_2 control options (in order of declining cost-effectiveness) for maintaining SO_2 at 1997 levels are:

- Simplified FGDs installed in existing plants using low and medium quality coal;
- Wet FGD installed in the remaining existing plants; and
- Either simplified or wet FGD installed in new plants.

As Figure 4.10 illustrates, limiting NO_x to 1997 levels will increase the cost of electricity from an average of 0.262 RMB/kWh to 0.265 RMB/kWh, a 1% increase. The cost of such a reduction is low compared to the case of SO_2 emission abatement. About two thirds of the reduction can be achieved by the application of low cost measures such as combustion tuning/optimization and low-NO_x burners, while the rest may be achieved by the moderately expensive measure of selective catalytic reduction (SCR). Again, the level of reduction is better decided with a consideration for the benefits that the reduction may bring, rather than with arbitrary numbers.

Figure 4.9: SO_2 Emission Abatement of Henan Power System
(Future Emissions Limited to 1997 Level)

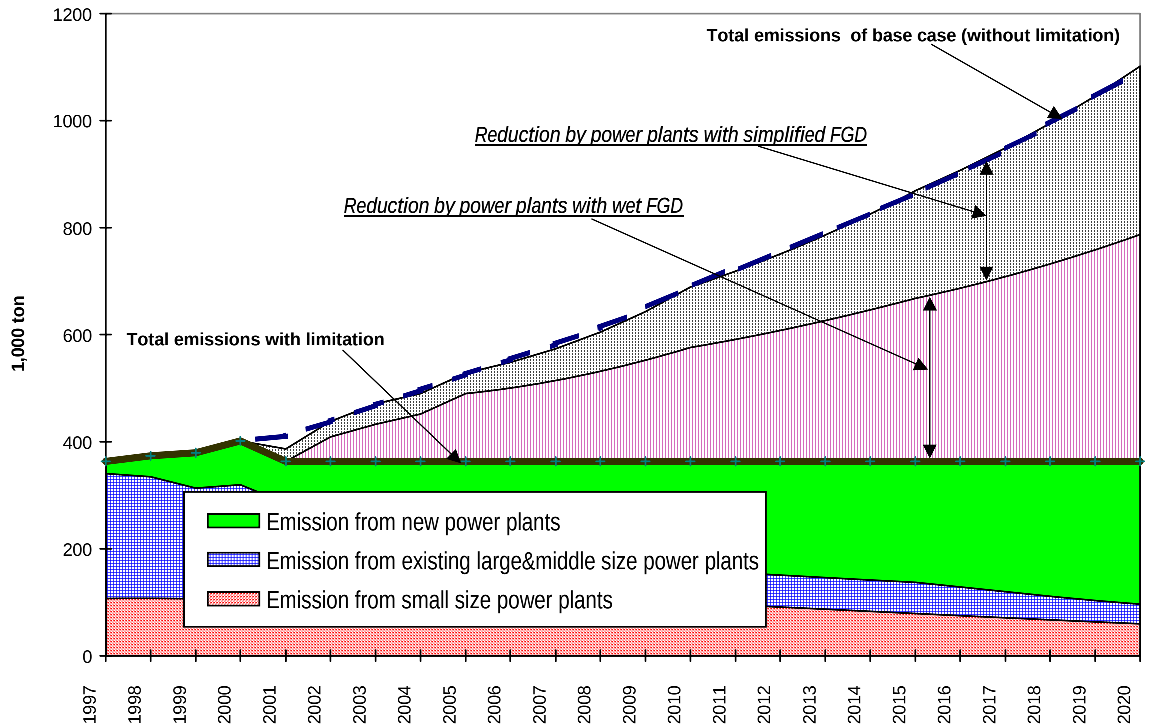
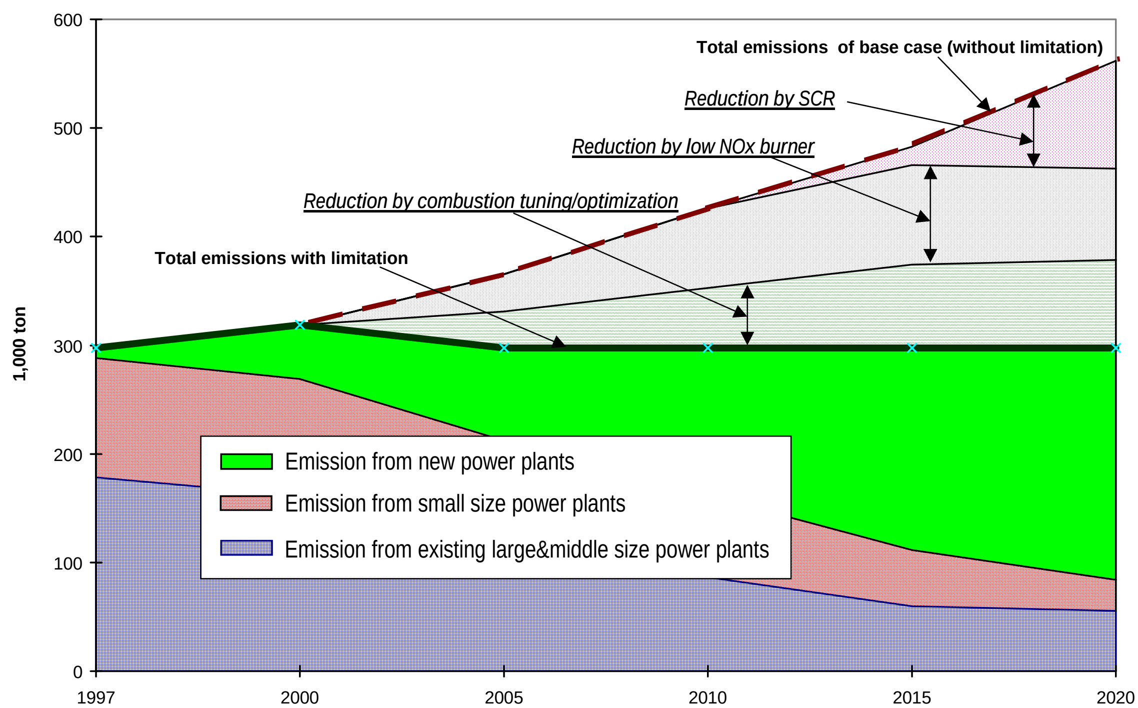


Figure 4.10: NO_x Emission of Power Sector in Henan
(with NO_x limitation)



4.44 Table 4.1 summarizes the investment of fuel and O&M costs, as well as the impact of each emission limitation on the cost of electricity. It is important to note that the control of particulates and NO_x does not have any significant impact on the cost of electricity, which increased from 0.262 Yuan/kWh to 0.264 and 0.265 Yuan/kWh, respectively. However, the cost of electricity increased by 10% in the SO_2 control scenario and 12% (from 0.262 Yuan/kWh (3.16 cent/kWh) to 0.294 Yuan/kWh (3.54 cent/kWh)) in the case concerned with the limitation of all pollutants.

4.45 The above analysis pertains only to the power sector. The selection of environmental control options in non-power sectors is still based on the cost-effectiveness analysis described earlier. Based on the cost-effectiveness estimated for the various environmental options, the following combination of controls seems to be the optimum for maintaining SO_2 and TSP to 1997 levels after the year 2000 (see Table 4.2):

- Industry replaces 15%, 65% and 90% of the raw coal with briquettes by 2000, 2010 and 2020, respectively.
- Urban households replace 25%, 65% and 80% of the raw coal with coal gas by 2000, 2010 and 2020 respectively.
- Rural households replace 20%, 40% and 65% of the raw coal with briquettes by 2000, 2010 and 2020 respectively.

The incremental cost for implementing these options is 57,885 million Yuan (11,400 million Yuan at present values).

Table 4.1: Present Value of System Cost of Each Case in Henan Power Sector

Million Yuan	*Total cost*	*Investment cost*	*Fuel cost*	*O & M Cost*	*Environmental control cost*	*Cost of electricity Yuan/kWh*
Base Case	159,360	63,769	67,413	28,178	0	0.262
TSP limitation	159,648	63,804	67,404	28,216	731	0.264
SO_2 limitation	165,746	64,404	67,710	29,332	4,300	0.289
NO_x limitation	160,154	63,795	67,403	28,233	217	0.265
Limitation of all pollutants	166,582	64,428	67,683	29,211	5,261	0.294

Table 4.2: Proposed Strategy

	2000	*2010*	*2020*
Briquettes for Industry	15%	60%	80%
Briquettes for H/S	15%	55%	75%
Gas for H/S	5%	15%	20%

Total cost: 57,885 million yuan

PV of Cost: 11,400 million yuan

Hunan

4.46 In Hunan, four kinds of reduction technologies that are currently used, LSFO, SWS, SSD and FSI, were considered as basic SO_2 reduction options. Four new technologies, SP, AFBC, BFBC and IGCC, were also considered as basic SO_2 reduction options for the Hunan electric power system. The first 3 currently used options, LSFO, SWS and SSD, are all post-combustion technologies, for only one technology can be adopted at a time. Because the FI is not a post-combustion technology, it could be adopted into a unit together with one kind of FGD (LSFO, SWS or SSD) to form a combined SO_2 reduction technology. So we have an additional three combined SO_2 reduction options: LSFO + FSI, SWS + FSI, and SSD +FSI.

4.47 Figure 4.11 and Table 4.3 presents emission abatement for the SO_2 limitation case as compared to the Base Case (BAU). The detailed information of pollutants emission and reduction can be found in the attached table.

4.48 From the years 2003-2005, due to the retirement of a large number of small-size power plants, the SO_2 emission decreases significantly. There are no new technologies competitive for the SO_2 reduction for the Hunan electric power system, and as such, other emission reductions should be considered as well.

Figure 4.11 SO_2 Emission Abatement for Hunan Power Sector

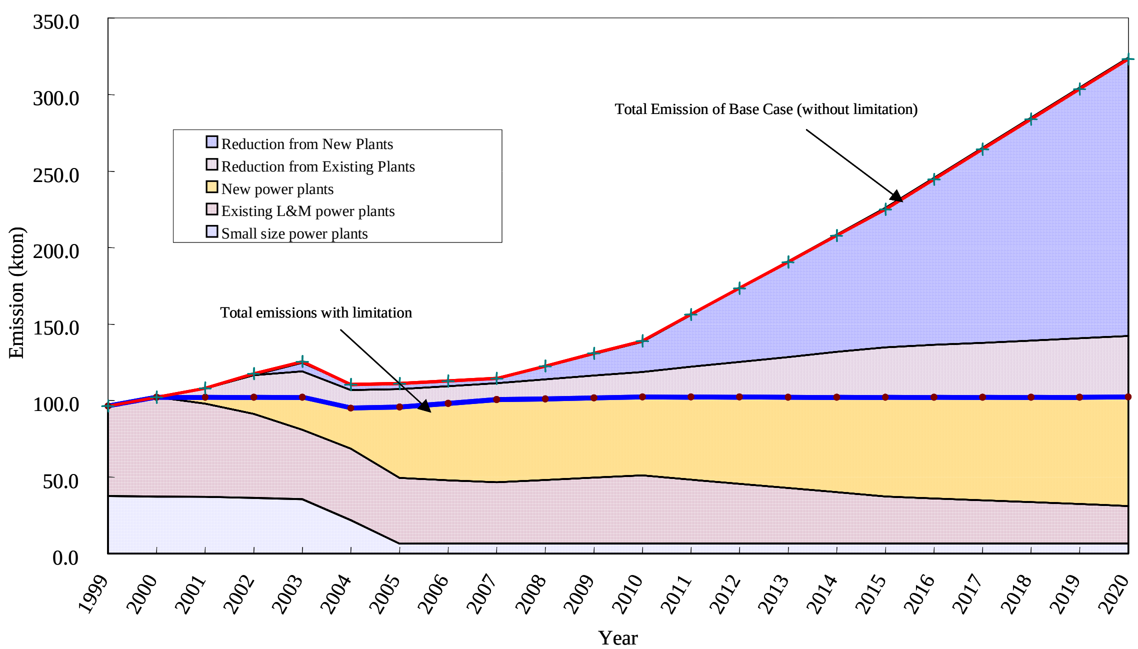


Table 4.3 Emission Reduction: Optimal Integrated Planning of Generating Capacity Expansion (SO_2-2000 Case), (000 tons)

	1996	*2000*	*2005*	*2010*	*2015*	*2020*
SO_2	96.5	102.3	95.8	102.3	102.3	102.3
TSP	180.1	183.3	49.2	51.2	51.7	52.9
NO_x	79.9	84.2	85.8	116.0	151.9	192.3
CO_2	17425	18414	19795	25903	41178	58751
SO_2 reduction vs. BAU Case	0.0	0.0	15.3	36.7	122.6	220.8

4.49 The least-cost plan to achieve NO_X stabilization includes a mix of NO_X reduction options: Tuning/Optimization (T/O), Burner Component Modification (BCM), Low-NO_X Burner type-I (LNB-I), Low-NO_X Burner type-II (LNB-II), Selective Catalytic Reduction (SCR) and Selective Non-catalytic Reduction (SNCR). As Figure 4.12 illustrates, the model selects first the low cost options (T/O, BCM and LNB) and then the most expensive options (SNCR and SCR) when additional NO_X reduction is needed in later years.

4.50 As with the SO_2 situation, from the years 2003-2005, due to the retirement of a large number of small-size power plants, NO_X emission decreases significantly as well. Figure 4.12 and Table 4.4 present the composition of NO_X emissions for the NO_X limitation case. Some of this data also represents the composition of NO_X emission reduction as it compares with the BAU case. The detailed information of pollutants emission and reduction can be found in the attached table.

Figure 4.12: NO_x Emission of Power Sector in Hunan
(with NO_x limitation)

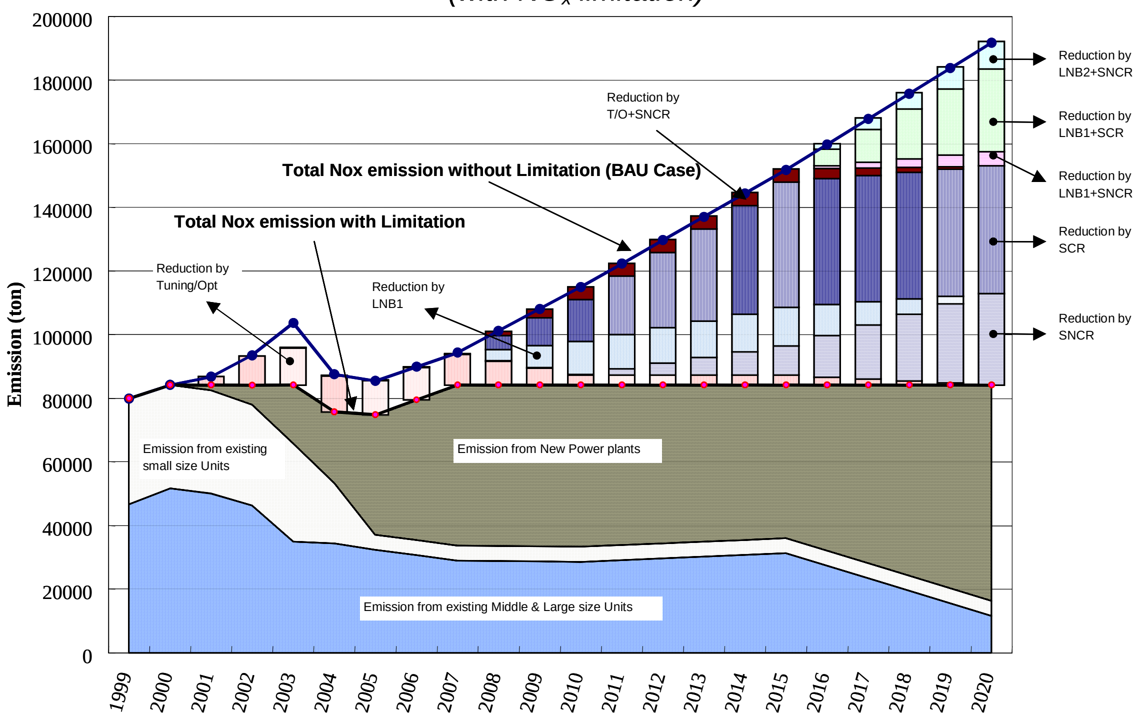


Table 4.4 Emission Reduction: Optimal Integrated Planning of Generating Capacity Expansion (NO_x-2000 Case), (000 tons)

	1999	*2000*	*2005*	*2010*	*2015*	*2020*
SO_2	96.7	102.0	111.0	139.2	225.4	324.0
TSP	180.1	183.3	50.9	55.9	62.3	68.6
NO_x	80.0	84.2	74.8	84.2	84.2	84.2
CO_2	17423	18418	19755	25855	40991	58541
NO_x reduction vs. BAU Case	0.0	0.0	10.6	30.7	67.6	107.5

4.51 Lastly, an integrated system planning project was completed that used both SO_2 and NO_X limitation. Its goal is to determine the optimal scenario that can limit emissions of all main air pollutants, SO_2, NO_X, TSP, and CO_2, to levels under their year 2000 emission levels. One interesting and significantly different result is that although the AFBC was chosen as the optimal option in neither the SO_2 nor the NO_X limitation scenario, the AFBC is chosen by the optimal planning model as the least-cost option to burn.

System Marginal Pollutant Reduction Cost

4.52 To achieve the respective pollutant reduction targets, an additional cost input for pollutants control must be made. The system marginal pollutant reduction cost is an important index to measure the pollutants control cost/effectiveness. By comparing the marginal reduction cost with the marginal damage cost, the optimum target can be set.

4.53 Table 4.5 presents the system marginal pollutant reduction cost for the three scenarios. As this table demonstrates, integrated control costs saves money.

4.54 Clearly, more expensive NO_X reduction options seem to be needed as the NO_X reduction target becomes more difficult to meet. For the SO_2 limitation case, the SO_2 reduction marginal cost is relatively flat, since only LSFO is selected to meet the SO_2 reduction target. Lastly, the combined marginal cost of the individual limitation cases for SO_2 and NO_X is nearly always greater than the combined pollutants limitation scenario (the only exception is 2003). This reflects the advantage of a combined pollutants reduction strategy over a single pollutant reduction strategy and demonstrates the higher cost-effectiveness of the former.

Table 4.5 System Marginal Cost of Pollutant Reduction

Scenario	*Limit NOx Emission under Year 2000 Level*	*Limit SO_2 Emission under Year 2000 Level*	*Limit Both NOx and SO_2 Emission under Year 2000 Level*	
Period	***US$ / Ton of NOx***	***US$ / Ton of SO_2***	***$ / Ton of NOx***	***$ / Ton of SO_2***
1999-2002	261	1034	40	1026
2003-2007	1338	2784	1681	2735
2008-2010	603	646	105	608
2011-2015	475	517	441	415
2016-2020	1383	723	1148.3	467.3

Integrated System Optimal Planning with SO_2 Externality Costs

4.55 The optimal planning model balances the externality cost of SO_2, NO_X and TSP (pollutants control cost) and the benefit (avoided pollutants damage or externality cost) based on the situation of the specific system. Such a model presents the least-cost system expansion plan for the generating system with a suitable pollutants control strategy. Lastly, the pollutants damage/externality cost varies by year, and extrapolated values were used for the middle years.

4.56 The SO_2 reduction options considered in this analysis are the same as those considered in the analysis of 'integrated planning with emission limitation,' and the results are presented in Table 4.6.

Table 4.6: Air pollutants and emission reduction of optimal integrated planning of generating capacity expansion (SO_2-2000 Case), (000 tons)

	1999	*2000*	*2005*	*2010*	*2015*	*2020*
SO_2	95.9	101.8	100.8	95.6	96.1	107.4
TSP	180.0	183.4	50.5	50.4	50.9	53.1
NOx	79.9	84.2	93.7	115.5	152.3	192.3
SO_2 reduction vs. BAU Case	0.6	0.5	10.3	43.4	128.8	215.7

4.57 The least-cost planning result, similar to the result in the case of SO_2 limitation, suggests that low-sulfur coal and the LSFO are chosen as the least-cost option for Hunan electric power system's SO_2 reduction option when the SO_2 externality cost is taken into account in the total system cost. As SO_2 externality costs increase, the ratio of thermal plant capacity with FGD increases too. From 2000 to 2020, it increases from 0% to 44%.

4.58 In addition to the adoption of FGD, changing the electricity generation mix of thermal power plants also contributes to the reduction of SO_2. In this case, compared with the BAU case, all thermal capacity with FGD have a higher load factor. However the capacity without FGD has a lower load factor. This arrangement of load factor for thermal power plants can reduce the SO_2 emission further based on the balance between reduction cost and benefit (avoiding externality cost).

Integrated System Optimal Planning with NO_x Externality Cost

4.59 The integrated system optimal planning with NO_X externality cost reduction target is summarized in Table 4.7.

Table 4.7: Air pollutants and emission reduction of optimal integrated planning of generating capacity expansion (with NO_X externality cost), (000 tons)

	1999	***2000***	***2005***	***2010***	***2015***	***2020***
SO_2	96.0	101.9	111.3	139.2	225.1	323.4
TSP	180.1	183.2	51.0	55.9	62.3	68.5
NO_X	79.9	71.3	64.4	83.4	109.4	147.8
NOx reduction vs. BAU Case	0.0	13.0	21.1	31.6	42.3	43.9

4.60 The least-cost planning result presents an optimal retrofit / new-installation combination of different technologies. The optimal result suggest that those plants with a higher NO_X emission rate should install SNCR. Those plants include existing plants and new plants burning anthracite.

4.61 Before the year 2005, the NO_X externality cost is relatively low. Only the cheapest NO_X reduction option–T/O–is selected to reduce the NO_X emission. With the increase of NO_X externality cost over time, BCM and SNCR are also selected to control the NO_X emission. The ratio of thermal power capacity with SNCR increases to 22% gradually. The combination of combustion-related and post-combustion NO_X reduction technology (such as BCM & SNCR) is selected to achieve higher NO_X reduction ability.

4.62 Besides the adoption of NO_X reduction technology, the change of electricity generation mix of thermal power plants also contributes to the reduction of NO_X. In this case, when compared with the BAU case, the thermal capacity with NO_X reduction technology has a higher load factor. However, the capacity without NO_X reduction technology has a lower load factor. This arrangement of load factor for thermal power plants can reduce the NO_X emission further based on the balance between reduction cost and benefit (avoiding externality cost).

4.63 The economically reasonable NO_X Total Amount Control (TAC) target for Hunan power system is: 64 k-ton for 2005, 83.4 k-ton for 2010, 109 k-ton for 2015 and 144 k-ton for 2010.

Integrated System Optimal Planning with All Pollutant Externality Cost

4.64 This analysis includes the costs of reduction and externality/damage for all three air pollutants (SO_2, NO_X and TSP). Table 4.8 provides a summary of emission and reduction.

Table 4.8: The air pollutants and emission reduction of optimal integrated planning of generating capacity expansion (with SO2+TSP+NOX externality cost), (000 tons)

	1999	*2000*	*2005*	*2010*	*2015*	*2020*
SO_2	95.9	101.1	79.8	47.1	52.0	60.9
NO_X	79.9	70.9	56.4	58.5	79.2	100.9
TSP	179.7	181.0	47.5	43.3	45.2	47.3
SO_2 reduction vs. BAU Case	0.6	1.2	31.2	91.9	172.9	262.3
TSP reduction vs. BAU Case	0.4	2.2	3.4	12.6	17.0	21.2
NOx reduction vs. BAU Case	0.0	13.3	29.1	56.4	72.6	90.9

4.65 There are some differences between the case with a multiple-pollutant externality cost and the cases with a single pollutant externality cost. One significant difference is that the new technology, CFB, is selected for an anthracite-fired power plant. This difference is due to the combined benefit of the multiple pollutants reduction function of the CFB. In the single pollutant (either SO_2 or NO_X) externality cost case, only one pollutant's reduction benefit, CFBC, can be considered; thus, the pollutant's reduction benefit of CFB is underestimated. This explains why CFB was not competitive in the single pollutant externality case.

5

Conclusions and Implications

Key Findings Regarding Environmental Control Options

5.1 In most cases, non-power sector options are more cost-effective than power sector options in reducing environmental pollution. However, the achievable reduction (total tons of pollutant) by non-power applications is limited and may not be adequate to achieve certain levels of environmental control. In the latter case, environmental controls in power sector applications would be needed. The following summarizes the key conclusions for the key pollutants (the particulates, SO_2, NO_x and CO_2).

5.2 *Particulates:* Both in Shanghai and Henan, particulate emissions come mainly from non-power sectors (78% and 84% respectively) . Total particulates from the power sector are expected to decline due to actions taken by the central and local governments including the utilization of higher quality coal, the retirement of small-inefficient power plants and the utilization of high efficiency ESPs in new and sometimes already existing coal-fired power plants. For further reduction of particulates, the use of gas and briquettes in households, coal washing and the installation of ESPs in existing small power plants are the most cost-effective options. Such options should be pursued because their costs (per ton of TSP removed) are lower than the estimated environmental damage (externality values).

5.3 Additional reductions of particulates can be achieved with a minor increase in the cost of electricity. For example, a 20% reduction of particulates from 1997 levels can be achieved in Henan by year 2020 by utilizing high efficiency ESPs in both new and existing power plants (including those that are small to medium in size, 50-200 MWs). The impact of such a constraint on the cost of electricity is relatively small (an increased average cost from 0.262 Yuan/kWh to 0.264 Yuan/kWh)

5.4 *SO_2 Control:* In Shanghai, the most cost-effective options for controlling SO_2 emissions are the use of coal briquettes in the residential and industrial sector, a simplified FGD in selected existing power plants, the burning of medium-to-high sulfur coal and coal washing in all sectors.

5.5 In Henan, the most cost-effective options for controlling SO_2 emissions are the use of briquettes in rural households and a simplified FGD installed in all units which burn medium-to-high sulfur coal. However, the costs of all options seem to be higher than the environmental damage. A least-cost plan with the stabilization of SO_2 emissions to 1997 levels by the year 2001 in Henan identified a combination of simplified and wet FGDs on existing and new coal-fired power plants as the key SO_2 control options. The impact of SO_2 emission constraint on the cost of electricity was significant; it increased the average cost of electricity from 0.262 Yuan/kWh to 0.289 Yuan/kWh, a 10% increase.

5.6 The stabilization of particulates and SO_2 in non-power sectors could be also accomplished through the introduction of gas in urban households, and briquettes in industry and rural households. The optimum conversion schedule is shown in the following table.

Table 5.1: Optimum Strategy for Controlling Particulates and SO_2 from Non-power Sectors

	2000	*2010*	*2020*
Briquettes for Industry	15%	60%	80%
Briquettes for H/S	15%	55%	75%
Gas for H/S	5%	15%	20%

5.7 *NO$_x$ Control:* While the control of NO_x emissions in existing plants is not currently required, it is commonly acknowledged that NO_x emissions will become a problem. In urban areas, a rapidly expanding transportation sector is responsible for the emission of volatile organic compounds, setting the stage for the creation of smog. Therefore, combustion NO_x controls should be applied to the largest extent possible (not only in new plants, but in existing plants as well, which are being rehabilitated) to reduce the growth rate of NO_x emissions. In addition to the utilization of low NO_x burners in new power plants, combustion tuning/optimization and low NO_x burners in existing power plants are cost-effective options (the cost is less than \$100 per ton, which is lower than the estimated externality value, \$250 per ton).

5.8 The stabilization of NO_x to 1997 levels can be achieved by using combustion tuning/optimization and low NO_x burners up to the year 2010. After this year, some SCR would need to be introduced. The impact of the NO_x emission constraint on the cost of electricity was relatively small (an increased average cost from 0.262 Yuan/kWh to 0.265 Yuan/kWh).

5.9 A more detailed assessment of urban pollution is recommended to better identify when smog will reach critical levels and what type of NO_x and VOC controls should be applied. Shanghai is particularly suitable for such study. It is experiencing high growth, and NO_x levels are reaching critical levels.

5.10 *Coal Washing*: The two case studies proved that the cost-effectiveness of coal washing depends upon site-specific considerations. In Shanghai, where coal is imported from other provinces over a long distance, coal washing emerges as a desirable option, especially when the synergistic effects of particulate and sulfur reduction, as well as ash disposal, are taken into account. However, in Henan, where most of the coal used contains less than 1.1% sulfur and is produced locally (low transportation costs), coal washing does not prove to be a cost-effective option.

Environmental Externalities

5.11 While the externality analysis in this study did not include a thorough evaluation of the externality costs, it developed indicative estimates. It assessed the impact of externalities on the cost-effectiveness of environmental options and developed least-cost plans using externality values to demonstrate their impact on the optimum combination of options.

5.12 The externality values were developed by taking into account the GDP in Shanghai and Henan, the population density, and the distance for the source of pollution. While these estimates are adequate as indicative values, a more detailed assessment is needed to develop environmental externalities reflecting the damages caused by each source on each setting (indoor, urban and rural). The Chinese Government has initiated efforts to carry out such assessments[11], which should provide the information needed to evaluate the cost-effectiveness of environmental control options against the damage costs.

Key Findings Regarding the Methodologies Used and Recommendations for Future Work

5.13 This study confirmed that system-level analysis is essential for evaluating alternative environmental control alternatives and policy options. Plant-level analysis is useful as a preliminary indicator of the cost-effectiveness of alternatives, but does not capture the role of each option in an integrated power system, which is being dispatched based on economic considerations.

5.14 Scenario analysis proved to be helpful in screening the various environmental control options based on their cost-effectiveness and reducing the number of options being considered in the development of a least-cost plan.

5.15 The assessment of non-power sector environmental control options was carried out satisfactorily, but the quality of the analysis was not the same with regard to the power sector. In future studies, further improvement is needed in:

- The level of detail of the data being collected
- The methodology for developing a least-cost plan for non-power sector applications (presently, identification of the best options is done based on their cost-effectiveness)
- The level of environmental damage being caused by each pollutant for each setting; for example, the impact of particulates in households (indoor air quality) is different than the impact of particulates from industrial facilities in an urban or rural setting

[11] Chinese Academy of Science (CAS), “Forestry Towards the 21st Century”, 1998

5.16 Future studies will benefit greatly from information about the environmental damages caused by each pollutant on the environment. It is recognized that the quantification of such damages is a very subjective and controversial activity, but even an indicative range of values would be helpful in evaluating the various options. The approach followed in this study (to identify the break-even point at which environmental control options become more cost-effective than the baseline option) has proven useful for policy-making, but the availability of environmental damage costs will make it even more useful.

5.17 More detailed assessments, which would be beneficial in the future, are:

- Simplified dispersion analysis to assess the impact of increased pollution in air quality
- Assessment of costs of environmental control options over time, as they are introduced in China. The costs are reduced due to less expensive local manufacturing and better knowledge of the technology ("learning curve"); examples of such technologies are: ultrasupercritical pulverized coal, PFBC, IGCC and SCR
- Improvement of methodology to distinguish between marginal and average cost-effectiveness in developing a least-cost plan to meet a set of environmental goals

5.18 Scenario analysis proved very helpful in identifying the most cost-effective environmental control options for Shanghai and Henan. A least-cost optimization analysis can provide a combination of strategies to achieve the specific environmental policy target at minimum cost. Also, the externality analysis provides useful input to policy-makers on how to target future policies to achieve the desirable results.

5.19 In future assessments, the methodology could be enhanced further by:

- Analyzing the learning curve for advanced technology, and analyzing the new technology that reaches the local market (international price vs. domestic price)
- Providing complete options for an industrial and household sectors comparison and developing a methodology to analyze multi-sectors in a more integrated manner
- Addressing CO_2 externalities to compare whether it can be integrated to other pollutants
- Comparing cost effectiveness of environmental control options for coal-fired power plants with renewable and nuclear options
- Evaluating the impact of options such as demand-side management and market-based mechanisms on environmental control cost-effectiveness

Annex 1: Environmental Regulations

China first enacted environmental laws and standards in the early 1970s. More recently, the government has been supplementing traditional command-and-control type regulations with market-based incentive regulations. China's pollution control policies are based on three main principles:

- Prevention first,
- Polluters pay, and
- Strong regulatory framework.

The framework is based on a two tier system: 1) pollution prevention efforts are focused on new pollution sources through a requirement for environmental impact assessments; and 2) pollution control efforts are focused on existing sources through a system of pollution fees and penalties. The system targets mainly state-owned enterprises. Township and village industrial enterprises are generally unregulated.

Pollution Prevention

According to the Chinese government, environmental impact assessments (EIA) are used to prevent environmental pollution by installing pollution control equipment in industrial facilities. To build a new facility or expand an existing one, business enterprises must receive approval from the National Environmental Protection Agency (NEPA) or the local environmental protection bureau. In this way, pollution control facilities are integrated with enterprises' development plans. However, EIAs are not effective in controlling pollution because:

- In most cases, EIAs are not comprehensive, and
- EIAs are project-specific and do not assess the cumulative impact of multi-year development programs.

Pollution Fees and Penalties

Pollution levies, discharge permits and mandatory pollution controls are utilized in the effort to control pollution from existing sources. Pollution levies are the most commonly used tool, but they are often set too low and their application is uneven. Mandatory pollution controls under threat of closure have been used as a last resort to force highly polluting enterprises to adopt control measures. Many of these enterprises are old plants using obsolete technologies, so forced investment for end-of-pipe control often wastes scarce capital by inducing pollution abatement at excessively high cost.

In recent years, both the national and local governments have begun to experiment with more market-based regulations for controlling air pollution. The central government has initiated a test program in which SO_2 emission fees are being applied in nine cities in Guizhou and Sichuan provinces. Provincial and city regulations are sometimes more stringent than national standards and many local governments are undertaking innovative programs to protect their local environment. About one dozen city governments have begun trial implementation of SO_2 emission trading schemes.

Ambient Air Quality Standards

The first ambient air standards in China were established in 1982 (Regulation GB 3095-82) and in recent years have been tightened to a level where they are now comparable to international standards. Ambient air quality is currently regulated under the National Ambient Air Quality Standards established in 1988. This law was promulgated to address the deteriorating urban air environment and sets maximum allowable ambient pollution concentrations. The standards designate three categories for different types of areas:

- **Class 1** standards are the most stringent standards and apply to national nature reserves, tourist and historic areas, and conservation sites,
- **Class 2** standards apply to residential urban and rural zones, and
- **Class 3** standards apply to industrial and heavy traffic areas.

The national government designates Class 1 areas and local authorities set Class 2 and 3 areas. In the Table A1-1 below, the ambient air standards proscribed by the 1982 and 1998 laws are compared to standards of the United States and international guidelines set by the World Health Organization (WHO) and the World Bank.

Table A1-1: Ambient Air Quality Standards (micrograms per cubic meter, μ/m^3)

Pollutant	Sampling Period	China Class 1	China Class 2	China Class 3	U.S.	WHO	World Bank
Total Suspended Particulates	Daily	150	300	500	150	150-230[a]	110
	Annual Mean	60	120	150	75	60-90	70
	Max. any time	300	1000	1500	--	--	--
Particulate Matter (PM-10)	Daily	50	150	250	260	70	--
	Annual mean	20	60	100	75	--	--
	Max. any time	150	500	700	--	--	--
Sulfur Dioxide (SO2)	Daily	50	150	250	260	--	125
	Annual Mean	20	60	100	80	40-60	50
	Max. any time	150	500	700	--	--	--
Nitrogen Oxides (NOx)	Daily	50	100	150	100	150	150
	Max. any time	100	150	300	--	--	--
Ozone(O3)	1 hour average	120	160	200	235	100-120[a]	--

a. 8-hour average

Emission Standards and Targets

Emission standards for coal-fired plant were introduced in 1991 by the regulation on 'Standards on emissions of air pollutants from coal-fired plants' (GB 13223-91). This regulation came into force in 1992 and set standards for particulates and SO_2 for existing and modified plants. These standards were revised in December 1996 by Regulation GB 13223-96 and went into effect on January 1, 1997. The new standards retain the same standards on existing plants, now referred to as Phase I or Phase II plants, but establish a new category and standard for recently built plants and initiate regulation of NOx, a previously unregulated pollutant. Under the new standards, there are now three categories of power plants:

- **Phase I**: applies to thermal plants built or examined and approved for construction before August 1, 1992,
- **Phase II**: applies to plants built or examined for construction between August 1, 1992 and December 31, 1996, and
- **Phase III**: applies to plants built or approved for construction on or after January 1, 1997.

Phase I and Phase II plants continue to be regulated by the 1991 emission standard which utilize simplified dispersion models to assess the impact of each plant on ambient air concentrations. The 1991 standards have been effective in addressing particulates--since 1991, 90% of new or additional generator units have installed ESPs, greatly reducing the growth in particulate emissions. However, to address the continuing deterioration of air quality in many of China's large cities, especially problems from SO_2 and NOx emissions, Phase III emission standards were designed to ensure that new plants meet more stringent standards for SO_2, particulates, and NOx emissions.

In Table A1-2 below, the new emission standards are compared with U.S. standards and international standards of the World Bank. Under the new standards, maximum emission rates are set on a plant-by-plant basis through the use of a formula that takes into account stack height, topography, average wind velocity, and whether the plant is in a rural or urban area. The emission is calculated based on total capacity of the plant, including its planned future capacity. The standards listed in the table are for dry-bottom boilers.

Table A1-2 Emission Standards for Thermal-Fired Power Plants (mg/Nm^3)

Pollutant	China Phase III (new plants)	United States	World Bank
Total Suspended Particulates (TSP)	• 200 for cities [a] • 500 for rural areas [a]	In most cases 50; new PM 2.5 standards are proposed by EPA	50
Sulfur Oxides (e.g. SO_2)	• 2,100 for coal w/ ≤1% sulfur • 1,200 for coal w/ >1% sulfur[b]	920 - 1,210	• For background air quality <50 $\mu g/Nm^3$, total SO_2 emission: 100 tons per day (tpd). • For SO_2 air quality ≥50 $\mu g/Nm^3$, total SO_2 emission: 100 tpd or 0.2 tpd/MW (whichever is lower)
Nitrogen Oxides	• 650 for dry bottom [c] • 1,000 for wet bottom [c]	350 - 620	Coal: 750 Coal w/ VM<10%: 1,500 Oil: 460 Gas: 320 Combustion turbine units: Gas: 125 Diesel: 165 Fuel oil: 300

a. Applies to plants over 55 MW_{th}.
b. Curiously, Phase III plants that burn high sulfur coal are held to a tighter SO_2 emission limit than plants burning low sulfur coal. The standard is still reported to be under review and may be modified to address this contradiction.
c. Applies to plants over 835 MW_{th}.

Particulates

Correction factors for particulate emissions for boiler types other than dry-bottom are given in Table A3-3.

Table A3-3: Particulate Emissions - Correction Factors for other types of boilers

Pulverized Coal Boiler		Cyclone-fired Boiler		Fluidized bed boiler	
Dry bottom	Wet Bottom	Vertical	Horizontal	Bubbling bed or low flow	High flow rate
x 1.0	x 0.7	x 0.5	x 0.3	x 0.5	x 1.0

Sulfur Dioxide

SO_2 control is based on the laws GB 13223-91 enacted in April 1982 and modified most recently by GB-13223-96, enacted in January 1997.

SO_2 emission standards are set on a plant by plant basis through the use of a formula that takes in to account stack height, topography, average wind velocity and whether the plant is sited in a rural or urban area. The emission should be calculated on the bases of total capacity of the plant including its planned future capacity. The formulas used to calculate emission standards are:

$Q_{SO2} = PUH_g^m \times 10^{-6}$
Where:
Q_{SO2} = total allowable SO_2 emissions from the plan in tons/hr
P = emission control factor (see below)
U = average wind velocity at the outlets of the stacks, m/s
H_g = geometric stack height, m;
d = local atmospheric dispersion index (see below)

Table A3-4 Emission Control Factors and Local Atmospheric Indices for SO_2 Standards

Area	*Emission Control Factor (P)*			*Dispersion Index (d)*
	Phase I	Phase II	Phase III	
Urban Area	8.947	7.460	5.802	1.893
Rural Area plain	6.186	3.608	3.608	2.075
Rural Area other	13.421	11.936	11.936	1.893

These Phase III standards encourage the installation of FGD on plants using high sulfur coal. In addition, the government has committed to cap particulate and SO_2 emissions in the year 2000 at 1992 levels and the MOEP has set a target for the installation of FGD of between 10 and 12 GWe of power capacity by the year 2000. There are several FGD demonstration plants in operation or under construction in China using a wide variety of processes to determine the most suitable FGD process for Chinese conditions (see section 4). In some areas of China, provincial and municipal regulations are more stringent than these federal regulations.

Monitoring and Enforcement

Enforcement is the weak link in China’s environmental protection system. National and local environmental regulations and standards are enforced primarily by municipal and county environmental protection bureaus which report to local governments. However, local governments face a tradeoff between protecting the environment and safeguarding the financial and employment performance of local firms. Even when the local authorities seek to uphold national standards, their ability to monitor compliance is seriously constrained by limited financial and human resources. Although China’s environmental standards are generally consistent with international standards, pollution generally exceeds these levels. According to recent surveys, during 1993-94 only 36-49% of industries were in compliance with their environmental impact assessments.

Annex 2: GESP II Model

Introduction

Developed in the mid-1980s, the Generator of Electric System Planning (GESP) model has been used in the economic justification of the Three Gorges Project, the expansion of South China Generation system, and World Bank projects including Sichuan Electric Power, Shuikou Hydropower, Tianhuangping Pumped Storage, Yangzhou Thermal Power and Ertan Transmission. It also has been used for the economic justification of several Asian Development Bank (ADB) projects such as Yuzhou Thermal and Mianhuatan Hydro.

Another model used in the study was the GSRA model, a sub-model of GESP-II that can be used to calculate the reliability indexes of the power system such as LOLP and EENS.

Brief Description

(1) Name: GESP (Generator of Electric System Planning)

(2) Type: Multi-regional Power Generating System Expansion Planning Optimization Software Package

(3) Mathematical Method: Mixed Integer Programming

(4) Language: FORTRAN-77

(5) Standard: Commercialized software package

(6) Objective: For long-term power generating system expansion planning of multi-regions of national scale or within a region

(7) Adaptable to the following types of computer:

UNIVAC/1100
EDC.VAX series
IBM370, 43 series, 30 series and compact series
CDC CYBER 930
Workstation
Desktop/Notebook

Function of GESP

GESP can be used to determine:

(1) optimum generation mix and plant commissioning for system expansion within a planning period,

(2) daily dispatch of the generating units to meet the demand,

(3) maintenance schedule of units,

(4) optimum transmission capacity of the interconnecting lines and load flows among considered subsystems,

(5) total investment and cash flow associated with the optimum expansion plan, and

(6) generation and operating cost of each type of the power station and the fuel consumption of each thermal plant.

Features of GESP

(1) GESP is a multi-region planning model. It can handle single node studies of well interconnected systems or multi-regional sub-systems taking into account interconnection transmission lines.

(2) Three main types of the power plants, i.e. hydro, thermal (include nuclear), and pumped-storage, can be considered in GESP. The description of hydro power stations and pumped-storage stations is typically very detailed and the performance of hydro power stations can also be considered.

(3) GESP is very flexible for the user with user friendly input data forms and output reports convenient to use.

Output of GESP

(1) least-cost system expansion plan, i.e. the optimal installation schedule of selected units,

(2) cost streams of the investment program and of each power plant,

(3) power demand and installed capacity balance of the system and sub-region,

(4) optimal load dispatch schedules of all power plants under the daily load duration curves of the system,

(5) maintenance schedule of each power plant,

(6) water spilling of hydro power stations,

(7) power flows and energy exchange among sub-regions, and

(8) technical and economic indexes of the system, subsystem and each power plant. (fuel consumption, etc.)

Mathematical Method of GESP

The mixed-integer programming (MIP) method was used in GESP Model.

The general mathematical model of MIP is:

Objective function

$$\mathbf{MIN\ F=AX+BY}$$

where:

F : objective function
A,B: matrixes of constant coefficients
X : continuous variable vector
Y : 0-1 variable vector

Constraints:

CX >= M
DX - EY <= 0
Y <= 1
X >= 0

where:

C,D,E : matrixes of constant coefficients
M : constraint constant vector

The objective function of GESP

The objective of GESP is to minimize the present values of the total costs during the planning period.

The objective function of GESP is:

MIN Z = I - S + F + V + E

where:

Z: objective function
I: total investment over the planning period
S: the savage values of the investment at the end of the planning period
F: the fixed operating costs over the planning period
V: the variable operating costs over the planning period, (mainly fuel costs)
E: the costs for the short of electricity in the system over the planning period.

The constraints considered in GESP

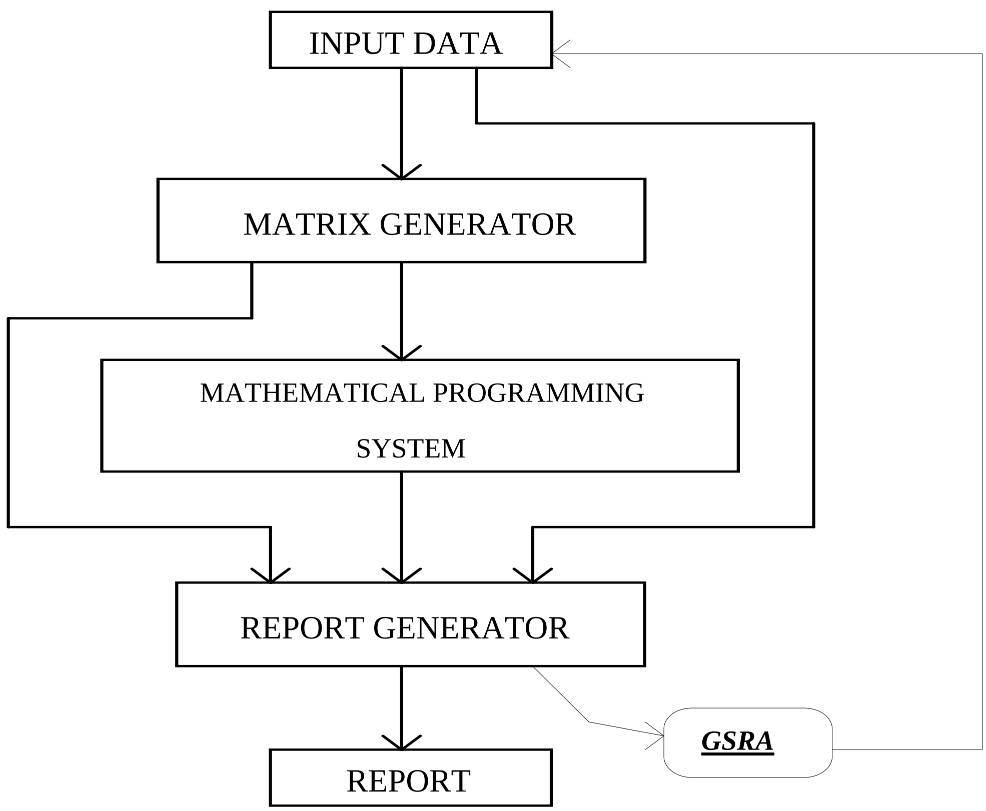
- Electric power and energy balance constraints
- Hydro power station sequence constraints
- Hydro power station commissioning order constraints
- Hydro energy constraints
- Fuel resources constraints
- The minimum output constraints of power plants
- The maximum output constraints of power plants
- The electric energy balance constraints of the pumped storage stations

- The upper reservoir capacity constraints of the pumped storage stations
- Plant scale constraints
- Construction ability constraints
- The maintenance constraints of the power plants
- The cold reserve constraints
- The spinning reserve constraints
- The dispatchable capacity constraints
- Gross system reserve constraints
- Determined schedule

Software Structure

GESP Software Package is composed of three main parts, i.e. Matrix Generator, commercial Linear Mathematical Programming System and Report Generator and a sub-model GSRA as shown in the Chart A2-1.

Chart A2-1 Structure of GESP-II Model



Modifications of GESP Module to Consider Environmental Impacts

For consideration of environmental impacts in power system planning, one method is to set pollutant emission limitations for the power system to generate an environmentally acceptable and least-cost power system expansion plan. In the power system, in order to meet the pollutants emission limitation, two pollutant control measures can be adopted: the first is the change the structure of fuel consumption, the second, is the adoption of less-polluting technology, such as the installation of pollutant control devices. Thus the environmental features of fuel and pollutants emission and the control feature of thermal power plants could be described in power system planning model.

From the macro-economic perspective, pollutant damage can also be measured in financial terms by using pollutant externality cost. Another method for considering the environmental impact is to use the least-cost power system expansion plan and environmental externality costs. For the least-cost study, the pollutant externality cost could include the total social cost as well as the equipment investment cost, O&M cost and fuel cost.

The old version of the GESP module, while using a least-cost study, could not consider the emission and impact of pollutants. In order to consider the environmental impacts in power system planning, some new features associated with pollutant emission, control and externality cost were added to the new version of the GESP module. The three modifications are:

a) For the calculation of different pollutant emissions, the GESP module should have a good description of output by pollutant. There are three key factors used to determine this: fuel, power plants and pollutant control devices.

- For fuel description, environmental features are involved

  In the old GESP version, the fuel is described only by its price whereas in the new version, fuel is divided by type. Resource limitations, such as lower heating value (LHV) and coal features, could be included in the description of each type of fuel, such as ash content, sulfur content, and carbon content. Each type of fuel can be defined by the user according to the actual situation;

- New items are added to describe the pollutants emission and control feature of thermal power plants;

  Thermal power plants can select certain fuels, the inherent control rate of TSP and SO_2 and also the emission rate of NO_x. Different pollutant control devices can be considered in each power plant.

- The pollutants control devices are added;

  For each pollutant control device, investment cost, O&M cost, pollutants (SO_2, NO_x, TSP) control rate, auxiliary energy consumption, and the influence to plant efficiency and reliability is described. They can be defined as ESP, FGD, etc. based upon the need of each power system.

b) The pollutant emission amount is calculated in new GESP version, and pollutant limitations can be considered.

The new version can calculate the emission amount of TSP, SO_2, NOx and CO_2 according to the type of fuel used, electricity system dispatching and adoption of pollutants control devices. Based on the pollutant emission amount calculation and liner programming method, the emission amount constraints are applied on different pollutants in different year. This can be applied as a pollutants control strategy for power system planning.

c) Pollutant control cost and pollutant externality cost are added into the total cost of least-cost analysis.

In the old GESP version, the total system cost is composed of the investment cost and O&M cost, and fuel cost of power system. In the new version, in addition to the costs described above, following costs are also included:

- investment and O&M cost of pollutant control devices;
- pollutant externality cost; the unit externality cost of different pollutants are inputted by the user according to their own analysis. This can be applied as another pollutants control strategy for power system planning.

The objective function of new GESP version is:

$$\mathbf{MIN\ Z = I - S + F + V + E + \mathit{IC} + \mathit{FC} + \mathit{VC} + \mathit{EC}}$$

where:

IC: investment cost of emission control device
FC: fixed O&M cost of emission control device
VC: variable cost of emission control device
EC: externality cost

The added constrains mainly are pollutants emission limitations.

The added output of new GESP version is:

- installation of different pollutants control devices in each year;
- investment cost flow of the installation of pollutants control devices;
- pollutants (SO_2, NOx, TSP, CO_2) emissions in each year;
- externality cost of pollutants (SO_2, NOx, TSP, CO_2) in each years;
- pollutants (SO_2, NOx, TSP, CO_2) emissions reduction by control devices in each year; and
- consumption of different types of fuel in each year.

Environmental Analysis with the New GESP Version

With the new GESP version, environmental analysis can be performed. When pollutant externality cost is applied, the GESP can incorporate the environmental assessment into the power generation system expansion optimization to generate the least cost expansion plan based on total social cost. When different pollutant emission limitation are applied, least cost expansion program, including determination of emission control strategies under the pollutants emission constraints, can be carried out by GESP. These two strategies can also be applied at the same time to generate an environmentally-acceptable and least-cost power system expansion plan.

Besides the environmentally acceptable and least-cost power system expansion planning study, the model can also perform many other case studies, such as the cost/benefit analysis of certain pollutants control device in certain power system. The environmental associated study of the power system can be performed by new GESP model and include:

- least-cost power system expansion plan study with the consideration of pollutant externality cost and the pollutant emission limitation;
- pollutant emission control strategy study in electric power system;
- pollutant emission control devices cost and benefit evaluation in power system;
- optimization of the installation of pollutant emission control devices on the thermal power plants in the power system; and
- marginal control cost analysis of pollutant emission for optimal fuel selection of the power system.