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Guangzhou Air Quality Action Plan 2001

Air Quality Management and Planning System for Guangzhou

(NORAD Project CHN 013)

Participating Institutions:

P.R. China: GMSTC, GEPB, GRIEP, GEMC
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This document is the result of a common effort by all task groups that together have made up the project team for the Sino-Norwegian co-operation project «Air Quality Management and Planning System for Guangzhou» (see Preface). Many people in the participating institutions have provided data input, comments and suggestions. Knut Aarhus (ECON) has been the principal author. Steinar Larssen (NILU) has also played a key role in developing this action plan. Textual contributions have been made by Kristin Aunan (CICERO), Haakon Vennemo and Henrik Lindhjem (ECON), Jan Henriksen (NILU), and Kathrine Sandvei (IFE).

Preface

Funds were made available from the Norwegian Department of Foreign Aid and development, NORAD, to initiate a co-operative work in order to establish an Air Quality Management and Planning System for Guangzhou in China.

Four Norwegian research institutions were joined together in the Norwegian Consortium for Energy and Environment, NORCE:

- NILU Norwegian institute for Air Research;
- IFE Institute for Energy Technology;
- CICERO Centre for International Climate and Energy Research;
- ECON Centre for Economic Analysis,

with NILU acting as secretariat for NORCE.

The work on the Chinese side was lead by the Guangzhou Municipal Science and Technology Commission (GSTC), as a cooperation with:

- GRIEP Guangzhou Research Institute of Environmental Protection;
- GEMC Guangzhou Environment Monitoring Centre;
- GEPB Guangzhou Environmental Protection Bureau;
- GESI Guangzhou Environmental Supervision Institute,

and other institutions in Guangzhou, with GRIEP acting as Project Office for the project.

Mr. Steinar Larssen, NILU and Mr. Wu Zhengqi, GRIEP were Project Leaders for the NORCE and the Guangzhou side, respectively.

The main objectives of the project have been the following:

- Develop and establish an air quality management and planning system for Guangzhou.
- Develop an air quality action plan as part of a city Environmental Master plan to reduce the air pollution in Guangzhou.
- Update and improve the monitoring system by additional measurements in Guangzhou.

- Transfer tools and knowledge to the extent necessary to enable the Guangzhou counterparts to continue the Air Quality Management Strategy work in a qualified fashion.

The project started with a kick-off-seminar in Guangzhou in November 1996, and was finished at the end of 1999. The results of the project have been presented during semi-annual workshops, in Project Reports and in Technical Reports.

The project was divided into separate tasks:

		Task leaders	
Task	Text	Guangzhou	NORCE
1	Emission inventory	Ms. Huang Qingfeng, GEMC	Mr. Frederick Gram, NILU
2	Energy consumption and coal smoke pollution	Ms. Zhong Jieqing, GRIEP	Mr. Fridtjof Unander, IFE Mr. Thomas Krogh, IFE Mr. Andy Yager, IFE
3	Dispersion modelling	Mrs. Fang Xingqin, GRIEP Mr. He Liangwan, GRIEP	Mr. Atle Riise, NILU Mr. Håvard Slørdal, NILU
4	Monitoring	Mr. Dong Tianming, GEMC	Mr. Steinar Larssen, NILU
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7	Control options	Mr. Cui Xia, GRIEP	Mr. Andrew Yager, IFE
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9	Cost/benefit analysis	Mr. Yu Jichan, GRIEP	Mr. Haakon Vennemo, ECON
10	Pollution control management and policy options	Mr. Liang Yujie, GRIEP Ms. Ge Yi, GRIEP	Mr. Knut Aarhus, ECON Mr. Thorleif Haugland, ECON
11	Motor vehicle pollution	Mr. Yu Kaiheng, GRIEP	Mr. Andy Yager, NILU
12	Pollution forecasting	Ms. Liu Li, GEMC	Mr. Dag Tønnesen, NILU

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1 Executive summary

1.1 Introduction

The city government of Guangzhou has decided that Guangzhou should qualify as an Environmental Model City by 2001. National environmental authorities have defined the model city criteria to include *air quality indicators* for three different compounds, namely SO_2, NO_x and total suspended particles (TSP), as well as other environmental indicators. The indicators are given in terms of concentrations of the pollutants. *The key concern of this action plan is to identify a package of control options that may meet these targets in a least cost manner.*

This action plan has been developed as a part of the joint Sino-Norwegian project: Air Quality Management and Planning System for Guangzhou. The plan draws upon the integrated system for air quality planning and management in Guangzhou that has been established in the project. This system includes the establishment of a grid and an emissions inventory for the different emission sources that can also be applied in projections of future emissions. Further, it includes a dispersion model with which we may calculate the ground level concentrations at any different location in the city/study area which in turn can be compared with measured levels in order to check the quality of the model. Then different control options that will reduce the emissions are identified, and their potential for reduction of emissions and air pollution concentrations is calculated. Finally, we estimate the costs of applying the different control options and select the package of control options that will achieve the stated air quality objectives (in terms of concentrations) at lowest possible costs.

1.2 SO_2 targets easier to obtain than NO_x targets

The measured levels in 1995 exceed the targets for all three pollutants. The values are shown in table 1-1. The ranges are due to different values at different monitoring stations. As can be seen, the SO_2 targets will be the easiest to achieve, while the targets for NO_x will be very difficult, if possible at all to achieve. TSP lies in between.

Table 1.1 Necessary improvements in air quality from 1995 levels to reach 2001 targets (reduced concentrations).

	SO_2	NO_x	TSP
Annual average	0 – 20%	23 - 62%	8 - 50%
Max 24-hour average	11 – 52%	70 - 87%	48 - 78%

Each source category's contribution to concentration levels for each of the three air pollutants have been calculated and given in table below. This indicates what kind of sources that must be focussed on in a plan to reach the targets.

Table 1.2 Calculated 1995 contributions to concentrations (sum of the concentration values, in $\mu g/m^3$, in all 2×2 km grid cells).

CONCENTRATIONS, % of sum	SO_2	NO_x	Particles
Large point sources	68.3	30.4	67.9
Small point sources	25.9	10.2	18.3
Domestic & commercial	1.6	6.1	7.9
Main roads & local roads	4.1	53.3	5.9
Sum	100	100	100

The main conclusions are first that approximately 60 large point sources represent nearly 70% of all contributions to concentrations of SO_2. Traffic is not important for SO_2. Second, traffic is the main source for NO_x concentrations, representing 53% of contributions. Third, for particles only combustion sources have been included in the calculations while resuspended dust from streets and dust from sources such as construction have been excluded. Almost 70% of contributions to particles concentrations stem from large point sources.

It is important to bear in mind that a very limited number of point sources are responsible for large contributions to concentration levels of SO_2 and combustion particles. This fact facilitates goal achievement because it is normally much easier to handle a few number of sources than a large number of sources, both in terms of formulating policies and regulations and in terms of enforcement.

1.3 Control options and least cost packages

For each substance we have sought to identify the potential of each option for reducing concentration in central Guangzhou and the costs of reducing e.g. the SO_2 concentration level by one percentage point relative to the 1995 level. The end result of this exercise is a cost curve consisting of the costs and additional concentration reduction potential of each option. This exercise takes into account that several control options address the same sources and same emissions.

1.3.1 SO_2

For SO_2 the following options were considered:

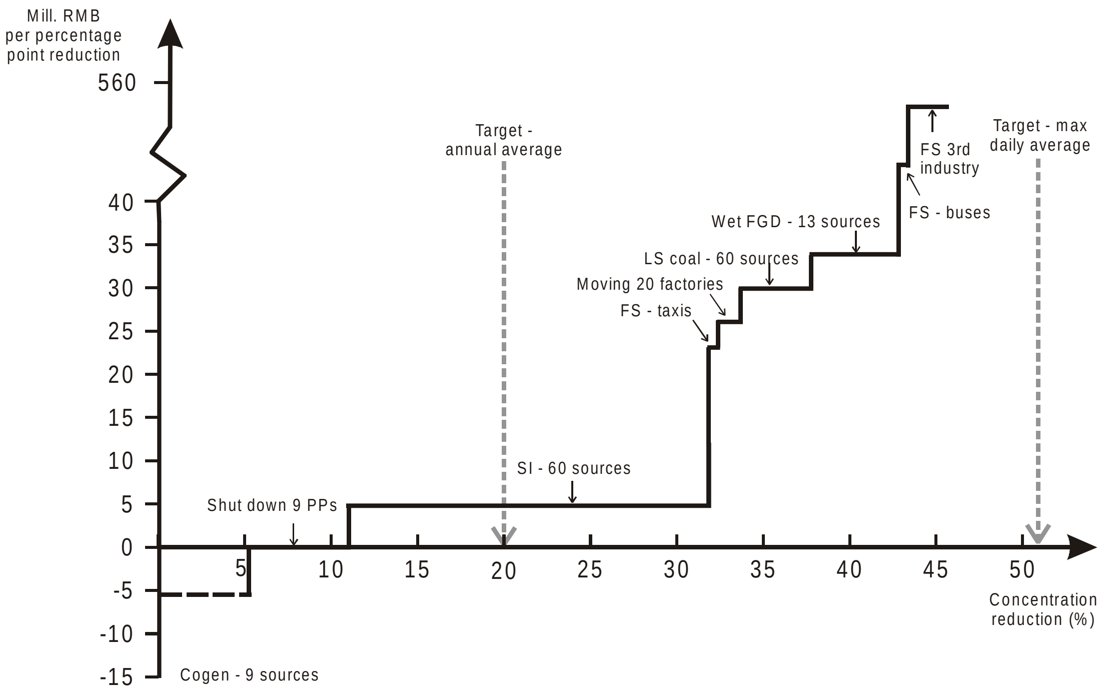
- Sorbent injection (SI) in all large point sources (60 sources)
- Shut down a number of small, polluting power plants (with low stacks and located within the populated part of the city) and increase production in

bigger, less polluting plants with taller stacks, located further away, and with idle capacity

- Shift to low sulfur coal (LS coal) in all large point sources (60 sources)
- Wet flue gas desulfurization (FGD) in the 17 largest point sources
- Fuel switch (FS) for 15,000 taxis - from gasoline to LPG
- Fuel switch (FS) for 1000 buses - from diesel to LPG
- Co-generation of steam and power in 9 industrial facilities
- Switching fuel from coal and diesel to piped gas in restaurants and hotels (FS 3rd industry)
- Moving 20 factories out of urban area

The cost curve for these control options is shown in figure 1.1. Each option's additional potential for reducing concentration of SO_2 in central Guangzhou relative to the 1995 level is measured along the horizontal axis while the cost, expressed in mill. RMB per percentage point reduction, is shown along the vertical axis.

Figure 1.1 Cost curve, SO_2 control options.



The least cost package for achieving the target for *annual average* consists of cogeneration in 9 industrial facilities, shut down of a group of small power plants and sorbent injection in all 55-60 large point sources. The option of cogeneration involves a direct economic saving while the shut down of small power plants is a zero cost option. Sorbent injection has a moderate positive cost. The net annual costs of this package is estimated to be less than RMB 70 mill.

The technologies of cogeneration and sorbent injection are mature and well-known, and they are both used in Guangzhou already. These facts increase the feasibility of the options. The option of shutting down small power plants might face some institutional and political hurdles in the short term, but should be feasible in a somewhat longer term.

As for the maximum daily target, it is clear that it will be more difficult and costly to achieve, but not impossible. It will probably require a different composition of the package of control options where some of the most effective and more costly control options such as the wet or dry FGD needs to be applied on a larger number of large point sources than we have done here.

1.3.2 NO_x

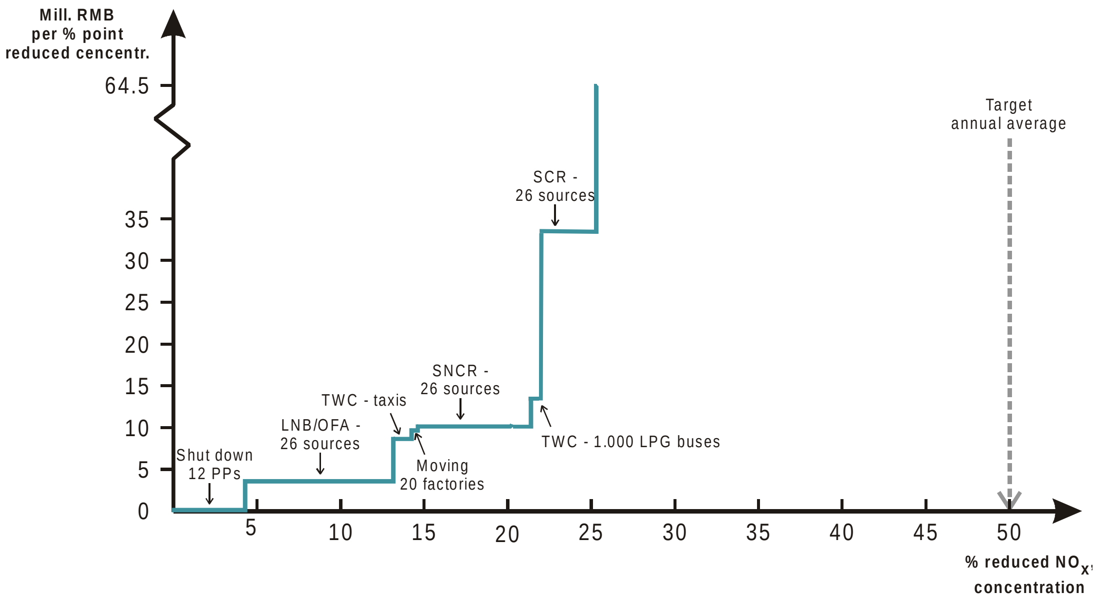
For NO_x we considered the following control options:

- Low NO_x burners in the 26 largest point sources
- Selective non-catalytic reduction (SNCR) in 26 largest point sources
- Selective catalytic reduction (SCR) in the 26 largest point sources
- Retrofit of three way catalytic converters on taxis
- Retrofit of three way catalytic converters on LPG buses

In addition, two options considered under SO_2 will also reduce NO_x emissions: moving 20 factories and close down of small and highly polluting power plants.

The cost curve for NO_x is shown in figure 1.2.

Figure 1.2 Cost curve, NO_x control options.



For NO_x we can conclude that the control options covered in this report will not be sufficient to meet the stated targets. There are two important reasons for this:

- background contribute significantly to concentration levels
- traffic also accounts for large shares of concentrations and the control options for traffic are not very effective.

From this, different responses should be considered in terms of the targeted NO_x concentrations. *First*, Guangzhou should consider how it might help reduce out-of-area emissions because background levels significantly restricts the city's space of manoeuvre in terms of achieving the NO_x targets. *Second*, Guangzhou should consider more aggressive or potent options towards emissions from traffic. *Third*, Guangzhou might relax the NO_x target and instead focus on NO_2 as this compound is clearly the more significant one in terms of health effects. The NO_x target in China equals WHO's guideline for NO_2. This implies that the Chinese NO_x target is approximately twice as ambitious as the WHO guideline.

Finally, it would probably pay off to apply the most effective NO_x control options on a larger number of sources than have been considered here.

If the annual target is relaxed by 50%, this would imply a required reduction of concentrations of 25 percentage points from 1995 levels in central Guangzhou (annual average). The total annual costs of achieving such a target would be in the order of RMB 250-300 mill. Achieving the *current* targets for NO_x could easily prove to be a rather costly affair with questionable health improvements.

1.3.3 TSP

For TSP the following control options were considered:

- Low ash coal
- High efficiency electrostatic precipitators (ESP)
- Baghouse filters
- Street cleaning

In addition, some options considered under SO_2 and NO_x will also produce reductions of particles: close down of small power plants, moving 20 factories out of urban area, fuel switch for taxis and buses and cogeneration in 9 industrial facilities. Since the Guangzhou AQMS project primarily has focused on *combustion particles* whereas the air quality target is defined for *TSP*, we have not been able to construct a cost curve for TSP as we did for SO_2 and NO_x.

Nevertheless, we conclude that three options – cogeneration, shut down of small power plants and high efficient ESP on 11 sources – will reduce total emissions of combustion particles by 40,000-50,000 tons, or 35-40% from 1995 level. The total costs will be small, and all three options should be feasible. Cogeneration and high efficiency ESP are mature technologies which are also in use in Guangzhou.

2 Introduction

2.1 Why this action plan?

The city government of Guangzhou has decided that Guangzhou should qualify as an Environmental Model City by 2001. Central authorities have defined the model city criteria to include air quality indicators for three different compounds, namely SO_2, NO_x and TSP, as well as other environmental indicators. The objective of this action plan is to provide a sound basis for the political decisions on how to improve the air quality in Guangzhou. It seeks to answer the following question: *How can the city's air quality objectives be reached at lowest possible cost?* Significant funds will probably be spent on programs seeking to achieve improved air quality, what is crucial is that the investments with the largest benefits per RMB invested are selected and implemented, and that costly investments with small environmental benefits are avoided.

Traditionally, air pollution control programs have focused on reducing *emissions* of different pollutants. This makes sense when the problem is global (CO_2 and other greenhouse gases) or regional (SO_2 for acid rain). When focusing on local air pollution and local air quality, our immediate concern is with *concentrations* (e.g. milligram SO_2 per m^3 in the air we breathe), *and exposure* (how many people exposed to different levels of concentrations). Obviously there is a relationship between emission and concentration/exposure of e.g. SO_2, but some emissions contribute much more to the concentrations than others. This will depend on factors such as *where* the emission take place, the height of the stacks, meteorological conditions or how the pollutants are dispersed, and on where people live and work. As we are dealing with impacts and management of local air quality, our prime concern is with concentrations, not emissions *per se*.

In this approach, it is more important to attack the emissions which produce high concentrations in areas where many people live and work before one starts dealing with other emissions which might even be larger in terms of tons[1] per year, but which may be less significant for people's health.

This might sound simple, but requires extensive work and analysis, and is what the Guangzhou Air Quality Management Strategy is all about. First we need to identify the different sources and their emissions, register them in an inventory, model the dispersion and calculate the contributions of each source to ground

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1 In this document we use the term ton (not tonne) when referring to 1000 kgs.

level concentrations at any different location in the city. Next, we hold these results up against actual or measured levels in order to check the quality of our model. Then we compare the concentrations with the geographical distribution of the population and thus find the exposure, identify technical control options that might reduce the emissions and calculate how this will affect the concentrations. Finally, we estimate the costs of applying the different control options select a package of control options that will achieve the stated air quality objectives at lowest possible costs.

Add to this that Guangzhou is a highly dynamic city with rapid socio-economic change. Any air quality management system which seeks to stay relevant in such an environment needs to allow for rapid changes over time. Our exercise starts out from the year of 1995 and focuses on what will be necessary in the year 2001 given the objectives that the Guangzhou government has set for itself.

2.2 Outline

The outline of this action plan is as follows: Chapter 2 deals with the situation in 1995: it describes levels of emissions and concentrations of the three air pollutants as they are modelled and compares the results from the *modelling* with the results from the *measurements*. Chapter 3 describes the projections of emissions and concentrations for the year 2001. Chapter 4 briefly presents the air quality targets which the government has decided for 2001 and the required reductions if these targets are to be met. Chapter 5, analyzes different control options for reducing emissions and concentrations of the three pollutants. It assesses the concentration reduction potential of each option and the costs associated with each one. Chapter 6 summarizes the analysis by recommending packages of control options that will reach the air quality objectives in a cost effective manner.

3 Present situation

3.1 Calculated emissions

Based upon the data in the emission inventory which has been established for the Guangzhou Air Quality Management Project, the total emissions of SO_2, NO_x and particles in the model area has been calculated. This calculation has taken 1995 as the base year and includes emissions from 5 different source categories:

- large point sources (industrial sources with emissions > 50 kg/h of one or more of SO_2, NO_x, or particles)
- small point sources (industrial sources with emissions < 50 kg/h)
- households and commercial sector (domestic)
- traffic on main roads, and
- traffic from local roads.

The model area covers 52 x 56 km. The data in the inventory are based upon approximately 1300 questionnaires covering point sources and information on fuel use, fuel quality and traffic (traffic volume, speed, vehicle fleet composition) in Guangzhou. The calculation shows that, from these sources, in 1995, the total annual SO_2 emissions in the model area were 144,000 tons. By comparison, total emissions of SO_2 in the entire city of GZ was 153.000 tons in 1995, according to Guangzhou Statistical Yearbook. Total NO_x emissions were 70,000 tons and the annual emissions of particles were 118,000 tons. Sources of particles are not complete.

Table 3.1 shows the emissions per hour (kg, average for the entire year) and how the total annual emissions (tons) are distributed between the five different categories:

Table 3.1 Total emissions in 1995, in the GZ emission data base, per Oct. 1998.

EMISSIONS, kg/h	SO_2	NO_x	Part.
Large point sources (POI 50)	12 688	3 966	11 312
Small point sources (SmPOI)	1 664	578	1 269
Domestic & commercial (Dom)	1 937	358	545
Main roads (mtraf)	140	1 873	212
Local roads (straf)	92	1 200	135
Sum	16 523	7 976	13 474

EMISSIONS, 1000 t/year	SO_2	NO_x	Part
Large point sources	111.2	34.7	99.1
Small point sources	14.6	5.1	11.1
Domestic & commercial	17.0	3.1	4.8
Main roads	1.2	16.4	1.9
Local roads	0.8	10.5	1.2
Sum	144.7	69.9	118.0

Source: Air Quality Management and Planning System for Guangzhou*: Report from Workshop 2, 1998, Guangzhou, 5-13 November*. Report no. GZAQMS A5. Draft February 1999

As can be seen from the table, large point sources is by far the most important category for total emissions of SO_2 and particles, representing 77% of total SO_2 emissions and 84% of total particles emissions. Large point sources are also responsible for a large share of total NO_x emissions (50%). However, for NO_x traffic is also an important category, accounting for 39% of total emissions.

3.2 Calculated concentrations

As stated in the introduction, the primary concern for an action plan aiming at improving local air quality and thus the welfare of the citizens in a city like Guangzhou, is the *concentration* of various air pollutants and the exposure of the population, not the emissions *per se*. Even though there is a relationship between emissions and concentration, this is not a direct relationship, it is influenced by *where* the emissions take place, the height of the stacks, meteorological conditions, etc. Therefore, we have calculated how much each source category contributes to concentration levels of the various pollutants. This calculation is based upon emissions and stack data from the database. These preliminary calculations were done as part of the 1st sequence of AirQUIS analysis done in 2nd half of 1998 using the KILDER program.

The upper part of table 3.2 shows the calculations for the contribution to air pollution concentration for each source category to *the grid square with the highest concentration of the particular air pollutant*. The lower part of the table shows the relative contribution of each source category calculated on the basis of the sum of contributions to concentrations in all grid squares, but not including the contributions of background concentrations.

Table 3.2 Calculated 1995 contributions to concentrations, in 2×2 km grid cells.

Highest concentration	ug/m3		
	SO_2	NO_x	Part
Large point sources	120.4	34.5	53.7
Small point sources	21.3	9.1	17.4
Domestic & commercial	40.7	22.9	11.5
Main roads	1.6	7.5	2.6
Local roads	0.8	11.3	1.3
Background	15.0	20.0	25.0
Max concentration in any grid cell	139.8	74.3	85.0
CONCENTRATIONS, % of sum			
Large point sources	68.3	30.4	67.9
Small point sources	25.9	10.2	18.3
Domestic & commercial	1.6	6.1	7.9
Main roads	2.2	33.9	4.0
Local roads	1.9	19.4	1.9
Sum	100	100	100

Source: Air Quality Management and Planning System for Guangzhou*: Report from Workshop 2, 1998, Guangzhou, 5-13 November*. Report no. GZAQMS A5. Draft February 1999

As can be seen from the table, the conclusions from the section on emissions above need to be modified on several points.

For SO_2, large point sources represent 68% of all contributions to concentrations, while they represent 77% of emissions. In other words, a limited number of large point sources are responsible for more than two thirds of SO_2 concentration levels. Traffic is not important for SO_2.

For NO_x concentrations, the main source category is traffic. Traffic represents 53% of contributions to NO_x concentrations (while accounting for 39% of emissions). The role of large point sources is smaller for concentrations than for emissions (30% and 50% respectively).

For particles, it is especially important to bear in mind that only combustion sources have been included in the calculations. Sources of coarse particles, such as resuspended dust from streets and from construction, are not included so far. The largest contribution to concentrations, or almost 70%, comes from large point sources. Traffic is not important for particles, while small point sources contribute 18% to concentrations.

3.3 Observed air quality

In Guangzhou there are 37 manual air quality monitoring stations and 6 automatic stations. Obviously, the air quality differs from location to location. If we look at the data from the automatic monitoring stations, the status of the air quality in 1995 can be summarized as follows[2]:

The average SO_2 concentration (annual average) for all stations is 0.059 mg/m^3; values for individual stations range from 0.045 to 0.075 mg/m^3. For the maximum daily average concentration, the average for all 6 stations is 0.240 mg/m^3, varying between 0.169-0.317 mg/m^3.

For NO_x the average annual concentration is 0.127 mg/m^3 (average for all 6 stations), and varying between 0.065- 0.238 mg/m^3. The maximum daily average for all 6 stations is 0.725 mg/m^3, varying between 0.340-1.625 mg/m^3.

Finally for TSP, the annual average concentration is 0.306 mg/m^3 (average for all 6 stations), and varying between 0.218-0.402 mg/m^3. The maximum daily average for all 6 stations is 0.906 mg/m^3, ranging between 0.580-1.396 mg/m^3.

These data can be compared with the air quality targets for Guangzhou, which is done in chapter 4 below.

The *observed* levels correspond quite well with the *calculated concentrations* of SO_2 which result from using data on emissions, stacks, traffic and fuel use. Calculated NO_x values are somewhat lower than observed levels, while for TSP, the calculated concentrations are well below the observed or measured levels of TSP, since coarse particles sources are not included in the calculations. This question is further dealt with in section 3.7 below.

3.4 Beyond the source categories: Large individual point sources

In the preceding paragraph we concluded that large point sources is by far the most important source category for SO_2 and combustion particles concentrations, and also that large point sources are important for NO_x concentrations although traffic is the main problem regarding NO_x concentrations. Large point sources are important for particles concentrations, however, they are *not* giving the dominant contribution to TSP which also include coarse particles (see above).

A quick look into the data contained in the emission inventory reveals that a rather limited number of sources are responsible for significant parts of the current concentration levels of the different pollutants. As an example, we have identified 17 individual sources for SO_2, 20 sources for NO_x and 12 sources for particles. The 17 sources are responsible for roughly 50% of the contributions to SO_2 concentrations. For NO_x, 20 individual sources represent 12% of all contributions to concentrations (should be adjusted up according to new NO_x emission factors). With regard to particles, 12 single sources account for more than 40% of combustion particles concentration contributions in the model area.

The main conclusion we can draw from this is that by focusing on a few selected sources, Guangzhou may achieve *large reductions* in both emissions and

2 See GZ AQMS task 4 (1998).

concentrations of SO_2 and combustion particles, but also significant reductions in NO_x levels. For TSP, the reductions will not be substantial because combustion particles represent a rather limited share of TSP concentrations. For NO_x, improvements in NO_x concentration levels must address traffic. Focusing on the few large sources will also *reduce the overall costs* of achieving improvements in air quality compared to a more general or sector-wise approach since the investments or pollution control measures can be targeted towards a limited number of sources. Last, but not least, such an approach is *far easier to implement and enforce in an effective manner* than an alternative approach considering hundreds or thousands of different sources.

3.5 Impacts

The various types of health effects that are connected to air pollution are often rather common. It is difficult to assess to which extent the frequency of an effect is enhanced due to pollution or not, and subsequently to which extent air pollution reductions would lead to reduced health damage. By means of dose-response functions based on studies in China, Europe and the U.S.A., task 6-1 has made some preliminary estimates of the health effects that may be attributed to air pollution in Guangzhou at present. Table 3.3 renders the numbers of these «excess» cases for the various health effects, or «endpoints». The estimates are obtained by combining the dose-response functions and the population weighted exposure level in 1995. The exposure estimate is based on calculations by the KILDER model. The dose-response functions are given in the Task 6-1 Report «Health damage assessment for Guangzhou - using exposure-response functions». Information about baseline frequencies of health effects in Guangzhou are incorporated in the functions. The estimates should be regarded as tentative and only serve as rough indications of the present excess number of cases.

Table 3.3 Estimated annual cases attributable to air pollution in Guangzhou, calculated for 1995.

	Central	Low	High
Number of premature deaths	1420	1010	1800
Infant deaths	190	110	240
Outpatient visits (mill. cases)	1.2	0.5	2.0
Emergency room visits (cases)	14,700	4,010	25,390
Hospital admission (cases)	25,920	17,370	32,340
Work day losses (mill. cases)	4.9	2.5	7.4
Acute respiratory symptoms in children (mill. cases)	5.7	3.8	8.7
Acute respiratory symptoms in adults (mill. cases)	7.6	5.6	9.5
Chronic respiratory disease in adults (cases)	9,180	7,810	10,550
Asthma attacks (mill. cases)	0.47	0.26	1.56

[1] Based on PM_{10} functions, except for premature deaths, where the SO_2 function is applied and a threshold level for effect of 40 $\mu g/m^3$ is assumed (see Task 6-1 Technical Report)

Even taking into account the considerable uncertainties associated with these numbers, it is rather evident that Guangzhou and its population pay a heavy price for its present levels of air pollution. Over 1600 excess deaths, 1.2 mill. additional cases of outpatient visits and 26,000 cases of hospital admissions, and 470,000 additional asthma attacks *per year* are quite disturbing numbers and illustrate the potential for improving the welfare of the population by reducing the air pollution.

As a comparison, the total number of annual deaths in Guangzhou (8 central districts) is about 22,500, and the annual number of outpatient visits, emergency room visits and hospital admissions are 30.1 mill., 1.9 mill., and 0.34 mill., respectively.

3.6 Policies and regulations

The main legal basis for air pollution regulations and policies in China and Guangzhou are the Environmental Protection Law (EPL) and the Air Pollution Prevention and Control Law (APPCL). The legal, political and organizational basis for air pollution control has evolved rapidly in China and has, in a formal sense, reached a relatively high degree of sophistication and complexity. In the following, the main traits and components of the existing policies and regulatory system are described. A more detailed description and discussion can be found in GZAQMS task 10 (1999a; 1999b and 1999c)

A key element of air pollution policies in China is the air quality standards. The quality standards are formulated for a set of pollutants and varies according to the functional district (class), e.g. whether the area is intended for residential or industrial use.

Another basic building block for air pollution control of point sources is the *emission standards* for different kinds of activities, expressed as limits which emissions should not exceed and often specifying minimum stack heights. One weakness of the emissions standards is that they are not strictly binding as emission standards normally are in other countries. If emissions are found to exceed these limits, factories will have to pay a *pollution charge* according to how much the limit is exceeded. The only exception is for SO_2, where the charge applies to all emissions no matter the standard. The main weakness of this system is that the pollution charge levels are too low to stimulate any additional abatement, since it is cheaper to pay the pollution charge than to invest in abatement measures. Currently the relevant pollution charges are: SO_2: RMB 0.2/kg (RMB 200/ton), dust: RMB 0.02-0.1/kg (RMB 20-100/ton) and soot: RMB 3-6 per ton fuel. Later in this document, it will become evident that the pollution charge levels are far too low to stimulate any measures that could significantly reduce the air pollution concentrations.

Another weakness is that the pollution charge system is practiced in such a way that the charge is only collected for the pollutant which exceeds the standard by the highest rate, also when standards are exceeded for several pollutants. This means that exceeding emissions of particles are «free» in cases where pollution charge for SO_2 is collected, and vice versa.

Air emission standards in China have traditionally focused on smoke and dust emissions, but in the 1990s, SO_2 and later NO_x have also been included for some new sources. In general, standards are stricter for new and recent sources than for older sources. Emission limits also vary according to the location of the source (functional area). Apart from emission standards, Guangzhou has also introduced regulations on the maximum sulfur content of the coal that is being used.

A fourth key feature of the air pollution control system is what is called «*treatment within a prescribed time*». This system means that the local government regularly elaborates a list of the most polluting factories which must achieve their corresponding emission standards within a fixed deadline. If they are not able to reach the standards, they will have to close down their operations. A fifth system is the *Environmental Impact Assessment* (EIA) of new projects over a certain size (or expansion of existing facilities). Construction of a project may not be initiated (or approved) before the EIA has been finalized and approved. A sixth feature is the system of what is called the «*three synchronizations*». It stipulates that equipment for pollution control and prevention must be designed, built and commissioned in parallel with the main construction project.

The seventh feature which is gradually being introduced is the system of *individual discharge permits*. The emission standards mentioned above are of a general nature, that is, they apply to an activity (e.g. cement production in general), even though the size and/or age of the installations, properties of the fuel used, etc. are taken into account. The permits however, are designed for each specific source setting a limit on the total emissions of a pollutant from the source, whereas an emission standard is expressed as maximum concentration of a pollutant in the waste gas.

There is also the system of *central pollution control* which aims at reducing pollution control costs for small and medium sized units by setting up a central unit which delivers e.g. heat or steam and in which the waste gas can be treated at a much lower (total) cost than if each of the small units were to undertake this individually. An example of this approach is the development of the town gas system which supplies the household and commercial sectors with gas produced from coal. This centrally produced gas substitutes the previous widespread and highly polluting use of coal.

Finally, the system of «*target responsibility*» should be mentioned. This is a mechanism that seeks to hold the heads of local governments (e.g. the mayor) responsible for fulfilling environmental objectives and through this push environmental issues higher up on the political agenda. In this connection, the objective of being an *environmental model city* should be mentioned. The national environmental authorities have formulated a set of requirements that should be fulfilled if cities want to classify as a model city. On the of the requirements is the fulfillment of air quality standards for SO_2, NO_x and TSP in class 2 areas (see chapter 4).

With respect to mobile sources, the air pollution regulations are also quite complex, including emission related *product standards* for new vehicles and a mandatory system for *annual testing* of used vehicles where emission levels are controlled. Guangzhou standards follow the respective national standards. There are also regulations for scrapping of old vehicles, restrictions on the issuance of new MC licenses, regulation of fuel quality (lead content of gasoline) as well as restrictions on when and where certain kind of vehicles (such as MCs) may circulate and other traffic management measures. Other policies aiming at reduced air pollution from mobile sources include road construction to increase road capacity and reduce congestion, expansion of the public transport system such as the construction of metro lines, and encouraging the use of alternative fuels for taxis and buses.

3.7 Shortcomings and uncertainties

The Guangzhou Air Quality Management Strategy Project is comprehensive. It seeks to integrate all major aspects of air pollution management, covering the whole chain from emissions of pollutants and their dispersion, the exposure of people, material assets and vegetation to air pollution and the impact of this exposure. It seeks to identify technical control options to reduce emissions and exposure as well as quantify the associated costs and benefits if these options are implemented, and finally, to explore what kind of policies and regulations that best could facilitate or support the implementation of such control options. There will always be uncertainties related to each component.

On the other hand, uncertainties and shortcomings can never be eliminated. By and large, we feel that an exercise such as this represents a considerable advance in understanding air pollution in Guangzhou and how it best can be addressed. Nevertheless, we should point to the most important limitations of this approach and how it has been applied in the Guangzhou context:

- The data in the emissions inventory are based upon questionnaires filled in by personnel at each source and upon data on fuel use and traffic. If input data does not reflect the actual situation, this will necessarily affect the quality of the output.
- This can be illustrated in the following simple example: if data suggest that sulfur content of coal used is 1% and actual sulfur content is 1,5%, the reduced emissions and contributions to concentrations from switching to low sulfur coal (e.g. 0,5% sulfur) will be underestimated. Next, if the reduction of SO_2 by using low-sulfur coal is underestimated, this will be the case for health improvement and entailed economic benefit as well. Likewise, if data on existing cleaning efficiencies for particles are reported to be lower than they actually are, the estimated reductions of emissions and in contributions to concentrations will be exaggerated. Thus, the estimates of health improvements and entailed economic benefits will also be exaggerated.
- We have only to a limited extent been able to consider *process emissions* since few emissions data are available. Process emissions are emissions which are not related to energy use.
- Based upon the data on traffic, point source emissions, stacks and fuel use, the model estimates concentration levels that are fairly well in line with observed concentrations for SO_2 and NO_x. For particles however, the modelled concentration levels are well below the actually measured levels. This is due to several factors. Important factors could be: First, the fact that the model does not include emissions from construction activities, a factor that most probably is quite significant in a high-growth city like Guangzhou. Second, particles from transport of building materials could contribute to particles concentration levels, and this is not included in the model. Neither

are emissions from agricultural activities included. Third, and probably quite important, heavy particles that fall down could be resuspended due to traffic (or wind speed increase).

- There are inherent difficulties in measuring health effects, since a whole range of background and health status variables need to be controlled for. Problems connected to transferring risk estimates from one population to another, ad to this difficulty. For instance, the composition of the car fleet in Western Europe and the U.S., where most of the epidemiological studies have been performed, differs substantially from that in China. There are also fundamental differences in the use of coal, overall health status, age distribution in the population etc. between China and USA/Europe, as well as somewhat more negligible differences between the main study region in China (Beijing) and Guangzhou.
- The main rationale behind the Guangzhou Air Quality Management and Planning Project has been knowledge transfer and capacity building. Thus, the overall purpose of the work related to this document has been to *show how concepts and methodologies can be applied and used for developing rational action plans for air quality improvement*. Less effort has been put into checking and verifying all details which serve as input data for such a plan. Even though we have tried our best to check the quality of the data and information, actual errors might well occur.

4 Targets

Guangzhou city government has expressed its ambition to become an environmental model city. One of the criteria for achieving the status of an environmental model city is the air quality. In short, Guangzhou needs to achieve the air quality standards of class 2 areas for its central urban area. The air quality targets which Guangzhou has set for itself require that the *daily average concentrations* of SO_2, NO_x and TSP in the central urban area of Guangzhou do not exceed the limits shown in table 4.1 below. In addition, the annual average concentrations of SO_2, NO_x and TSP must not exceed limits which are given in the table below. In a previous section we summarized the data for the air quality status in 1995 and these numbers are shown in brackets.

Table 4.1 Guangzhou air quality targets to be achieved by 2001, mg/m^3. Air quality status (1995) is shown in brackets.

	SO_2	NO_x	TSP
Maximum 24-hour average	0.15	0.1	0.30/0.25
	(0.169-0.317)	(0.340-1.625)	(0.580-1.396)
Annual average	0.06	0.05	0.20
	(0.045-0.075)	(0.065-0.238)	(0.218-0.402)

The target value for SO_2 in the table above is pretty much in line with corresponding international air quality guidelines such as the EU or the WHO. The same holds basically true for TSP. For NO_x, the Guangzhou targets are rather ambitious by international standards. Guangzhou target for 24-hour NO_x average is 0.1 mg/m^3. The corresponding WHO guideline for NO_2 is 0.150. If it is assumed that NO_2 accounts for 30% of the total NO_x concentration, the implicit WHO guideline for NO_x would be 0.5 mg/m^3, or 5 times higher than the Guangzhou limit for maximum 24-hour average[3]. Thus it could be asked whether the NO_x targets are too strict and whether the potentially high costs of achieving these will be justified by the benefits, or if these resources would yield more benefit if they are used in alternative ways.

Acknowledging that this is basically an issue to be resolved by the political authorities of Guangzhou, we leave this aside for the moment and proceed to the

3 Guangzhou measurements indicate a much higher NO_2/NO_X ratio than what is usually reported internationally. In Guangzhou the ratio is reported to be 50-75% (NO_2's share of NO_X-concentrations).

question of how large air quality improvements (from 1995 level) are needed to reach the targets. This is not a straightforward question to answer, since concentrations differ significantly from area to area. In table 4.2 below, we have calculated the *range* of relative changes needed for each substance and air quality target indicator (max 24-hour average and annual average). The range is given by the measured concentration at the automatic monitoring stations with the highest and lowest levels. In the table, we have excluded the value for NO_x at one of the stations (GEMC traffic station) because it is the only station located near a major traffic source, giving substantially higher NO_x values than the other stations. If this station had been included, the necessary improvements for NO_x would have been even higher than indicated in the table.

Table 4.2 Necessary improvements in air quality from 1995 levels to reach 2001 targets (reduced concentrations).

	SO_2	NO_x	TSP
Annual average	0 - 20%	23 - 62%	8 - 50%
Max 24-hour average	11 - 52%	70 - 87%	48 - 78%

As can be seen from the table, large improvements are required for all of the pollutants included and the largest improvements are required for NO_x. Also, the required reductions are significantly larger for maximum daily average than for the annual average.

5 Control Options

5.1 Introduction

In this section a set of defined options to reduce concentrations of SO_2, NO_x and TSP in the model area is analyzed.

The objective is to identify a package of practically feasible air pollution control options that will achieve the targets for air quality in 2001 at lowest possible cost for society (Guangzhou) as a whole.

The process for selecting «candidate options» included the following steps:

1. First a wide set of possible control options were identified.
2. Second, we narrowed down this set of options by analyzing the potential reduction of concentrations that can be expected when each option is implemented and selected those options with greatest reduction potential. Each option was classified as A, B or C option. An A-option may reduce the concentration of one (or more) of the pollutants by more than 25%, B-options between 5-25%, and C-options less than 5%.
3. Third, we also include some other options which are already being undertaken by the Guangzhou authorities. The main purpose of including these options has been to illustrate how the analytical and technical tools of the Guangzhou Air Quality Management project may be utilized for *evaluation* of past or present policies.

The next step then is to identify a package of options that may achieve the targets at lowest costs, i.e. in a cost-effective way. Thus each option needs to be classified in terms of its unit cost. In traditional cost-effectiveness analysis, the unit cost is usually expressed in terms of *costs per ton reduced emission* of a pollutant (e.g. RMB 2000 per ton SO_2 reduced). In this Action Plan we strive to calculate the unit price in terms of *costs per percentage point reduced concentration* and/or population exposure of a pollutant. The objective is to rank the different options in terms of costs per percentage point reduced concentration of a pollutant and to calculate their potential for reducing concentrations.

Many options that will be examined in the following carry substantial investment costs. These investment costs will be important for the calculation of cost per ton air pollutant removed. So the method for converting total investment costs into annual capital costs has to be explained. This is done in the following section before we start examining the individual SO_2 control options.

5.2 The annual cost of a capital investment

Several of the control measures includes an investment cost that is incurred once. To compare the investment cost to an annual reduction in emission we transform the investment cost into an equivalent annual cost called the *user cost of capital*. The relation between investment cost and user cost is the following:

$$c = (r + \delta)p$$

where c is the user cost of capital, r is the interest rate, δ is the depreciation rate and p is the investment expense. $(r+\delta)$ is in other words the conversion factor between one-time investment cost and annual cost. There are two ways of arguing why the conversion factor consists of these two elements.

The informal argument

The intuitive argument says that when one decides to make an investment (in pollution abatement or something else) one gives up the interest income that the investment fund would have generated in a bank. Or, if one takes up a loan equal to the investment, one pays interest on that loan. From an economic perspective it does not matter whether one gives up a potential interest income or pays an actual interest, the economic cost is the same. The annual cost of interest payment (or interest income forgone) is

annual interest cost = rp

(recall that r is interest and p is investment expense). The interest cost makes up one part of the overall annual cost. The other part consists of spreading the investment cost over the life time of the machine (ignoring, for the moment, the interest). The spread over time is guided by what we call depreciation. All capital equipment depreciates over time, meaning that it functions less well. Abatement equipment, for instance, has a limited life-time and functions less well over time. *How fast* the equipment depreciates – geometrically, linearly or some other way – depends on the circumstances. A convenient assumption is geometrical depreciation, that is a fixed percentage of the equipment is depreciated each year. The annualized cost of the investment expense is then equal to the percentage that is depreciated:

annual depreciation cost = δp

The sum of depreciation and interest gives us the annual user cost $c=(r+\delta)p$ as indicated above. If the interest rate is 8 per cent, as is the recommendation for municipal infrastructure projects in Guangzhou, and the depreciation rate is 7.9 per cent, the user cost correction to the investment cost is 15.9 per cent. 7.9 per cent depreciation allowance corresponds to 20 years life time in the sense that the discounted value of depreciation allowance is equal to that of 20 years linear depreciation.

The formal argument

The formal argument looks at the investment decision concerning some abatement equipment (say) of size K and purchase cost pK that yields an improvement in emissions $E(K)$. The costs and effects characterizing this investment decision is

$$- pK + \int_0^{\infty} E(Ke^{-\delta t})e^{-rt}\,dt$$

The initial cost is $-pK$ and the gross benefit in terms of emission reductions is the integral of discounted, instantaneous benefits over the life-time of the equipment. Note that we maintain the assumption of a constant depreciation rate. We also assume a constant interest rate.

A small change in investment, say an additional piece of abatement equipment, is denoted dK and has the following effect on emission reduction and costs:

$$(-p + \int_0^{\infty} E'(K)e^{-(r+\delta)}dt)dK = (-p + \frac{E'(K)}{r+\delta})dK$$

The second of these equations can be rearranged to state the relation between the annual (instantaneous) emission reduction and its annual cost:

$$E'(K) = (r+\delta)p$$

This is the same formula as above.

Box 5.1 Some frequently asked questions.

Q: Why is the forgone interest income *rp* constant over time when there is compound interest?

A: Because compound interest is related to how one spends the interest income. That is a different decision that carries its own costs and benefits. If one chooses to save it in the bank, there will be interest on that saving. If one spends it differently, eg., purchases abatement equipment, there is a cost in the form of forgone interest income. We shouldn't attribute the costs of that new saving decision to «our» decision.

Q: Why is the forgone interest income constant over time and remains even when the loan is paid back?

A: Because the decision to pay back is a saving decision that carries its own costs and benefits. Saving via repaying a loan earns interest in the form of lower interest payment on the loan. The interest payment is due to the saving decision and shouldn't be attributed to «our» decision. (Note the symmetry with the preceding answer). Another way to look at it is this. If one purchases abatement equipment, the expense is stuck in a non-interest bearing asset forever. It is stuck there regardless of the repayment schedule of the loan.

Q: Why is a life time of 20 years and linear depreciation equivalent to 7.9 per cent annual geometric depreciation? Shouldn't it be 5 per cent?

A: With a life time of 20 years and linear depreciation the depreciation rate is 5 per cent the first year. Thereafter it is rising as the basis of depreciation allowance declines. The last year it is 100 per cent.

Q: Why is a life time of 20 years and linear depreciation equivalent to 7.9 per cent annual geometric depreciation? Given 7.9 per cent almost a quarter of the equipment is alive after 20 years!

A: 7.9 per cent is chosen to equal the *discounted* value of depreciation allowance (using a 8 per cent interest rate). The discounted value puts heavy emphasis on the first years of the life time. Since 7.9 is larger than 5 the depreciation allowance is larger the first years, and smaller thereafter.

5.3 SO_2 options

For SO_2 we will examine the following control options:

- Sorbent injection - large point sources
- Shut down of small power plants
- Shift to low sulfur coal
- Wet flue gas desulfurization in the largest point sources
- Fuel switch for taxis - from gasoline to LPG
- Fuel switch for buses - from diesel to LPG
- Cogeneration in 8 industrial facilities
- Fuel switch third industry
- Moving 20 factories

5.3.1 Sorbent injection (duct or furnace injection)

Sorbent injection is a simple technology for SO_2 removal for power plants and industrial boilers. Sorbent injection may be done through different processes. Sorbent may either be injected directly into the furnace (furnace injection), or into the duct (duct injection). Then there are several «hybrid» alternatives where 1. Sorbent is injected both into the furnace and the duct; or 2. sorbent is injected into the furnace and then later reactivated by humidification in a reactor, or 3. furnace injection where unreacted sorbent is separated and removed in the electrostatic precipitator and then reactivated and recycled.

$CaCO_3$ or $Ca(OH)_2$ are two common sorbents. The cleaning efficiency of this option depends first of all on the ratio between Ca and S. A higher ratio will result in a removal efficiency, though sorbent costs will increase with higher ratio. The main advantage of sorbent injection is the simplicity of the technology. Other advantages of sorbent injection compared to other options such as flue gas desulfurization, are low capital costs, low maintenance costs and low power consumption (0,5%). The efficiency of furnace injection is normally between 30-60%, while duct injection achieves between 50-70%. Hybrid systems may achieve efficiencies between 80-90%. Retrofit of SI is most realistic for units up to 300MW.

Concentrations reduction potential

It has been estimated that SO_2 emissions could be reduced by 40,000-50,000 tons per year and that concentrations could be reduced by 25% if SI is applied on *all power plants and other major industrial point sources* ("POI 50 = all sources with emissions over 50 kg/h). These sources are listed in Annex 1. In this calculation it is assumed that emissions from each individual source where SI is applied will be cut by 50%, even though, as indicated above, higher efficiencies are feasible.

Costs

The costs of SI processes vary quite significantly between different sources. World Bank (1997b) indicates that the cost effectiveness ratio of a new furnace or duct sorbent injection on a *new* installation will be around RMB 4000 per ton and closer to RMB 6000 per ton for *retrofit* of a hybrid system on an existing power plant. In a feasibility study for Guangzhou Paper Making Factory a hybrid process with a cleaning efficiency of 83% was estimated to have of cost of RMB 1490 per ton SO_2 removed (new installation). In this case, however, it is not clear how the total capital costs of 65 mill. were spread over time. A Chinese survey of costs of different SO_2 removal options concluded that furnace sorbent injection would have a cost effectiveness between RMB 790-1290 per ton removed (Hao Jiming 1998). Thus, the Chinese studies seem to report lower costs than for example World Bank (1997b).

We believe much of this variation in costs is produced by making different assumptions in the calculations, particularly so for capital costs and how total capital costs are turned into annual capital costs. Given this wide variation, it seems appropriate to try to compare the data in different sources by applying equal assumptions and thus have a clearer understanding of the costs. We will do this by applying the different cost data for applying sorbent injection for SO_2 removal from *existing* power plants and major industrial sources. First we will use the Guangzhou power plant (200 MW) as one example (box 5.2), then we will make another calculation for power plant at Guangzhou nitrogen fertilizer factory (box 5.3). Both are important sources for SO_2 emissions and concentrations, but the Guangzhou power plant has smaller SO_2 emissions per MW installed than the fertilizer factory. In each example we first use Chinese cost data, then two different sets of cost data from international sources, a high cost estimate and low cost estimate. Finally, we compare these numbers with numbers from a feasibility study for Guangzhou Paper Making Factory where sorbent injection is currently being installed (box 5.4).

Box 5.2 Estimating sorbent injection abatement costs in Guangzhou Power Plant.

Chinese cost data:

Capital cost for sorbent injection is reported to be RMB 212 per kW (Environmental Protection 1998). The total capital cost for a power plant like Guangzhou power plant will then be

RMB 212 per kW x 200,000 kW (200 MW) = RMB 42,4 mill.

The annual capital cost is RMB 42.4 mill. x 0.159 = RMB 6.74 mill. assuming 20 years lifetime and 8% interest rate. The factor of 0.159 is explained above

In addition there will be operating and maintenance costs (O&M) which include sorbent material, power, water (in some hybrid processes), salaries, repair, etc, which are reported to be RMB 9.12 mill. per year for a 100 MW plant. Assuming linearity, this would constitute RMB 18.2 mill. for a 200 MW plant like Guangzhou power plant. Thus total annual costs will be RMB 24.94 mill.

The emissions inventory reports that 1995 emissions of SO_2 from Guangzhou power plant were 10,281 tons. If the cleaning efficiency is 50%, 5,140 tons of SO_2 will be removed. If cleaning efficiency is 70%, 7,200 tons will be removed. The cost effectiveness ratios are found by dividing the total annual costs by these quantities: *RMB 4,850* per ton SO_2 (50% removed) and *RMB 3,470* per ton SO_2 (70% removed). We would assume that the latter is the most realistic assumption in this case.

International data*:*

International cost estimates we have come across vary a lot. World Bank (1997b) reports capital costs for retrofit of furnace sorbent injection on existing installations to be closer to RMB 800 per kW (US$ 100). However, information gathered from an international supplier like ABB, indicates significantly lower costs, roughly US$ 15 per kW[4]. By first applying the estimates from World Bank (1997b) on a 200 MW plant like Guangzhou power plant, capital costs would constitute RMB 160 mill., or 25.4 mill. per year (160 mill. x 0.159). Annual fixed operating and maintenance costs (O&M) are reported to be RMB 48 per kW, or RMB 9.6 mill. In principle variable O&M costs should be added, but these are very small - RMB 0,02 per kWh - and can be neglected. Total annual costs would then be RMB 35.04 mill., which is approximately 40% higher than the costs above based upon Chinese data. Thus, the cost effectiveness ratios will also be approximately 40% higher, or *RMB 6,820 per ton in the case of 50% cleaning efficiency, and RMB 4,870 per ton if 70% cleaning efficiency* (here and in the following we use the term «high» cost effectiveness ratio when costs per ton are high and "low" C/E ratio when costs per ton are low).

Alternatively we may assume that capital costs for SI are US$ 15, or RMB 120 per kW. Additional filters for particles removal (electrostatic precipitators – ESP) which are needed would bring costs up to US$ 30 (RMB 240) per kW. This would constitute an annual capital cost of 200,000 kW x RMB 240 x 0.159 = RMB 7.63 mill. On top of this, we should add annual O&M costs for sorbent injection and electrostatic precipitators of RMB 88 per kW (RMB 17.6 mill.). Total annual costs would be RMB 25 mill. Costs per ton SO_2 removed are RMB 4,910 when 50% of the SO_2 is removed (RMB 25 mill./5140 tons) and RMB 3,510 when 70% is removed. In addition, TSP emissions will be significantly lower due to the installation of ESP; and if the costs were to be allocated both to SO_2 and TSP, the cost effectiveness ratio would be lower.

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4 Personal communication, Gõran Wickstrõm, ABB (Vãxsjo, Sweden).

Box 5.3 Sorbent injection abatement costs in Guangzhou Nitrogen Fertilizer Factory.

Chinese data:

The power plant at this factory has an installed capacity of 24 MW. The 1995 emissions of SO_2 were 2,654 tons. Total capital costs would be RMB 212 x 24,000 kW = RMB 5.088 mill. This would constitute an annual capital cost of RMB 5.088 mill. x 0.159 = RMB 809,000, assuming 20 years lifetime and 8% interest rate. Annual O&M costs would be 24,000 kW x RMB 91.2/kW = RMB 2.2 mill. Total annual costs would be RMB 3.0 mill.

If the SO_2 removal efficiency is 50%, the reduced emissions of SO_2 would be 1327 tons, and the cost effectiveness ratio would be RMB 3.0 mill. / 1,327 tons ≈ *RMB 2,250 per ton*. If cleaning efficiency is 70%, cost effectiveness ratio is 2.99 mill. / 1,857 tons ≈ *RMB 1,610 per ton removed.*

International cost data (high estimate):

By using the high cost estimate from World Bank (1997b) we get the following calculation for GZ Nitrogen Fertilizer Factory:

Annual capital costs: 24,000 kW x RMB 800 per kW x 0.159 = RMB 3.05 mill.

Annual O&M costs: 24,000 kW x RMB 48 = RMB 1.15 mill.

Total annual costs: RMB 4.2 mill.

Cost effectiveness if 50% removal: RMB 4.2 mill./1,327 tons = *RMB 3,170 per ton*

Cost effectiveness if 70% removal: RMB 4.85 mill./1,857 tons = *RMB 2,260 per ton*

International cost data (low estimate)

By using the low cost estimate from ABB and add ESP costs, we get the following calculation:

Investment cost: RMB 120 per kW + ESP capital costs = RMB 240 per kW

Annual capital costs: 24,000 kW x RMB 240 per kW x 0.159 = RMB 916,000.

O&M costs: 24,000 kW x RMB 98 per kW per year = RMB 2.11 mill.

Total annual costs: RMB 3.02 mill.

Cost effectiveness ratio (50% SO_2 removal): RMB 2,280 per ton

Cost effectiveness ratio (70% SO_2 removal): RMB 1,630 per ton

If costs are allocated to TSP also (TSP emissions will be reduced with ESP), the cost effectiveness ratio will be further improved.

Box 5.4 Sorbent injection abatement costs, Guangzhou Paper Making Factory.

Guangzhou Paper Making Factory

As mentioned above, a feasibility study has been undertaken for the Guangzhou paper making factory where duct sorbent injection was one of the options considered, and the option that were selected, for SO_2 removal[5]. This option is undertaken on the *new* boiler systems that are being installed. The feasibility study concluded that the cost of SO_2 removal would be RMB 1,490 per ton. It is not clear however, how the total capital costs of 65 mill. were calculated into annual capital costs. It has been indicated that the unit investment cost in this case is RMB 330 per kW, implying that the combined capacity of the 3 boilers is equivalent to approximately 200 MW.

A total capital cost of RMB 65 mill. would constitute an annual capital cost of RMB 10.3 mill. if we use the same assumption as in the two previous examples. In addition, the annual O&M costs in Guangzhou paper making factory are reported to constitute RMB 16.4 mill. Total annual costs related to the duct sorbent injection will then be RMB 26.7 mill. The feasibility study states that planned SO_2 removal will be 83% or 1428 kg/h. The planned coal consumption is 2300 tons per day. If this is 1% sulfur coal, and if the factory is run 6000 hours a year, a rough approximation of the potential SO_2 emission is 11,250 tons per year (assuming that 100% of the sulfur will form SO_2). If 83% of the SO_2 will be removed, it means that 9,335 tons of SO_2 will be removed annually. The cost effectiveness ratio would be 26.7 mill. / 9335 tons = RMB 2,860.

Conclusion

The cost of removing one ton of SO_2 through furnace sorbent injection varies from RMB 1,600 to RMB 6,870 in the cases we have covered here. Using high international cost estimates results in cost effectiveness ratios that are roughly 50% higher than the ratios resulting from using Chinese data and low international cost estimates. The option is, quite obviously, more economic for units with high SO_2 emissions per MW installed capacity than for units with lower SO_2 emissions per MW installed capacity.

Chinese sources report cost-effectiveness ratios of sorbent injection to be approximately RMB 800-1200 per ton, but we are not sure about the assumptions underlying these estimates. When we later in this document compare the cost effectiveness ratios of different options, we will consider RMB 2000-2500 per ton SO_2 as a representative ratio for this option. At the same time it should be emphasized that the real cost could well be higher or lower, depending on plant characteristics, assumptions used and other factors.

5.3.2 Shut down of small power plants

In Guangzhou there is a considerable number of small power plants which have high emissions per unit electricity produced compared to the larger units. At the same time, the big units with cleaner production are only utilizing parts of their capacity, even though production costs are lower in these units than in the small

5 Guangzhou Paper Making Factory: EIA report. (In Chinese).

units. The reasons for this are mainly due to institutional and regulatory characteristics of the electricity market, but these facts make little sense from an environmental and economic point of view.

One option that could be beneficial both in terms of air quality and in direct economic terms would therefore be to shut down the small, highly polluting and inefficient units and instead increase capacity utilization at the big, cleaner and more economically efficient units, or, if necessary, increase imports from the provincial network. Such an option is very attractive since the required additional investments are very limited and restricted to some upgrading of local distribution lines (see below).

One alternative could be to shut down all units with installed capacity of 200 MW or less. In Guangzhou this would constitute a group of 18 power plants, see Annex 4. The total energy consumption of these 18 plants is 3.2 mill. tons, most of it bituminous coal («smoke coal») and some heavy oil and diesel. In 1995 these 18 power plants emitted 48,000 tons of SO_2 per year, or almost half of total estimated emissions from *all large point sources*. Their combined particles (smoke dust) emissions were 52,000 tons, representing approximately 50% of total particles emissions from large point sources in the study area.

In terms of installed capacity, the total for the 18 plants is approximately 1,400 MW (1,392 MW). In 1995 total installed capacity in Guangzhou (regardless of ownership) was approx. 3,000 MW (GZAQMS task 8). Thus, the 18 plants represent approximately 45% of total installed capacity. After a shut down of small, highly polluting power plants, electricity will be have to be provided by the big power plants that have spare capacity today and possibly also from the provincial network. If importing electricity from provincial network, the costs of expanding transmission lines must be considered. Our information indicates that investments in transmission lines are already undertaken, but that there may be some need for upgrading local distribution lines.

Reduction potential

The first question to be answered is how much emissions could be reduced if big power plants are replacing production from small ones. That will depend on the emission factors for the big and small plants respectively. We may use Huangpu coal fired units as a representative for the big plants. Based on data from the inventory, the emission factor[6] of the Huangpu coal fired units has been calculated to *0.00693 ton SO_2 per ton coal* (12,733 tons SO_2 / 1,837,000 tons anthracite).

The coal fired units of Huangpu emit *0.00733 ton particles per ton coal burned* (13,480 tons particles / 1,837,000 tons coal), and for NO_x the emission factor is *0.00444 tons NO_x per ton coal*.

The power plants smaller than 200 MW consume 3,030,000 tons of coal, 104,000 tons of heavy oil and 141,000 tons of diesel. This is equivalent to 3,030,000 + 352,800 ≈ 3,383,000 tons of coal. Since we do not been able to get data on electricity production for individual plants, we assume that existing big power plants which replace production at the small power plants have the same efficiency and will have to burn the same amount of coal as the small ones in order to produce

6 Refers to actual emission per ton fuel (after cleaning).

the same amount of electricity. It should be emphasized that this is a purely technical assumption; most probably, big plants are more efficient than small plants. Let us further assume that the second of the two power plants larger than 200 MW (Zhujing Dianchang) has emission factors equal to the coal-fired units at Huangpu.

According to the emission inventory, the 18 small power plants emitted 48,021 tons of SO_2 in 1995[7]. Increasing coal consumption at big coal fired power plants with 3,383,000 tons will produce a partial increase of 3,383,000 x 0.00693 = 23,444 tons. Thus total reduction is 48,021 - 23,444 tons = 24,577 tons less SO_2.

According to the emissions inventory, the small power plants emitted 52,000 tons of particles. The emission factor for particles at Huangpu coal-fired units is 0.00733 tons particles/ton coal. Increasing coal consumption at big coal-fired power plants with 3,383,000 tons will produce a partial increase of 3,383,000 x 0.00733 ≈ 24,800 tons. Thus total reduction is 52,000 - 24,800 tons = 27,200 tons less particles.

By examining the emissions inventory, it can be found that total NO_x-emissions (1995) for 14 of the 18 smaller power plants were approximately 19,000 tons/-year. Assuming an average of 750 tons for the remaining four plants (diesel generators) gives a total of 22,000 tons. If small plants are shut down and consumption increased at big plants correspondingly, assuming an emission factor of 0.00444 ton NO_x/ton coal, the partial increase from big plants is: 3,383,000 x 0.00444 = 15,000 tons. The net reduction from closing down small plants will be: 22,000 – 15,000 = 7,000 tons NO_x.

Summing up: If Guangzhou authorities decide to shut down small power plants and the production is replaced by increased capacity utilization at big plants, it will result in 24,577 tons less SO_2, 27,200 tons less particles and 7,000 tons less NO_x. This would cut total SO_2 emissions by 17%, total NO_x emissions by 10%, and total particles emissions by 23%.

If instead the electricity «lost» from the small plants is imported from the provincial network, the reductions in local emissions will be higher: the emission reductions will be equal to present emissions from small plants: 48,000 tons SO_2 (33% of total emissions, all sources), 52,000 tons particles (44%), and 22,000 tons NO_x (31%). Obviously, these extra reductions of emissions in Guangzhou will lead to increased emission somewhere else outside Guangzhou.

Above we have assumed that efficiency in terms of electricity produced per coal unit input is the same in the big plants as in the small plants. We do not have detailed information on the energy efficiency of the individual plants. In reality however, efficiency is more likely to be higher in the big plants than in the small plants. Thus, the extra coal needed to compensate for loss of production in small power plants will be less than we have assumed above. Consequently, the emission reductions of closing down the small plants will be higher than the above estimates.

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7 Deducted from table presented by task 2 (March 1999).

Costs

It may be argued that the main attractiveness of this option is that, in the short term, no new investments are needed since the big and cleaner plants have spare capacity. On the other hand, it might be argued that closing down the small plants before the end of their technical life will be associated with capital costs since future investments in new capacity will be needed at an earlier stage than otherwise would have been the case. Proponents of the «zero cost» argument could claim that at close down after 15 years, the machinery will not have any economic value (impossible to sell) and that these capital costs are sunk and therefore can be ignored. We shall follow both lines of reasoning in box 5.5 below.

In both lines of reasoning we assume that variable production costs are equal in small and big plants. However, fuel costs will be lower in the big plants due to higher energy efficiency. We do not have detailed information on this matter, so we assume equal variable costs. Since big plants are more efficient than small plants, the estimates we end up with will be exaggerated (real costs will be smaller).

Box 5.5 Alternative cost assumptions, shut down of small power plants.

Alternative 1:

Assuming that the average age of the small plants is 15 years (put into operation in 1985), and that the economic lifetime of a plant is 20 years (World Bank 1997b), this option means that society decides to close down a power plant which otherwise could operate in 5 more years. If we assume that the investment costs for a new 100 MW-plant are equal to RMB 360 mill. (World Bank 1997b) the investment costs for 1400 MW capacity would have been 14 x 360 mill. = RMB 5,040 mill. This should be multiplied 1/4 because they have already served 3/4 (15 out of 20 years), and we end up with a lost investment of RMB 1,260 mill.

This amount will produce emission reductions of SO_2, particles and NO_x in each of the coming 5 years. Thus total reductions for the 5-year period are as follows: SO_2: 123,000 tons; particles: 136,000 tons; NO_x: 35,000 tons. If all costs are allocated to SO_2, the costs per ton SO_2 will be RMB 10,244. If all costs are allocated to particles, abatement costs will be RMB 9,264 per ton particles. If all costs are allocated to NO_x, abatement costs will be RMB 36,000 per ton NO_x.

Since the RMB 1260 mill. will produce simultaneous emission reductions of SO_2, particles and NO_x, it could be argued that it is not fair to allocate all costs to *one pollutant only*. The costs could be allocated to different pollutants according to some criteria. One way to do this is to assume that all three pollutants are equal. The shut-down will reduce SO_2, particles and NO_x emissions by 123,000 tons + 136,000 tons + 35,000 tons = 295,000 tons of air pollutants. Abatement costs will then be RMB 1260 mill. / 295,000 tons = RMB 4,270 per ton air pollutant (SO_2, NO_x or particles). Another alternative would be to spread costs according to external cost associated with each pollutant, e.g. SO_2 equivalent.

The estimate of RMB 4270 per ton assumes equal variable costs in small and big plants, which is quite certainly not the case. Allowing for lower variable costs in big plants will bring this estimate downwards.

Alternative 2:

An alternative approach is to assume that the capital equipment is fixed in a given plant and that capital costs are sunk. The machinery cannot be sold and its remaining value after 15 years is zero[8]. Alternatively one might consider the equipment as fully depreciated after 15 years. The extra net income that would have followed if it is operated after year no. 15 can be regarded as a bonus. Society's cost of closing down these fully depreciated plants will be the forgone net income from electricity sales during the remaining 5 years. However, since *gross income* will shift from small plants to large plants, this will not entail a social loss, except that the *net income* in the small plants might have been higher than it would have been in big plants, since big plants need to allow for depreciation of capital equipment. On the other hand, since big plants have income before they increase production, it might be argued that this initial income already has allowed for capital depreciation and that the net income will be the same in big plants as it would have been in small plants.

The consequence of this line of reasoning is that society will loose nothing as a result of closing down small plants and *that abatement costs therefore are closer to zero than to the estimate given above (RMB 4270)*. Factors that pull this estimate upwards to a positive cost could be extra investments in transmission and distribution lines. Factors that could turn it into a negative cost (saving) are superior thermal efficiencies and lower O&M costs per kWh in large plants compared to small plants.

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8 Another argument supporting the proposition that the remaining value of the capital equipment is zero is that it will not be possible to decommission the plant and sell the equipment. Such sales of old equipment is not compatible with present regulations.

The fact that the small plants are indebted, does not affect the calculation of social costs. This remains an important political question which needs to be addressed by the authorities, since the local governments/governmental branches which own the small and dirty plants will see their revenue decrease and may suffer problems servicing the debt they have incurred. But for society as a whole this is irrelevant, as the loss of revenue for the small plants are compensated by the higher income for the big plants.

Politically, this option will face two main challenges: first it could be in partial conflict with national policies on electricity production which emphasizes the need to increase total installed capacity in order to facilitate further economic growth. However, it is also a stated goal to shut down small inefficient units and replace them with new efficient units which could make such an option or a revised form politically more feasible. Second, this option could be hard to accept for the owners of the small plants, namely local governments or others on a lower administrative level than the city, who might be indebted and dependent on the cash flow from the electricity sales which are guaranteed by its local monopoly rights.

5.3.3 Shut down of power plants less than 150 MW

As we have seen, a major drawback of closing down power plants with installed capacity of 200 MW or less, is the fact that a large share of total installed capacity will have to be shut down (45%). If, as an alternative option, all power plants smaller than 150 MW are closed down, this will constitute 13 power plants with a combined installed capacity of 510 MW (instead of 18 power plants and 1400 MW capacity). The estimated 1995 emissions from the 13 plants were roughly 30,000 tons of SO_2, 12,000 tons of NO_x and 39,000 tons of particles. The 13 plants represented:

- 27% of SO_2 emissions
- 40% of particles emissions, and
- roughly 35% of NO_x emissions

from large point sources.

If Huangpu was to replace the production at these 13 plants, it would lead to partial increases of each of the air pollutants equal to the total coal consumption at the 13 plants multiplied with the Huangpu coal units emission factors. Total fuel consumption at the 13 plants is equivalent to approximately 1,950,000 tons bituminous coal[9]:

Partial increase of SO_2: 1,950,000 x 0.00693 = 13,500 tons

Partial increase of particles: 1,950,000 x 0.00733 = 14,300 tons

Partial increase of NO_x: 1,950,000 x 0.00444 = 8,700 tons (new NO_x emission factor)

9 Data gathered by task 2 (table, march 1999).

Net reductions will be:

SO_2: 30,000-13,500 = 16,770 tons per year, or 82,500 tons over 5 years

Particles: 39,000-14,300 = 24,700 tons per year, or 123,500 tons over 5 years

NO_x: 12,000-8,700 = 3,300 tons per year, or 16,500 tons over 5 years

Costs

The calculation of costs will be the same as in the preceding section. By following the reasoning in *alternative 2* in box 5.5, *the cost is zero*, or even negative when the fuel saving associated with shifting production from small inefficient to large more efficient plants is taken into account.

Alternatively, we might repeat the same calculation as we did under *alternative 1* above. This variant would entail a lost investment of 510 MW x 3,6 mill./MW x 5/20 years = RMB 460 mill. If the costs are allocated to each one of the three pollutants, the abatement costs would be:

SO_2: RMB 5,575 per ton

Particles: RMB 3,725 per ton

NO_x: RMB 27,880 per ton

If instead costs are spread evenly on each of the three pollutants, the costs wold be 460 mill./222,500 tons SO_2, particles and $NO_x \approx$ RMB 2,050 per ton.

Thus, by being a bit more selective when deciding which power plants to close down, the abatement costs is reduced by more than 50% from RMB 4,270 per ton to RMB 2,050 per ton.

All in all we would argue that the arguments for the zero cost estimate are the strongest.

5.3.4 Low sulfur coal (from 0.75% to 0.5% S bituminous coal)

Fuel switch involving a shift to coal with lower sulfur content is usually regarded as a low cost measure to reduce SO_2 emissions. Therefore, this option should also be considered for Guangzhou, as there are few practical constraints on the supply of low sulfur coal.

Reduction potential:

Even though the sulfur content in the coal consumed by industrial sources in Guangzhou can be assumed to be relatively modest by Chinese standards, shifting to low sulfur coal - defined as 0.5% sulfur – should be considered. Reducing the sulfur content from 0.75% to 0.5% in all coal consumed by the large point sources would mean that each large coal fired point sources (see Annex 1) will contribute 33% less to SO_2 emissions. Since large point sources is the main contributing source category, this implies a reduced concentration of SO_2 of approximately 20%.

Large point sources emit roughly 111,000 tons SO_2, of which approximately 88,000 tons stems from coal burning, the rest from heavy oil/diesel. Total coal consumption in all sources of POI 50 (sources with SO_2 emissions over 50 kg/h) is 7,736,000 tons. This implies an average sulfur content of close to 0.5% assuming that no SO_2 is abated. However, some SO_2 is cleaned, so it may be realistic to assume that sulfur content is in the order of 0.75%.

Of the 88.000 tons SO_2 from coal fired large point sources, approximately 75.000 tons stems from sources using *bituminous coal*. A 33% reduction from these sources imply a reduction of 25,000 tons SO_2.

Costs

The coal price differs according to quality of the coal. Coal with lower sulfur content costs more than coal with a higher sulfur content. In Guangzhou the price of bituminous coal is reported to vary from RMB 204 to RMB 300 while sulfur content varies between 0.5 and 1.5%. If this price variation is entirely due to difference in sulfur content, we may assume that bituminous coal with 0.75% sulfur costs RMB 275 per ton. The price difference between 0.75% and 0.5% bituminous coal is thus RMB 25 per ton. If it is assumed that bituminous coal with 0.75% sulfur is replaced with bituminous coal containing 0.5% sulfur, we can make the following calculation:

1 ton 0.75% sulfur bituminous coal will, without abatement, result in 15 kg SO_2

1 ton of 0.5% sulfur bituminous coal will, without abatement, result in 10 kg SO_2

The difference in SO_2 emissions is 5 kg per ton coal. This means that 200 tons of 0.5% coal will result in 1 ton less SO_2 than 200 tons of 0.75%. The corresponding cost per ton SO_2 will be 200 tons of coal x price difference = 200 x RMB 25 = 4,500. The cost of reducing SO_2 emissions by a switch to 0.5% sulfur coal (from 0.75%) is RMB 4500 per ton SO_2 reduced.

However, it is quite probable that only part of the price difference of RMB 25 per ton can be attributed to lower sulphur content. The rest may be attribute to lower ash content and higher calorofic value. We do not possess the necessary information to make a more accurate calculation, so the estimate above should be regarded as a higher range estimate. The real cost per ton will therefore be lower than the estimate above.

Abatement cost of switching from bituminous (0.75% S) to anthracite coal (0.5% S):

Much of the coal used by large point sources are bituminous coal, not anthracite. Bituminous coal is sold at a lower price than anthracite with the same sulfur content. Anthracite has a higher energy content than bituminous coal. For the coal qualities normally used in Guangzhou, approximately 5-10% more bituminous coal is needed compared to anthracite coal to produce the same amount of energy.

If a firm decides to shift from 0.75% sulfur bituminous coal to 0.5% sulfur anthracite coal, they will reduce their SO_2 emissions and at the same time reduce the coal quantity needed for producing the same amount of energy. They will face the following calculation:

1.075 tons of bituminous, 0.75% sulfur: 8 kg S

1 ton of anthracite, 0.5% sulfur: 5 kg S

This gives a difference of 3 kg S, equivalent to 6 kg SO_2

If the price for 1 ton of bituminous (0.75% sulfur) with 30% ash content is RMB 275 and the price for 1 ton of anthracite (0.5% sulfur) with 22% ash content is RMB 325 per ton, the abatement cost for SO_2 by switching to low sulfur anthracite will be:

(1 ton x 325 RMB/t) - (1.075 ton x 275 RMB/t) = RMB 29

RMB 29 / 6 kg SO_2 = RMB 4.9 per kg SO_2 = RMB 4900 per ton SO_2

Thus, the SO_2 reduction cost of switching from bituminous to anthracite is higher than switching between bituminous coals with 0.75% and 0.5% sulfur due to a larger price difference. However, if the energy content of anthracite is more than 7.5% higher than for bituminous, the SO_2 reduction cost will be lower than in the above calculation.

5.3.5 Wet flue gas desulfurization

Wet flue gas desulfurization (wet FGD) is a process which so far has had a very limited application in China, but which is the most commonly used end-of-pipe technology for SO_2-removal in western countries. The costs of wet FGD has decreased significantly, but it is still a capital intensive way to reduce SO_2 emissions. This is the main barrier against the wider application of the technology in many developing countries. The main advantages of wet FGD is the very high SO_2 removal efficiency (over 90%) and the low marginal abatement cost (RMB per ton SO_2 removed). If wet FGD is to be installed in existing plants (as we analyze in this action plan document), an important issue that has to be addressed, is the additional area requirement of the FGD-plant, which could be significant. In cases where the required area is not available, alternative options need to be considered (see next section on dry FGD).

Reduction potential

Wet FGD only makes sense for large sources due to the high capital costs. But since only a limited number of large sources contributes heavily to SO_2 concentrations, and since a significant reduction of SO_2 levels is needed if the target air quality is to be achieved, wet FGD could be a viable option. The data from the emissions inventory suggest that 17 single sources represent roughly half of all contributions to SO_2 concentrations. Their 1995 *emissions* were approximately 53,000 tons. See Annex 2 for a listing of the sources.

Assuming that wet FGD has a removal efficiency of 90-95%, the SO_2 *emissions* would be cut by approximately 50,000 tons if the option is applied on the 17 sources.

The 17 sources represents approximately 50% of all contributions to concentrations, an emission reduction of 50,000 tons from these sources would go a long way in achieving the air quality target for SO_2. On this basis, the Guangzhou AQMS has calculated the concentration reduction potential of this option to be in the order of 50%.

Costs

A series of sources refer to the abatement costs of wet FGD and the variation of the estimates is considerable. Estimates can be drawn from international literature, a few examples of wet FGD that has actually been undertaken in China, Chinese surveys of costs associated with wet FGD as well as costs reported by suppliers of wet FGD plants.

A lot of the variation between the estimates are due to the fact that actual costs to a large degree will depend on project or plant specific characteristics. Different assumptions underlying the estimates are also important in explaining the wide range of estimates.

Table 5.1 shows some of the abatement cost estimates:

Table 5.1 Wet FGD abatement cost estimates.

	Cost per ton SO_2 removed (RMB)
World Bank (1997a) (Shanghai study)	1150
World Bank (1997b)	4000-5000
SEPA-study	1220
Tsinghua study	750-1550
Guangzhou paper mill. feasibility study	1225
Luohong power plant, Sichuan province	865

Sources: World Bank 1997a; World Bank 1997b; Guangzhou Paper Mill, EIA report; Hao Jiming 1998

The costs referred to above are the end result of complex calculations. In box 5.6 the Luohong power plant in Sichuan province is taken as one example:

Box 5.6 Wet FGD abatement costs in Luohong power plant, Sichuan.

> The rated capacity of Luohong power plant is 720 MW consisting of two 360 MW units. The initial investment for the wet FGD was RMB 481,7 mill., or RMB 669 per kW. A major international supplier of wet scrubbers - ABB - has indicated that capital costs for retrofitting wet FGD in a power plant of 200 MW will be around RMB 800 per kW, while costs will be higher in smaller units and lower in larger units. Costs are lower for new plants than for retrofit on existing plants. In this context, the estimate for Luohong, which is a new, relatively large plant, seems to be realistic.
>
> This investment cost has to be spread over the period which the wet FGD will be functioning. For the Luohong power plant the annual investment costs has been reported to be RMB 58 mill. This would be the result if the investment is depreciated over 20 years with an interest rate of 10%, or alternatively if it is depreciated over more than 20 years and an interest rate higher than 10%. The technical lifetime of the plant is reported to be more than 30 years.
>
> Wet FGD have low operating costs compared to other SO_2 removal systems. For the Luohong power plant, the annual O&M cost has been reported to be close to RMB 60 mill. including desulfurization material (limestone), water, power, salaries, repair and maintenance[10].
>
> Total annual costs of SO_2 removal in the Luohong case is RMB 117.7 mill. and the cost per ton SO_2 removed is reported to be *RMB 865.8 per ton*. This indicates that total annual amount of SO_2 removed is very large, more than 130,000 tons. The sulfur content of the coal used is high (4-5%).
>
> Previously we mentioned that wet FGD with efficiencies as high as 95% has a substantial area requirement. In the Luohong plant, the area requirement is reported to be 12,000 square meters. Thus, for many of the existing point sources in Guangzhou, wet FGD will probably be difficult. Instead, dry scrubbers could be an alternative, offering high removal efficiency but requiring less space.

Alternatively, we might use international cost data for wet FGD and apply these on two power plants in Guangzhou: the Guangzhou power plant, the Guangzhou SINOPEC Petrochemical Factory. This is done in box 5.7. The cost data used are the following:

Investment costs: US$ 130 per kW = RMB 1040 per kW (retrofit)

O&M costs, fixed: US$ 12 per kW = RMB 96 per kW

O&M, variable: UScents 0.1 per kWh = RMB 0.012 per kWh

Operating costs for wet FGD do not depend on whether it is a new installation or retrofit on existing installation.

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10 Limestone: 20.5 mill., power: 20.7 mill, repair and maintenance: 12.1 mill, salaries: 0.55 mill.

Box 5.7 Abatement costs for wet FGD in Guangzhou Power Plant and Guangzhou SINOPEC Petrochemical Factory, international cost data.

Guangzhou power plant (200 MW)

Investment costs: 200,000 kW x RMB 1040 = RMB 208 mill. Assuming 20 years lifetime and 8% interest rate, the annual capital costs will be RMB 33.07 mill. (208 mill. x 0.159).

Fixed O&M costs: RMB 96 x 200,000 kW = RMB 19.2 mill.

Variable O&M costs: RMB 0.012 x 1,200,000,000 kWh (assuming 6,000 hrs/year) = RMB 14.4 mill.

Total annual costs: RMB 33.07 mill. + 19.2 mill. + 14.42 mill. = RMB 66.6 mill.

Sulfur removed = 95% of 10.281 tons = 9,767 tons

Cost effectiveness ratio: RMB 66.6 mill. / 9,767 tons = RMB 6,800 per ton

(The Guangzhou Paper Making Mill is currently replacing its old boilers with new boilers. The new boilers will have a capacity equivalent to 200MW, which is the same as Guangzhou power plant. The study contains data on O&M costs which we may use in combination with the international data on investment costs in the example above. The paper mill feasibility study reports O&M costs to be considerably lower than the international reference we have used in the example (RMB 13.4 mill. vs. RMB 32 mill.). If we use these data instead of the international data, the cost effectiveness ratio for Guangzhou power plant is RMB 4,760 per ton SO_2 removed, which is considerably lower than the ratio above. This number is more in line with international estimates, even though the feasibility study itself calculated a ratio of RMB 1240 per ton SO_2 removed. The reason for this is probably that the feasibility study does not calculate cost effectiveness ratio for a retrofit of wet FGD on the *old boilers*, but rather for the new boilers which have a much higher capacity, coal consumption and potential SO_2 emission.)

Guangzhou SINOPEC Petrochemical Factory (55 MW)

Total investment costs: 55,000 kW x RMB1040 per kW = RMB 57.2 mill.

Annual investment cost: 15.9% of total = RMB 9.09 mill.

O&M, fixed: 55,000 x RMB 96 = RMB 5.28 mill.

O&M, variable: 55,000 kW x 6,000 hours x RMB 0.012 per kWh = RMB 3.96 mill.

Total annual abatement costs: RMB 18 mill.

Emission reduction: 95% of 8,291 tons = 7,877 tons

Cost effectiveness ratio: RMB 18 mill. / 7,877 tons = RMB 2,285 per ton.

By making rough estimates for other large point SO_2 sources, one can conclude that in most cases, costs per ton SO_2 removed is closer to the amount indicated in World Bank (1997b) than to the estimates in various Chinese surveys and to the World Bank Shanghai study. In other words, costs seem to be closer to RMB 4000-5000 per ton removed than to RMB 1000-1500 per ton. The fact that SO_2 removal through wet FGD will be more costly in Guangzhou than in the Shanghai or other Chinese cities is most probably due to the relatively low sulfur content of the coal used in Guangzhou.

5.3.6 Other flue gas desulfurization technologies

Dry FGD

For dry flue gas desulfurization, costs per ton removed will be in the same range as for wet FGD. Reduction potential will also be the same, or somewhat less. Since the area requirement of this technology is significantly less than for wet FGD, this could be a more attractive option for many existing sources.

Simplified wet FGD

In addition to wet or dry FGD, there are some other options that should be investigated further. Simplified wet scrubbing (simplified wet FGD) has a lower cleaning efficiency than standard wet FGD, but investment costs are considerably lower. Since removal efficiency is lower, Chinese surveys (Hao Jiming 1998) report costs per ton SO_2 removed to be in the same range as for standard wet FGD.

Phosphate and ammonia sorbent injection

Phosphate and ammonia sorbent injection is a technology which is currently being developed in China. The main advantage of this technology is that the waste product may be used as fertilizer. Gross costs per ton SO_2 removed are reported to be slightly higher than other desulfurization technologies, but since the waste product may be sold at a price of approximately RMB 1600 per ton (Hao Jiming 1998), this could be a very attractive option in terms of net costs. Therefore further efforts should be taken to investigate this option and the maturity of the technology.

5.3.7 Fuel switch - taxis (from gasoline to LPG)

One option for SO_2 removal which has been decided by the Guangzhou government is a fuel switch for taxis from gasoline to LPG.

Our analysis of the potential reduction of SO_2 concentrations that can be expected from this option concludes that this potential is very small, probably in the magnitude of 1% or less. This calculation is based upon emission characteristics of gasoline and LPG-fuelled passenger cars, and that the fuel switch will cover 15,000 taxis which each year run 150,000 kilometers each.

Assuming that a fuel shift to LPG reduces SO_2 emissions by 0.3 g/km[11], that there are 15,000 taxis to be switched and that the average taxi drives 150,000 kilometers per year, the total annual emission reduction potential of this option will be:

15,000 taxis x 150,000 kms x 0.3 g/km = 675 tons.

Costs

A calculation of the cost effectiveness of this option should in principle take into consideration the costs of converting a gasoline car to an LPG car, the costs of establishing fuel stations for LPG vehicles, the fuel costs for a gasoline fuelled taxi vs. a LPG taxi.

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[11] The reduction potential per km is probably significantly lower.

The costs of converting the vehicles from gasoline to LPG is reported to be RMB 6,900 per vehicle. If we assume that the fuel switch will result in an emissions reduction of 0.3 g SO_2 per kilometer per taxi, and that each taxi runs 150,000 kilometers per year and for 5 years after the conversion to LPG, then 0.22 ton of SO_2 would be removed for each taxi. The cost of conversion RMB 6,900 should then be divided by the quantity of SO_2 removed: RMB 6,900 / 0.225 ton = *RMB 31.500 per ton*. The total costs for all 15,000 taxis would be 15,000 x RMB 6,900 = RMB 103.5 mill. while the total emissions reductions over the entire 5 year period would be 3,375 tons of SO_2 (675 tons per year). In other words, this option is a relatively costly way to reduce SO_2 emissions and has a very limited effect.

In addition we should include the costs of establishing a set of LPG filling stations needed to serve the taxis since these filling stations do not exist already. Also, we should consider the fuel costs of a gasoline taxi vs. those of a LPG taxi. Since LPG is reported to cost approximately the same as gasoline (unleaded) and since fuel consumption per kilometer is somewhat higher for LPG than for gasoline (25% higher), the true costs of this option will be even higher than RMB 31,500 per ton that we have calculated.

It can be argued that apart from SO_2, the fuel switch will also cut emissions and concentrations of TSP. By ignoring the costs of additional fuel consumption and of necessary filling stations, we have calculated the cost effectiveness for TSP to be RMB 38,300 per ton. In this calculation we have assumed that the fuel switch will produce an emissions reduction of 0.24 g TSP/km, a lifetime of 5 years, annual running distance of 150,000 km and conversion costs of RMB 6,900 per vehicle.

The potential reduction of TSP concentrations of this option is also very small (less than 1% reduction).

A combined cost effectiveness ratio where costs are allocated/divided between SO_2 and TSP would be RMB 6,900 / 0.225 ton SO_2 + 0.18 ton TSP = RMB 17,000 per ton SO_2 or TSP. We would argue that this is the most relevant estimate to use when we later compare the cost effectiveness ratios of different options.

5.3.8 Fuel switch - buses (from gasoline to LPG)

Another fuel switch option that is currently being implemented in Guangzhou is to switch gasoline fuelled buses to LPG. Converting diesel fuelled buses, of which there are 4000 in Guangzhou, is far more expensive and not feasible at present. The concentration reduction potential of converting 1000 gasoline buses to LPG has been estimated to be less than 1%.

Assuming that a fuel switch to LPG saves 1.96 grams of SO_2 per km and 1.5 g TSP per km, and that the average bus operates 72,000 kms per year (200 km/day x 30 days x 12 months) the annual emission reduction potential of this option will be

SO_2: 1000 buses x 72,000 km x 1.96 g/km = 140 tons

TSP: 1000 buses x 72,000 km x 1.5 g/km = 110 tons

Costs

The lifetime of a bus that is converted to LPG is considered to be 8 years. An LPG bus is assumed to emit 1,96 grams less SO_2 per kilometer than a diesel bus. If each LPG bus run 72,000 kilometers per year during its lifetime 8 years, it follows that a LPG bus will save 1.96 g/km x 72,000 km x 8 years = 1.129 tons of SO_2 during this 8 year period.

The costs will be the conversion costs, additional fuel costs (higher for LPG than for diesel) and each bus' share of the costs of establishing the filling stations. We do not have information on the costs of filling stations, so we will only consider conversion costs and fuel costs[12].

The costs of converting a bus from gasoline to LPG is reported to be RMB 9,960. The fuel costs for a LPG bus is reported to be RMB 14 higher per 100 km than for a gasoline bus. Total additional fuel costs for a LPG bus which runs 72,000 km per year (200 per day, 30 days per month, 12 months a year) during the 8 year lifetime will then be 8 x 72,000 km x (RMB14/100 km) = RMB 80,500.

The cost effectiveness ratio of this option will then be RMB 9,960 + RMB 80,500 = RMB 90,500, divided by the emissions reduction (1.129 ton) = *RMB 80,100/ton.*

As for the fuel switch for taxis, this option will also result in reduced emissions of particles. Each LPG bus will save an estimated 1.5 g TSP per kilometer compared to a gasoline bus, which constitutes 0.864 tons for the entire 8 year period (assuming 72,000 km/year). The cost effectiveness ratio is (RMB 9,960 + RMB 80,500) / 0.864 ton = RMB 105,000 per ton TSP.

A combined cost effectiveness ratio where costs are allocated/divided between SO_2 and TSP would be RMB 90,500 / 1.129 ton SO_2 + 0.864 ton TSP = RMB 90,500 / 2 tons = RMB 45,000 per ton SO_2 or TSP. In addition we should add infrastructure costs (filling stations).

In sum, converting a bus from gasoline to LPG is a relatively costly way to reduce both SO_2 and TSP *emissions* and has a limited potential for reducing the overall concentrations of the two air pollutants.

5.3.9 Cogeneration in major industrial sources

In industrial sources in which there is a need both for *electricity and steam* for processing purposes, cogeneration units are far more efficient than conventional condensing turbines. In cogeneration units turbines are back pressure turbines with significantly higher efficiencies than the conventional condensing turbines that are presently in use in industrial sources in Guangzhou today (see below). Most industrial sources in Guangzhou which produce both steam and power use the less efficient condensing turbines, even though cogeneration units has or is presently being installed in several factories. This makes cogeneration a very attractive option.

In back pressure turbines, steam of high quality enters the turbine and steam of lower quality leaves the turbine. The steam that leaves the turbine can be used further for process purposes. In condensing turbines, high quality steam enters the turbine. In order to produce as much electricity as possible, the steam leaving the turbine is chilled so that the steam condenses. When the outlet steam is conden-

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12 A cost of RMB 1 million per station has been reported (SSTC-bulletin). In principle we could have used this estimate, multiply by 7 stations (being constructed) – or 40 stations (planned), convert to annual capital costs and allocate costs to each bus.

sed, the pressure difference between the inlet and outlet of the turbine is increased and the turbine works more efficiently. For plants where only electricity is required, this is the most energy efficient way to produce the electricity. In integrated plants where there is a need for electricity as well as steam, back pressure turbines are more effective. The reason for this is that energy is not lost to the cooling water. All the energy in the steam from the boiler is utilized in one way or another.

This means that less electricity is generated from the steam but in addition there is process steam which can be utilized. This increases the overall efficiency compared to separate systems and systems where some of the steam is withdrawn for process purposes before it enters the turbine. As a great part of the industrial sector has the requirement for both steam and electricity, cogeneration units are most suitable for these kinds of industries. The electricity/ steam ratio from cogeneration varies from good large steam turbines which give 56% steam and 44% electricity, to smaller back pressure turbines which give about 85% steam and 15% electricity. By shifting from separate steam and power systems to combined system producing 20% electricity and 80% steam, overall efficiency is on average 21% higher than in conventional turbines.

The old condensing turbine is replaced by a new back pressure turbine. The boiler connected to the turbine, must keep the same requirements for temperature and pressure as the turbine. As ordinary steam boilers are not designed for as high pressure as the back pressure turbine require and as the boiler for the condensing turbine do not have enough capacity, it is assumed that all the old boilers must be replaced. This option will increase efficiency through a combination of A. replacing old inefficient boilers with new and efficient boilers, and B. installing cogeneration unit (turbine and generator). Replacing a industrial boiler with capacity less than 50 MW will entail an efficiency improvement of 35% compared to existing industrial boilers in Guangzhou today[13]. On top of this, the cogeneration

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[13] The energy efficiency is generally dependent on the size of the boiler and the following data are obtained for the current boilers in Guangzhou:

Generating unit, MW	Specific energy consumption, gCE/kWh
6-25	500-550
50-100	420
125-200	388-395
300-600	336-370

Source: Data collected in Guangzhou by task 7.

For a typical 600 MW new efficient boiler, the coal consumption is 307 gCE/kWh, which corresponds to 40% efficiency. The efficiency of new boilers depends to some extent on boiler size, and the efficiency of smaller boilers such as 50 MW and less is assumed to have 4 % lower efficiency which corresponds to about 341 gCE/kWh. This is based upon personal communication with Geir Sollesnes, Kjelforeningen Norsk Energi, 1999.

The reduced coal consumption in % can be calculated as follows:

Reduced coal consumption, % = ((Old SEC[13] – new SEC)/ old SEC)*100

If the existing boilers are replaced by new efficient ones, the efficiency can be improved as shown in the table below.

will bring an improvement of 21% for a unit producing 80% steam and 20% electricity[14]. In sum, the efficiency improvement (and fuel saving) will be 49% compared with separate generation with old inefficient boilers.

The availability of this technology in China is good. In Guangzhou, the Guangzhou power plant and the Yuan Cun power plant have installed cogeneration. Guangzhou paper mill will install a unit in 2000.

Reduction potential

When calculating the emission reduction potential of increased cogeneration we have done so by assuming that the technology is applied on the industrial sources listed in Annex 5, representing almost a quarter of total SO_2 emissions from large point sources, or 24,500 tons per year. We have excluded Guangzhou paper mill, which will implement cogeneration in 2000. On average, efficiency is assumed to increase by 49% through the introduction of cogeneration (with a 80/20 mix of steam/electricity) which also requires replacing the existing boilers with new efficient boilers. Boiler replacement is assumed to increase efficiency by 35% (see note 13). Cogeneration improves efficiency by 21% (assuming an 80/20 mix of steam/electricity, see note 14), meaning that the overall improvement will be 49% (35% + 21% of 100-35%).

Present fuel consumption by the 9 industrial sources: 1,675,400 tons (bituminous coal)

Potential fuel savings: 1,675,400 x 0.49 = 821,000 tons

Present SO_2 emissions by industrial sources in Annex 5: 24,500 tons

Potential SO_2 reductions: 24,500 x 0.49 = 12,000 tons

Apart from SO_2 reductions, the reduction in fuel use will reduce emissions of NO_x and particles. The relative reduction of particles will be of the same order as for SO_2, while the NO_x reduction is more difficult to estimate. Thus we only consider

Generating unit, MW	New specific energy consumption, gCE/kWh	Reduced fuel consumption by replacement, %
6-25	341	35
25-50	341	31
50-100	307	27
100-125	307	24
125-200	307	22
200-300	307	17
300-600	307	13

14 Personal communication with Hans Petter Heggen and Tor Thorgersen, Borregaard, Norway.

the reduced particles emissions which are 33,600 tons – 49% or 16,500 tons (see Annex 5).

Costs

The cost components are first costs of scrapping the existing boilers, turbines and generators before the end of their useful life. We assume that existing boilers, turbines and generators on average have served 15 out of totally 20 years lifetime, and that their capital cost is RMB 2,700 per kW. The total cost for power plants are assumed to be RMB 4,500 per kW, of which boiler costs represent 30% and turbine and generators another 30% (INET/ITEESA, 1998), together 60% or RMB 2,700 per kW. The nine sources have a combined installed capacity of 380 MW, and «lost» investment costs may be calculated as follows: 380,000 MW x RMB 2,700 per kW x 15/20 = 256 mill. or 51 mill. per year.

Next, we replace these boilers, turbines and generators with new boilers which are efficient – more efficient than conventional new boilers in China today (341 gCE/kWh vs. 389 gCE/kWh). Thus additional capital costs for the more efficient new boilers should thus be included. The basis for estimating additional capital costs is that total capital costs for new efficient coal fired power plants are RMB 6,000 per kW[15]. Boiler costs represents 30%, and costs for back pressure turbines and generators another 30%, or RMB 3,600 per kW altogether. Compared to conventional new power plants in China, this represent an additional capital cost of RMB 900 per kW. Thus total additional capital costs for the 9 sources will be: 380,000 kW x RMB 900 = 342 mill. Annual additional capital costs, assuming 8% interest rate and 20 years lifetime, would be RMB 342 mill. x 0.159 = RMB 54 mill.

Then, the improved efficiency will reduce fuel consumption and costs by 49%. The annual total coal consumption of the 9 sources is 1,675,400 tons bituminous coal. 821,000 tons will be saved each year and with a price of bituminous coal of RMB 217[16] per ton, the fuel costs will be reduced by RMB 178 mill.

Other O&M costs are considered equal.

Annual capital costs: RMB 51 mill. + 54 mill. = 105 mill.

Fuel cost savings: 178 mill.

Total savings are RMB 73 mill. Abatement costs are RMB –73 mill./12,000 tons less SO_2 + 16,500 tons less particles = RMB 2,550 saved per ton SO_2 and particles removed, a true win-win situation[17].

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[15] An average based upon information from Hans Petter Heggen and Tor Thorgersen, Borregaard Industrier (1999), Geir Sollesnes, Kjelforeningen Norsk Energi (1999), INET/INTEESA (1998) and World Bank (1994).

[16] The price for bituminous coals with sulfur content between 1 and 1.5% and ash content between 28% and 35% is reported to vary between RMB 204 and 230 per ton.

[17] Here costs/savings are allocated to SO_2 only. This option will also reduce particles emissions by 49% and NOx to a lesser extent. In line with what has been done for other options, costs

Since this option will produce reductions of NO_x in addition, costs, or savings in this case, should also be allocated to NO_x , something which will reduce the saving per ton SO_2 avoided in the previous paragraph. We do not know the NO_x reductions, and consequently they are not considered any further.

Considering the fact that this option is applied on 9 of the 13 power plants considered for the close down option, and that cogeneration is far more cost effective, cogeneration will replace close down as it is meaningless to implement both for the same source. The close down option is therefore revised later in this chapter when we consider all options together.

5.3.10 Fuel switch - third industry

In Guangzhou there are about 16,000 hotels and restaurants that use diesel, fuel oil and coal for heating water and for cooking. Restaurants usually emit at low height and are often located in areas where people live. They are therefore considered to contribute significantly to concentrations of SO_2 and particles.

The combined fuel use of the third industry is, however, quite limited. Through this measure, 33,000 tons of coal (TCE) and 13,000 tons of oil products (equivalent to 18,700 tons TCE) could be substituted by city gas (and possible bottled gas (LPG))[18]. This represents approximately 3% of total fuel use in Guangzhou and approximately 2% of SO_2 emissions. In our preliminary evaluation of the overall effect of this measure, we classified it as "C-measure", meaning that it will have limited effect, less than 5%, on SO_2 concentrations.

Costs

According to our calculation, the fuel switch for hotels and restaurants is a very expensive way to reduce SO_2 concentrations, and as we concluded in the preceding paragraph, the total potential reduction is very limited. The calculated cost effectiveness ratio is RMB 605,000 per ton SO_2.

The main elements in the calculation of abatement cost are as follows:

In order to switch to piped gas an average restaurant must pay the connection cost of approximately RMB 200,000 (which includes fee for the necessary expansion of the infrastructure). We use the same method for calculating annual capital costs as above (assuming 20 years lifetime and 8% interest rate), even if the technical lifetime of the connection (and infrastructure expansion) is longer. Thus the annual «connection cost» is 200,000 x 0.159 = RMB 31,800.

In addition we should consider extra fuel costs, since these are higher for gas than for diesel. This extra fuel cost for an average restaurant (consuming 8.5 tons of diesel before the switch and 13,207 m^3 gas after the switch) is estimated to RMB 26,160/year. The fuel switch will, for an average restaurant, produce a reduction of SO_2 emissions of 0.107 ton/year, assuming that the sulfur content of the diesel

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(and savings) should also be assigned to particles (and NOx. The implication of this is that the profitability per ton SO_2 will decrease.

18 Data from GZAQMS task 2 (1998).

is 0,63% (GZAQMS task 1, 1998) and that burning piped gas will be SO_2-free. Thus the cost per ton SO_2 reduced is RMB (31,800 + 26,160)/0.107 ton = RMB 541,500 per ton.

This estimate does not take into account the costs of installing gas burner. Gas burners are cheaper than diesel burners, so this could reduce abatement cost, but it will only be a very small reduction. The estimate uses production costs of gas as its basis (RMB 3,3 per m^3). The production cost is higher than the end-use price (2,2 RMB per m^3) due to government subsidies. There is no reason to use end-use price in this calculation since we are concerned with social costs (not private costs).

5.3.11 Moving 20 factories

The Guangzhou Urban Master Plan stipulates that a group of 68 polluting factories which are all located in the urban area of Guangzhou will be moved out of this area. 48 of these factories will be relocated outside the urban area due to other environmental problems than local air pollution (water, noise, etc.) while the remaining 20 factories are relevant for air pollution. The 20 factories are listed in Annex 3.

Reduction potential

According to the emissions inventory (1995), these 20 factories (see Annex 3) together emit approximately 512 tons of SO_2 per year. In addition they emit 136 tons of NO_x/year and 1165 tons of particles/year. Many of these factories will be located outside the urban area in the four counties (Huadu, Panyu, Chongua and Zengchen). Although it cannot be ruled out that their new emissions may contribute to future concentrations in the urban area, we may for the sake of simplicity assume that their contributions will be zero. By making this assumption we exaggerate the reduction potential and underestimate the marginal abatement cost of this option, since the factories will emit at their new locations (though to a lesser degree due to modernization of the production equipment).

As can be seen from the numbers above, the reductions of total emissions that may be achieved by moving these 20 factories will be very small. A preliminary estimate is that this option alone will reduce overall concentration of SO_2 with less than 5%, and probably closer to the lower end (0%) than to the higher end (5%) of this range.

Costs

It has not been possible to obtain data on what moving the 20 factories will cost in terms of the process of moving, or in terms of the capital cost. We expect the capital cost to be the more important of the two. The capital cost is the cost of disrupting the use of buildings, machines and equipment before their life-times are up. The cost is low if others can make use of the buildings, machines, and equipment. But if nobody can use them for a purpose the capital cost is equal to what one could have saved by using the existing buildings, equipment, and machines longer.

To obtain a rough estimate of the capital cost we observe that the combined production value of 18 of the 20 factories is approximately RMB 350 mill., according to data collected for this project (see Annex 3). Data on two of the factories are lacking. The annual capital cost is certainly lower than the annual combined production value.

As a rule of thumb, 35 – 45 per cent of production value covers the cost of material inputs that are used in the production process. There are great differences between industries but without specific information, we assume that 40 per cent of production value covers material input.

A further 33 per cent covers the cost of labour assuming the following calculation holds: We have data on the number of employees in the factories. The average production value per employee is RMB 48,500. If average labour costs per employee are RMB 15,000 per year, labor covers slightly less than 33 per cent of production value.

Given that material inputs cover 40 per cent and labour covers 33 per cent, the remaining 27 per cent of production value is remuneration to capital. The percentage to capital is higher than the average for most economies. The average ratio of labour to capital in most economies is something like 7:3 or 6:4, as opposed to 33/27 (=11/9) in this calculation. However, polluting industries are usually more capital intensive than the average of the economy.

We use 27 per cent of production value, or RMB 95 mill., as an estimate of the capital cost of moving the factories. RMB 95 mill. is in other words our estimate of the value of services that one gives up by leaving the old buildings, machines and equipment behind in order to invest in new buildings, machines and equipment.

If one is willing to assume that the capital is sold and used by others, the cost is less than RMB 95 mill.

Cost-effectiveness ratios

The emission reduction from 18 of the 20 factories is 352 tons SO_2. A cost-effectiveness calculation based on emission reduction gives RMB 270/kg SO_2, or RMB 270,000/ton. This seems a high number despite the considerable uncertainty surrounding both the estimate of cost and emission reduction[19].

As we have seen, the relocation of the 20 factories will also result in reduced emissions of NO_x and particles. If all costs are allocated to SO_2, we calculated a cost effectiveness ratio of 270,000 per ton SO_2 removed. Likewise the cost effectiveness ratio for NO_x is 95 mill./ 92.5 tons = RMB 1.027 mill. per ton; and for particles 95 mill./868 tons = RMB 109,500 per ton. If we add all emissions and calculate one common ratio for all three pollutants, the cost effectiveness ratio will be: RMB 95 mill. / 1,312 tons = RMB 72,400 per ton pollutant.

[19] It is important to note that the figure for production value for *Guangzhou Hongmian Baowenping* (and *Guangzhou Penqichang*) is lacking, and therefore excluded in calculation of cost effectiveness ratio. This factory is an important source.

It may be concluded that this option is a costly way to reduce SO_2 emissions, and that its effect on emissions is marginal.

5.3.12 Comparison of options: abatement costs and potential

By now we can compare the different options in terms their *abatement* potential and costs. In the next section we will consider their *concentration* reduction potential and costs.

Table 5.2 Abatement costs and emissions reduction potentials of various SO_2 control options.

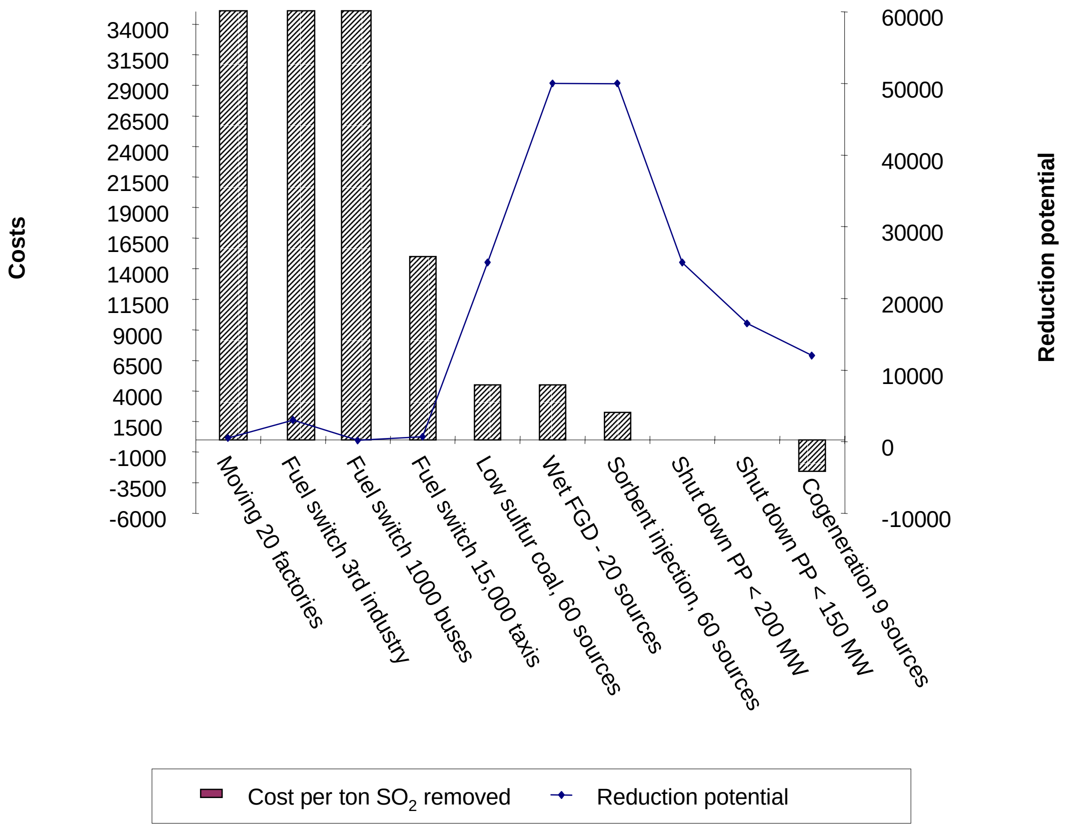
Option	Cost per ton removed	Emission reduction potential (ton/year)
Cogeneration 9 main industrial sources	- 2,550	12,000 (+ 16,500 tons particles)
Sorbent injection in power plants and large industrial boilers	2,250	55,000
Shut down 18 power plants, 200 MW or less	0*	25,000 tons (+ 7,000 tons NO_x + 27,000 tons particles)**
Shut down 13 power plants, 150 MW or less	0*	16,500 tons SO_2 (+ 3,300 NO_x + 25,000 tons particles)**
All large point sources use low sulfur coal (shift from 0.75% S to 0.5% S)	4,500	25,000 (max 33% of «bituminous part» of POI50 emissions)
All large point sources shift from bituminous (0.75% S) to anthracite (0.5% S)	4,900	4,500 tons (max. 33% of anthracite part of POI50 emissions)
Wet FGD on 17 largest point sources	4500	50,000 tons
Fuel switch – taxis	17,000	675 tons (15,000 taxis) (+ 540 tons TSP)
Fuel switch – 1000 buses	45,000	140 tons (1000 buses) (+ 110 tons particles)
Fuel switch third industry	540,000	2,000-3,000 tons (2% of total emissions)
Moving 20 factories	72,400	500 tons (+ 130 tons NO_x and 1,150 tons particles

*: lower range

**: Lower range; numbers assume that small plants' production is shifted entirely to big plants *within* study area.

These findings are illustrated in figure 5.1. As can be seen from the table and figure, the general picture is that the options with the highest costs are the options with the lowest *emissions* reduction potentials. Whether this conclusion holds when we consider the *concentration* reduction potential, is discussed below.

Figure 5.1 Emission reduction potential and costs of various SO_2 control options.



So far we have analyzed the each option as if each option is the first to be implemented. As the reader will have noted, there is an overlap between various options, meaning that two or more options remove the same ton of SO_2, and that some options will have smaller effects and thus poorer cost effectiveness if other options are implemented first. We will return to this question below.

Now we turn to the crucial question of what happens when abatement potential is converted to concentration reduction potential. In principle, this could change the whole picture.

5.3.13 Concentration reduction potential and costs

Table 5.3 below shows the potential of each option[20] for reducing SO_2 concentrations in central Guangzhou and the cost effectiveness ratio expressing the annual cost of reducing the SO_2 concentration from 1995 level with one percentage point. This ratio is arrived at by multiplying the abatement costs and abatement potential in the previous section and dividing by the concentration reduction potential in the table below. The concentration reduction potential may be

[20] For the sake of simplicity we have left out the more expensive low sulfur coal option as well as the most expensive of the two options involving shut down of small power plants.

calculated by simulating the option in AirQUIS, or more roughly by a calculation on the «back-of-the-envelope»[21].

Table 5.3 *SO_2 concentration reduction potential and costs for each control option.*

Control option	Total costs	Concentration reduction potential (%)	Cost per %-point reduced SO_2 concentration
Cogeneration 9 industrial sources	- 30 mill.	5.5%	- 5.4 mill.
Shut down 13 small power plants	0*	8%*	0*
Sorbent injection 60 large point sources	124 mill.	26%	4.8 mill.
Shift to 0.5% sulfur coal, 60 large point sources	112 mill.	12%	9.3 mill.
Wet FGD on 17 largest point sources	225 mill.	24%	9.4 mill.
Fuel switch – 15,000 taxis	11.5 mill.	0.6%	19. mill.
Moving 20 factories	36.2 mill.	1.4%	26 mill.
Fuel switch – 1,000 buses	6.3 mill.	0.15%	42 mill.
Fuel switch third industry	1350 mill.	2.4%	560 mill.

*: lower range

This shows that two options considered by the city government - fuel switch for a considerable number of taxis and buses – are only somewhat more cost-effective than one would conclude by focusing on emissions. But this calculation also shows that the concentration reduction potentials of these options are marginal and will do little to achieve the targets. The table also shows that a third option considered by the city, fuel switch in restaurants and hotels, is quite costly and not very effective in achieving SO_2 concentration targets.

The two options with the highest individual potential for reducing SO_2 concentrations are sorbent injection in the 60 largest point sources and wet scrubbing in the 17 largest point sources. If sorbent injection is selected, SO_2 concentrations

21 Method for approximate transformation of reduced emissions to reduced concentrations:

Concentration in central district = $a \cdot C_{Poi50} + b \cdot C_{small} + C_b$.

a (50-55) + b (30-35) + 15

C_{Poi50}: Concentration contribution from Poi50

C_{small}: Concentration contribution from (small point sources + domestic/commercial + traffic)

C_b: Regional background concentration

a,b: emission reduction factor, per source category

Thus, if POI50 emissions are reduced by 10,000 tons as a result of a given option, we may calculate the equivalent reduction in concentrations: 10000 less tons means that new POI50 emissions will be reduced to 100% – ((10,000/111,200)*100)=91% of previous emissions. Concentrations level will be 0.91• (50-55) + 1• (30-35) + 15 = 95,3% of 1995 level, or a reduction of 100-95,3=4,7%.

could come down by 26% at a total annual cost of RMB 50 mill., or RMB 4.8 mill. per percentage point reduced SO_2 concentration. However, two other options are more economical in reducing concentrations than any other: the introduction of cogeneration and close down of 13 power plants with a parallel increase of capacity utilization in big power plants.

5.3.14 Least cost package and total costs of reaching SO_2 targets

The final step in our analysis is to consider all options together. This is not straightforward as several options in varying degrees are mutually excluding. When several options are targeted against identical sources, concentration reduction potential, costs and cost effectiveness ratio of one option depends on which other options have been carried out first. As the picture is quite complex where several options dependent on each other, a reasonably accurate calculation of reduction potentials may only be done through simulating packages of options in AirQUIS. Before such calculations are available, we will in this section only provide a rough approximation to illustrate the line of reasoning.

Table 5.4 shows the results when all options are considered together, but implemented in a sequence starting with the most cost effective option in the table above and continuing with the second most cost effective. All reduction potentials refer to relative reductions from the 1995 concentration level in central Guangzhou. The line of reasoning behind the calculations of additional concentration reduction potential and new cost effectiveness ratios is given in Annex 8. However, cogeneration is applied on several of the «industrial power plants» which also are included in the «shut-down-small-power-plants» option. Obviously, it does not make sense first to introduce cogeneration in these plants and then shut them down. *Therefore we have redesigned the shut-down-option to include eight «pure» power plants (only producing power for the grid) smaller than 200 MW*, all eight indicated in Annex 4 (bold).

Table 5.4 SO_2 concentration potential and costs for different options when implemented in a sequence starting with option.

Control option	Total annual cost (mill. RMB)	Concentration reduction potential – additional reduction from 1995 level	Annual cost per % point reduced SO_2 concentration
1. Cogeneration – 9 industrial sources	-30	5.5%	-5.4 mill.
2. Shut down 9 power plants	0 *	5.3%*	0
3. Sorbent injection, 60 large sources	101.2	21%	4.8 mill.
4. Shift to low sulfur coal, 60 large sources	120	4%	30 mill.
5. Fuel switch – 15,000 taxis	11	0.5%	23 mill.
6. Wet FGD, 13 largest point sources[22]	170	5%	34 mill.
7. Moving 20 factories	36.2	1.4%	26 mill.
8. Fuel switch – 1,000 buses	6.3	0.15%	42 mill.
9. Fuel switch third industry	1,350	2.4%	560 mill.
Total, options 1-3	71.2	31.8%	2.2 mill.
Total, options 1-5	202	36.3%	5.56 mill.
Total, options 1-8	414.7	42.9%	9.6 mill.

*: Lower range

Recalling the fact that reaching the air quality target for annual average of SO_2 required a reduction of concentrations by 20% from 1995 levels, we may conclude that implementing the first three options will be more than sufficient, assuming that 2001 levels will be the same as for 1995 – (in the absence of a baseline 2001 concentration). The total annual costs will be less than RMB 70 mill., which is quite moderate and quite certainly much lower than the benefit involved in such a SO_2 reduction. Each percentage point reduced SO_2 concentrations would entail an average annual cost of a little over RMB 2 mill.

Achieving the maximum 24 hour average for SO_2 will be a more difficult goal to achieve. If all 8 options are implemented in the sequence above, concentrations could be brought down by 43% relative to 1995 level at a total annual cost of approximately RMB 400 mill., which implies a cost of RMB 10 mill. per percentage point.

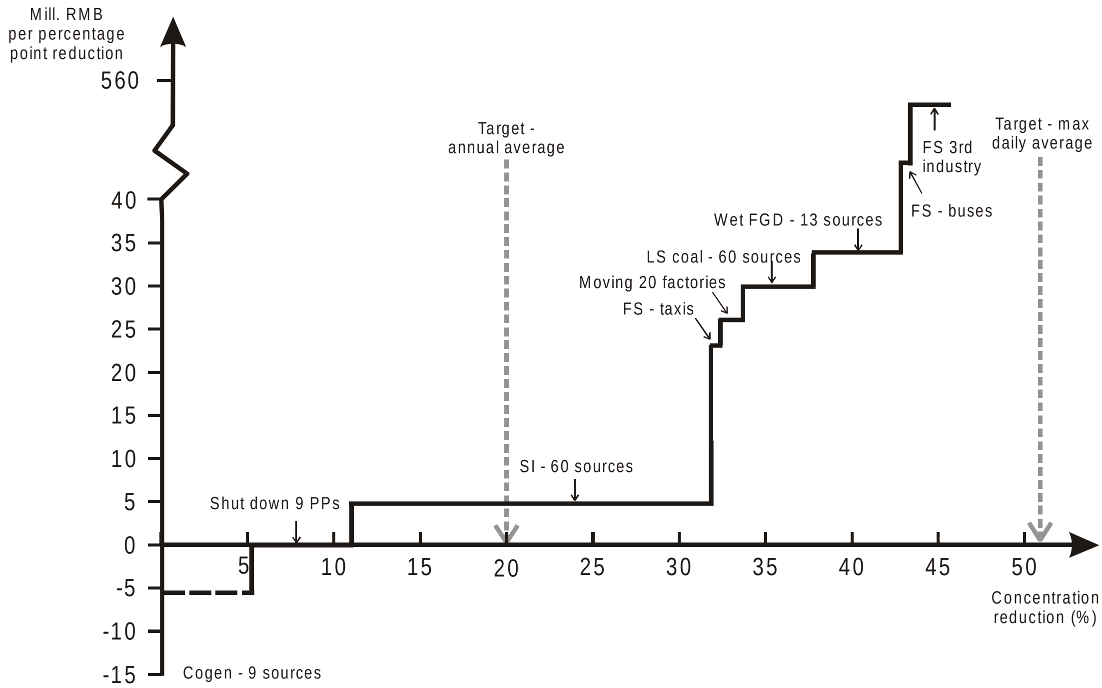
As argued in Annex 8, it does not make much sense to implement option 6 (wet FGD) on sources which already have introduced both cogeneration, sorbent injection and low sulfur coal. Rather, wet FGD on the restricted set of sources giving the highest contributions to concentrations should be implemented as the third option after cogeneration and close down of small power plants. It can be estimated that the cost effectiveness of wet FGD then becomes approximately 10 mill. per percentage point and the reduction potential 16%. Sorbent injection and

[22] The 17 sources have become 13 because 4 are eliminated in the option no.2 (close 9 power plants).

low sulfur coal should be reserved for those POI50 sources where wet FGD is not installed. Obviously, the reduction potential and, consequently, cost effectiveness ratios, of sorbent injection and low sulfur coal will change from what is reported in the table above.

The message from table 5.4 is visualized in the cost curve in figure 5.2.

Figure 5.2 Cost curve, SO_2 control options.



5.3.15 How sensitive are cost effectiveness ratios to different assumptions?

As the reader will recall, the estimated costs above assume an interest rate of 8% for those options where capital costs are involved. The lifetime of the abatement equipment varies from option to option, but in many cases we assume a lifetime of 20 years. It is obviously of interest to know how the costs will change if we use different assumptions on the interest rate. That will obviously vary a lot depending on how capital intensive the option in question is. For options where capital costs carry much weight, the assumed interest rate will influence the cost effectiveness ratio quite significantly, while the difference will be small if operating costs are more important than capital costs. Annex 10 (spreadsheet «ACPLAN2001.XLS») gives the calculated cost effectiveness ratios with different assumptions on interest rates. An option such as wet FGD is the most sensitive to interest rate, by reducing the interest rate from 8% to 5%, the cost effectiveness ratio (cost per SO_2 removed) is improved by 25-30%. For other options such as sorbent injection, the reduction in cost effectiveness ratio of a reduction in interest rate from 8% to 5% is much smaller (3-6%).

5.4 NO_x options

In the following we will examine the these options to reduce emissions and concentrations of NO_x:

- Low NO_x burners in large point sources
- Selective non-catalytic reduction (SNCR) in large point sources
- Selective catalytic reduction (SCR) in large point sources
- Retrofit of three way catalytic converters on taxis
- Retrofit of three way catalytic converters on LPG buses

In addition, several of the options analyzed under SO_2 will also reduce NO_x emissions.

5.4.1 SO_2 - related options also reducing NO_x emissions

As can be recalled from the previous section, several SO_2 control options would also affect NO_x emissions and concentrations.

Moving 20 factories

The option of moving 20 factories had a very limited reduction potential for NO_x (130-140 tons per year) and is a costly way to reduce NO_x emissions (70,000 per ton if costs are spread on SO_2, NO_x and particles).

Close down small power plants

The option of closing down small inefficient and highly polluting power plants with capacity less than 150 MW was found to be an attractive measure. It may reduce annual NO_x emissions by 3,300-12,000 tons. How large a reduction and how much less the cost will depend on how much of the cancelled power production is imported from the regional grid and how much is shifted to the big plants in Guangzhou itself, as well as on the remaining value of small plants' machinery at close down, cf. discussion under SO_2. We argued that the costs of this option should be considered to be close to zero. When a different line of argument was followed, the abatement costs were estimated to RMB 2050 per ton.

5.4.2 Low NO_x-burners

Emissions from new boilers with LNB may be less than half (45%) the emissions from a new boiler with a conventional burner. For retrofit of LNB on old coal fired boilers, the NO_x emissions may be 30-40% lower than for conventional burners. LNB is widely used as a means for controlling NO_x emissions, both for new and existing installations.

LNB may be applied as LNB only, or in combination with Over Fire Air. Over Fire Air (OFA) means that a portion of the combustion air is withdrawn from the combustion zone and added further up in the furnace to complete the combustion and thus reduce the formation of NO_x. The combined LNB and OFA option may reduce emissions of NO_x by 30-60% (World Bank 1997a, World Bank 1997b).

LNB is already applied in mainland China. According to World Bank (1997b), more than 20% of power plants in China use LNB. No power plants in Guangzhou has installed LNB. LNB has been installed in Shenzhen power plant, and in Hong Kong it has been installed in Nanya power plant and Qingshan B power plant where NO_x emissions have been reduced by 25-50%. As far as we know, LNB is now required on all new power plants in Hong Kong.

Reduction potential

According to the inventory data, large point sources (POI 50) emit a total of approximately 35,000 tons NO_x per year (1995). By examining the data further, and selecting the 24 sources that have the highest contributions to concentrations of NO_x, and including 2 more stacks with high emissions but moderate contributions to concentrations (two stacks at Huangpu power plant) we find that these 26 sources (stacks) emit 22,000 tons. See Annex 6 for a listing of the 26 sources and their emissions and contributions to concentrations. By applying LNB in combination with OFA on these 26 sources, emissions could be reduced by approximately 10,000 tons (6,600 – 13,200 tons). If LNB and OFA is applied on all large point sources, emissions could be cut by 10,000-20,000 tons.

Costs

In the literature on NO_x control options, it is generally concluded that LNB is the most cost-effective way to reduce NO_x emissions.

Capital costs for equipping new boilers with low NO_x burners (LNB) are very small, approximately RMB 10-15 per kW, and the operating costs are the same for the two kinds of burners. Capital costs for LNB is approximately 30% higher than for conventional boilers, implying that capital cost for a conventional burner is RMB 7-8 per kW[23].

World Bank 1997b indicates that capital costs for retrofitting LNB in existing boilers are RMB 80-320 per kW for plants smaller than 300 MW. The lower end of this range (RMB 80) represents large plants and the higher end (RMB 320) represents smaller plants due to economy of scale. Operating costs are the same as for conventional boilers. World Bank (1999) reports capital costs for combined retrofit of LNB and OFA to be $ 20-25 per kW or approximately RMB 180 per kW, while Takahashi (1998) reports a somewhat lower cost: RMB 80-160 per kW.

When calculating the cost effectiveness ratio of LNB or LNB in combination with OFA, we have to consider that also conventional burners have to be replaced after a certain time, normally 2-3 years, but this is highly dependent on how well the burner is operated and maintained. If LNB is applied, the costs that should be counted are the cost of the LNB boiler minus the cost of a conventional burner plus the lost investment in a conventional burner if it is replaced before the end of its full useful life. Since the operating costs are the same for low NO_x burners and conventional burners, we do not have to consider these.

In box 5.8 the cost-efficiency ratio of retrofitting LNB on Guangzhou Power Plant and on SINOPEC Petrochemical factory is calculated.

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23 Information gathered from Kvaerner.

Box 5.8 NO_x abatement costs - LNB and OFA in Guangzhou Power Plant and SINOPEC Petrochemical factory.

The Guangzhou Power Plant has an installed capacity of 200 MW. Assuming that the existing burners will soon end their technical life, we can ignore the costs of replacing burners that otherwise could be used for some additional time. We assume next that the capital costs for retrofit of LNB and OFA in the case of Guangzhou power plant is RMB 120 per kW (mean value of Takahashi above). The total costs of the LNB burners and OFA would then be

200,000 kW x RMB 120 = RMB 24 mill.

Then we should subtract the costs of a conventional burner since the power plant will have to replace these anyway. If the cost of a conventional burner is RMB 7-8 per kW less than for a LNB, this would constitute RMB 1.5 mill., which gives an additional capital cost of RMB 22.5 mill.

The annual capital cost (if lifetime is 3 years and interest rate 8%) is RMB 22.5 mill. x 0.72 = RMB 16.7 mill. (See section 5.2 for explanation of the factor 0.72.)

Next, we assume that LNB will cut annual NO_x emissions by 50%. According to the emissions inventory, Guangzhou power plant emits 5090 tons per year. Thus a 50% reduction means 2,545 tons less NO_x per year. The cost effectiveness ratio is RMB 16.7 mill./2,545 tons = RMB 6,560 per ton.

This estimate is quite high compared to the estimates of cost effectiveness ratios reported in the literature. The cost effectiveness ratio of retrofitting LNB in the existing power plants in Shanghai was calculated to be RMB 800 per ton NO_x (Takahashi 1998). World Bank (1997b) indicate a cost effectiveness ratio of LNB around RMB 3,000 per ton NO_x.

Possible factors behind this difference could be that the NO_x emissions for Guangzhou power plants are radically underestimated or actually much lower than other plants, that the different sources assume very different emission reduction potentials of LNB and/or very different cost estimates for retrofit of LNB vs. Conventional burners. In any case, further efforts should be undertaken to look into the costs of LNB, possibly in combination with OFA.

The power plant at the **SINOPEC Petrochemical factory** has a capacity of 55 MW. It is among the largest NO_x sources in Guangzhou.

Investment cost LNB and OFA: 55,000 kW x RMB 120 = RMB 6.6 mill.

Minus costs of conventional burner: 55,000 x RMB 7.5 = RMB 400,000

Total additional costs: 6.2 mill.

Annual capital costs (3 years, 8% interest): 6.2 mill. x 0.72 = RMB 4.47 mill.

Annual emissions reduction: 2,050 tons x 50% = 1,025 tons

Cost effectiveness ratio: RMB 4,370 per ton.

The figure for SINOPEC is more in line with international estimates of abatement costs of LNB. This shows that cost effectiveness ratios vary quite a lot. We believe that the international estimates are more reliable than e.g. the estimate for Guangzhou power plant above. In a comparison of cost effectiveness ratios of different options we have chosen *RMB 4,000 per ton NO_x removed as a reasonable estimate for LNB and OFA.*

5.4.3 SCR/SNCR

Since the options of modifications of the combustion technology has a limited potential for NO_x reduction, other options should also be considered. The NO_x in the flue gas can be treated by so-called Selective Catalytic Reduction (SCR) or Selective Non-Catalytic Reduction (SNCR). With SNCR, ammonia is injected into the high temperature zone of the boiler. The ammonia reduces the NO_x which has been formed to nitrogen and water. With SCR ammonia is injected in the presence of a catalyst.

These technologies are more capital intensive than LNB and OFA. On the other hand they have a larger potential for NO_x removal, usually reported to be 30-70% for SNCR and 70-90% for SCR. SNCR is best suited for smaller boilers. SNCR requires less additional space than SCR. SCR may be used in boilers of different sizes, but the area requirement may limit its applicability. Both technologies are most suited for low and medium sulfur coal.

None of these technologies are applied in China today, but internationally the two technologies are considered relatively mature. SNCR is presently being researched in China (World Bank 1997b).

Reduction potential

As we did for LNB and OFA above, we may select the 26 sources (see Annex 6) with the highest contributions to NO_x concentrations. These sources emitted approximately 22,000 tons of NO_x in 1995. Assuming that SNCR may cut NO_x emissions by 30-70%, emissions from the 26 sources would be reduced by approximately 11,000 tons (6,600-15,400 tons). If SNCR are installed on all large point sources, emissions would be cut by 10,000-24,000 tons.

As for SCR, the reductions would be higher since SCR has higher efficiency (70-90%). If we assume an average efficiency of 80% NO_x removal, the emissions from the 26 sources would be reduced by approximately 17,600 tons. If applied on all large point sources, emissions could be cut by 28,000 tons.

Costs - SNCR

The costs of retrofitting SNCR in smaller units are reported to be approximately RMB 160-200 per kW. Costs are lower for new plants and also for larger plants and could come down to approximately RMB 80 per kW. In addition, the cost of urea should be considered. The amount of urea/ammonia required depends on the NO_x reduction target. High NO_x removal requires high urea consumption. World Bank (1997b) reports a cost effectiveness ratio of RMB 8800 per ton NO_x removed in a 100 MW plant when 50% of NO_x is removed and an urea price of RMB 2400 per ton. In Guangzhou, the urea price is reported to be RMB 1300 per ton, so this would reduce the cost.

Box 5.9 NO_x abatement costs through SNCR in Guangzhou power plant.

By using the 200 MW Guangzhou Power Plant as an example, the cost of removing NO_x can be calculated as follows:

200,000 kW x 180 RMB = RMB 36 mill.

Lifetime: 20 years, interest rate 8%, gives annual capital cost = RMB 5.72 mill. (36 mill. x 0.159)

O&M (including urea): 0.15 Cents per kWh = RMB 0.012 per kWh

Power production assumed to be 200 MW x 6,000 hrs = 1.2 billion kWh.

1.2 bill. KWh x 0.012 RMB/kWh = 14.4 mill.

Total annual costs = 5.72 mill. + 14.4 = RMB 20.12 mill.

NO_x reduction per year: 60% = 5,090 tons x 0.60 = 3,050 tons

Cost effectiveness ratio: 20.12 mill. / 3,050 tons = RMB 6,600 per ton. This calculation is based upon a price for urea which is 85% higher than the price for urea in Guangzhou. We have not been able to estimate how much this would affect the cost effectiveness ratio.

Alternatively, we can use the SINOPEC Petrochemical Factory for a comparison:

Capital costs: 55,000 kW x RMB 180 per kW = RMB 9.9 mill.

Annual capital cost (20 years, 8% interest rate): RMB 9.9 mill. x 0.159 = RMB 1.57 mill.

Annual O&M costs: 55,000 kW x 6,000 hours x RMB 0.012/kWh = 3.96 mill.

Total annual costs: RMB 1.57 mill. + 3.96 mill. = RMB 5.5 mill.

Estimated emissions reduction: 2,050 tons x 60% = 1,230 tons

Cost effectiveness ratio: RMB 5.5 mill. / 1,230 tons = RMB 4,470 per ton.

From the above it can be seen that the estimate from the international literature is somewhat higher than the two Guangzhou examples we have used here. Thus, we believe it is reasonable to use the RMB 6000 estimate in a comparison between different options to control NO_x. However, in individual cases it could be higher as well as lower. The examples and estimates above illustrate the importance of having reliable data for NO_x emissions before selecting control options.

Costs - SCR

Capital costs of SCR on new plants are reported to be around RMB 320-640 per kW (US$ 40-80), while retrofit is more expensive, around RMB 700-1200 (US$ 90-150).

O&M costs for SCR are primarily related to ammonia (reagent) and the catalyst. We do not have data on the costs of these two factors, but World Bank (1997b) estimates total O&M costs to be roughly 0.2-0.4 UScents per kWh (RMB 0.024 per kWh) . If we use the power plant at the SINOPEC Petrochemical Factory in Guangzhou as an example, the cost effectiveness ratio of SCR can be calculated as follows:

Box 5.10 NO_x abatement cost – SCR in SINOPEC Petrochemical Factory.

> Total capital costs: 55,000 kW x RMB 1000 = RMB 55 mill.
>
> Annual capital costs (lifetime 20 years, 8% interest rate): RMB 55 mill. x 0.159 = RMB 8.75 mill.
>
> Annual O&M costs: 55,000 kW x 6,000 hours x RMB 0.024 = 7.92 mill.
>
> Total annual costs: 8.75 mill. + 7.92 mill. = RMB 16.67 mill.
>
> Reduced emissions: 2050 tons x 85% = 1,740 tons
>
> Cost effectiveness ratio: RMB 16.67 mill. / 1,740 tons = RMB 9,580 per ton.

The estimate for the SINOPEC factory fits rather well with other studies. In a World Bank study of power plants in Shanghai, the estimate for the SCR option was RMB 9600 per ton, though this is an estimate for SCR on new plants which have somewhat lower capital costs than retrofit (Takahashi 1998).

When we compare the different options we will use RMB 10,000 as the best estimate of cost per ton NO_x removed through SCR.

5.4.4 Retrofit three way catalytic converters (TWC) on taxis

Three way catalytic converter (TWC) is a technology which has shown to be a very effective way of reducing NO_x emissions from passenger cars in many western countries. TWC is now required on new passenger cars in Beijing and Shanghai. TWC can also be retrofitted on existing cars provided they are equipped with electronic injection. Germany has pursued this policy for its passenger vehicle fleet. One option to consider for the Guangzhou authorities could be to install TWC on taxis, since taxis constitute a significant number of the passenger cars circulating in Guangzhou, and since they represent a large share of the total number of passenger vehicle kilometers.

Costs

The cost of retrofitting TWC on a used car is approximately RMB 5,000. The NO_x-cleaning performance of TWC gradually declines after a certain amount of kilometers. If an average taxi circulates 150,000 kms per year, we may assume that the lifetime of the TWC is two years (i.e. that the NO_x removal after 300,000 kms is small).

Average NO_x emissions from gasoline fuelled passenger cars are estimated to 2.1 g/km. After retrofitting a TWC, an emission of 0.3 g/km may be assumed. In other words, NO_x emissions will be cut by 1.8 g/km for a vehicle with TWC.

Reduction over three years: 2 x 150,000 x 1.8 g/km = 540 kg

Cost: RMB 5,000

Cost effectiveness: RMB 5,000 / 540 kg = RMB 9,300 per ton

Reduction potential

If approximately half of the existing taxis are equipped with electronic fuel injection, TWC may be retrofitted on 7,500 taxis currently operating in Guangzhou, and if emissions before installing TWC is 2.1 g/km, the annual NO_x emission reduction will be 1,350 tons (180 kg less NO_x per taxi per year).

In addition, TWC will reduce or almost eliminate particles emissions. However, since particles emissions from light duty gasoline vehicles are quite small, this will not significantly affect the cost effectiveness ratio.

5.4.5 Retrofit TWC on LPG buses

If TWC is retrofitted on a bus buses that has been converted from diesel to LPG, NO_x emissions may be reduced further from approximately 5 g/km to 2 g/km, or a reduction of 3 g/km. The lifetime of TWC may be assumed to be 4 years (300,000 km). The cost of a TWC for a bus may be in the order of RMB 10,000. A preliminary calculation of the cost effectiveness ratio of this option is as follows:

72,000 km x 0.3 g/km = 0.0216 tons per year

Cost = RMB10,000/4 years = RMB 2,500 per year (interest rate = 0%)

Cost effectiveness ratio: RMB 2,500 / 0.0216 ton = RMB 11,500 per ton NO_x

Emission reduction potential: 1000 buses x 0.0216 tons = 216 tons

5.4.6 Comparison of NO_x options

Table 5.5 summarizes the conclusions on abatement costs and emissions reduction potentials of the different NO_x control options, analyzed as stand-alone-options.

Table 5.5 Abatement costs and potential of NO_x control options.

Option	Cost per ton removed	Reduction potential
Shut down 13 power plants, 150 MW or less	0*	3,300 – 12,000 tons
LNB (+ OFA) on 26 largest sources	4,000	6,600-13,200 tons
SNCR on 26 largest sources	6,000	6,600 – 15,400 tons
TWC retrofit on 7,500 taxis	9,300	1,350 tons
SCR on 26 large sources	10,000	15,500 – 20,000 tons
TWC retrofit on 1000 LPG buses	11,500	215 tons
Moving 20 factories	72,400	136 tons

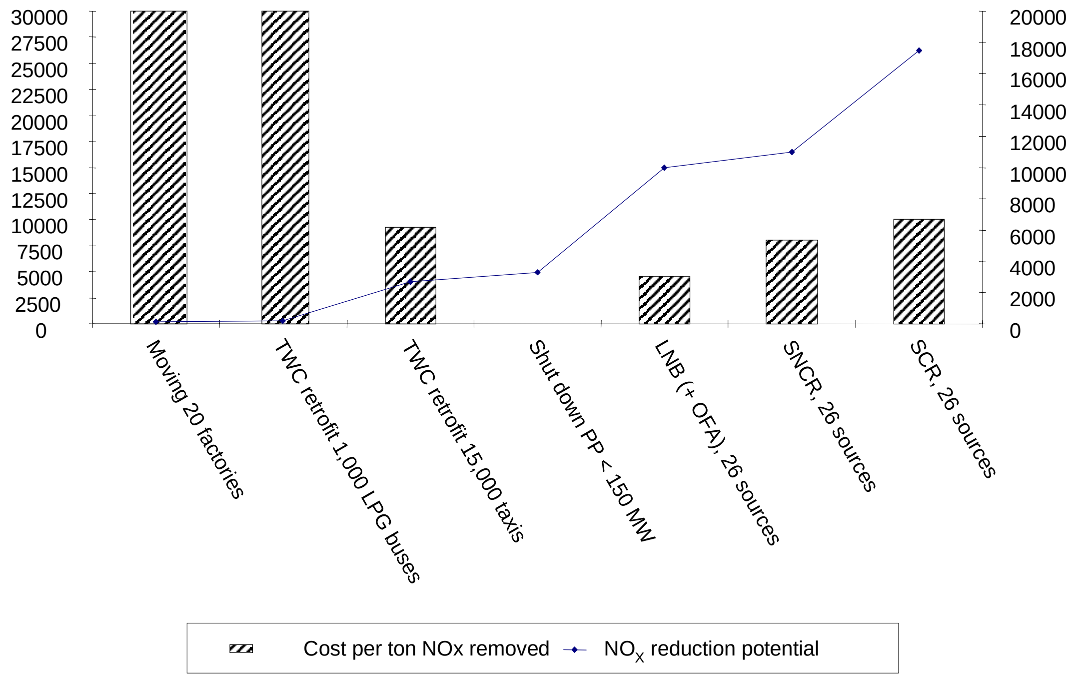
*: lower range

As can be seen from the table, some of these options are targeted at the same emission of NO_x. In other words, there is a certain degree of overlap between the shut down of small power plants on the one hand and LNB/OFA, SNCR and SCR on the other. That means that the 26 factories identified for either LNB/OFA, SCR or SNCR include some of the small power plants identified for shut down (e.g. Zini, Yongda, etc). The SNCR and SCR options as they are suggested here, are mutually excluding, as it does not make sense to install both technologies in the same plant. LNB and SCR or SNCR are not mutually excluding though, even if the reduction potential of one option obviously will decrease if the other option is already applied on the same source.

For the remaining options, none are overlapping with any other.

Figure 5.3 illustrates the information given in the table above. We may draw the same conclusion as we did for SO_2: The options with the lowest costs per ton removed generally have far larger reduction potential than high cost options. We will see whether this holds true when we turn to concentration reduction.

Figure 5.3 Abatement costs and potential of NO_x control options (RMB and tons).



5.4.7 Concentration reduction potential and costs

The total annual costs of each option may be found by multiplying the annual abatement cost per ton and the abatement potential. This is done in table 5.6 below.

Table 5.6 Total annual costs of each NO_x control option.

Option	Costs per ton NO_x removed	Emission reduction potential	Total costs
Shut down 13 power plants, 150 MW or less	0*	3300*	0*
LNB (+ OFA) on 26 largest sources	4,000	10,000	40 mill.
SNCR on 26 largest sources	6,000	11,000	66 mill.
TWC retrofit on 7,500 taxis	9,300	1350	12.5 mill.
SCR on 26 large sources	10,000	18000	180 mill.
TWC retrofit on 1000 LPG buses	11,500	215	2.5 mill.
Moving 20 factories	72,400	136	9.8 mill.

*: lower range

When emissions reductions are transformed to concentration reductions and the total costs from the table above is divided by concentration reductions, we find the cost per percentage point reduced NO_x concentration from the level in 1995. This is done in table 5.7[24].

Table 5.7 Total costs, concentration reduction potential, and costs per percentage point reduced concentrations for various control options.

Option	Total costs	Concentration reduction potential	Cost per percentage point reduced NO_x concentration
Shut down 13 power plants, 150 MW or less	0*	4%*	0*
LNB (+ OFA) on 26 largest sources	40 mill.	11%	3.6 mill.
SNCR on 26 largest sources	66 mill.	12.2%	5.4 mill.
TWC retrofit on 7,500 taxis	12.5 mill.	1.5%	8.4 mill.
SCR on 26 large sources	180 mill.	20%	9 mill.
TWC retrofit on 1000 LPG buses	2.5 mill.	0.2%	12.5 mill.
Moving 20 factories	9.8 mill.	0.1%	9.8 mill.

*: lower range

By comparing table 5.6 and table 5.7 we see that the internal relationship between the options are quite the same for emission reductions and concentration reductions. The only change is that the relative cost-effectiveness of moving 20 factories is somewhat better when looking at concentration than on emissions, but its reduction potential is insignificant.

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[24] Method for approximate transformation of reduced emissions to reduced concentrations:

Concentration in central district = $a \cdot C_{Poi50} + b \cdot C_{small} + C_b$

$a(30\text{-}35) + b(30\text{-}35) + 20 \Rightarrow 80\text{-}90$, for $a = b = 1$

C_{Poi50}: Concentration contribution from Poi50

C_{small}: Concentration contribution from (small point sources + domestic/commercial + traffic)

C_b: Regional background concentration

a,b: emission reduction factor, per source category

5.4.8 Least cost package and total costs of meeting target

So far we have analyzed each option as if it were the first and only option to be implemented. As for SO_2, several options are overlapping and attack the same ton of NO_x. Costs will also depend on which options have been implemented previously. Thus we need to analyze the reduction potential and total costs of each option when several options are to be implemented together. Table 5.8 shows the additional potential of each option for reducing NO_x concentrations, taking into account the reductions achieved by other options that are more cost-effective and therefore implemented earlier. The adjusted abatement and concentration reduction potentials, costs and cost effectiveness ratios are explained in Annex 9.

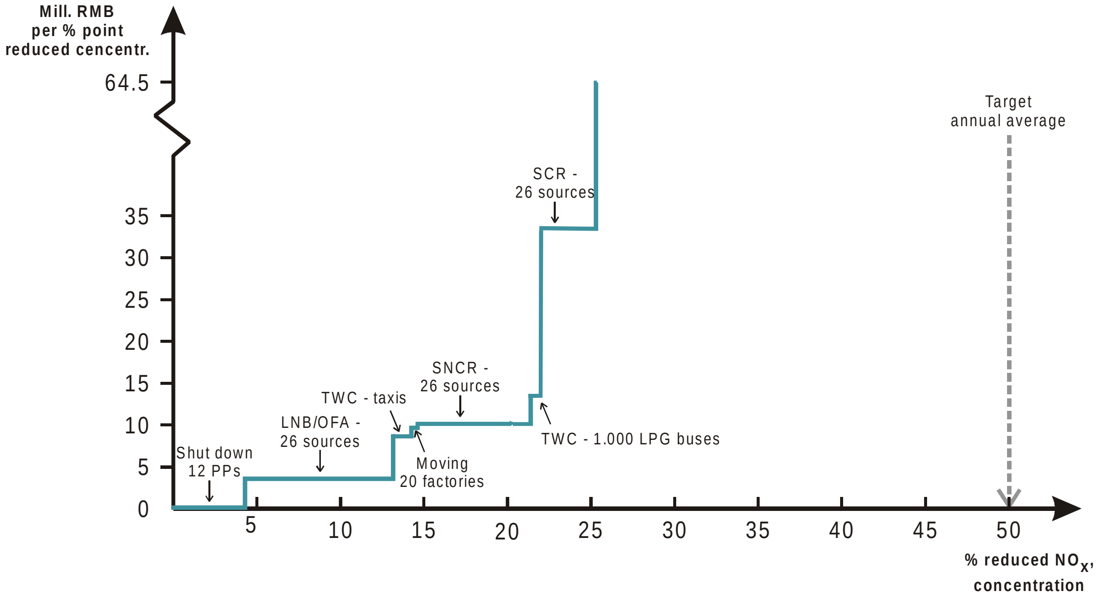
Table 5.8 Concentration reduction potential and costs of different NO_x control options when implemented in a sequence starting from option 1.

Option	Total annual costs – adjusted	Concentration reduction potential – additional (relative to 1995 concentrations)	Cost per percentage point reduced NO_x concentration
1. Shut down 13 power plants, 150 MW or less	0*	4%*	0*
2. LNB (+ OFA) on 26 largest sources	34 mill.	9.25%	3.6 mill.
3. SNCR on 26 largest sources	57 mill.	5.6%	10 mill.
4. SCR on 26 large sources	150 mill.	4.5%	33 mill.
5. TWC retrofit on 7,500 taxis	12.5 mill.	1.5%	8.4 mill.
7. TWC retrofit on 1000 LPG buses	2.5 mill.	0.2%	12.5 mill.
8. Moving 20 factories	9.8 mill.	0.1%	12.9mill.
Total options 1-3	91 mill.	20%	4.55 mill.
Total options 1-6 samme	256 mill.	25%	10.25mill.

*: lower range

This table supports the assumption that it will not be easy to reach the stated targets for NO_x. The options considered above have a combined concentration reduction potential of 25-26%. Next, the table shows that the first three options will reduce concentrations in the central area by 20% at a total annual cost of approximately RMB 100 mill. Further reductions will be more costly, as illustrated by the SCR option. This option is significantly less cost effective when implemented after the first four options than it was when considered in isolation from other options, as in table 5.7 above.

Figure 5.4 Cost curve, NO_x control options.



From this analysis it is evident that several options should be applied more widely, i.e. on a larger number of sources and that additional options need to be considered. It is quite obvious that we gain little extra in terms of additional concentration reduction by applying three different technologies on the same 26 sources. Rather one should analyze the effect of reserving SCR for the 25 largest point sources and at the same time apply LNB/OFA or SNCR on the rest of all large point sources (POI50).

Attacking large point sources is not enough for getting anywhere close to the NO_x target. The results (chapter 2) show that traffic is very important for the NO_x concentration levels, and our analysis in this chapter have shown that much more powerful options (in terms of concentration reduction potential) are needed. Options that could be considered are TWC on all new passenger cars and possibly also retrofit on used gasoline fuelled cars where technically feasible, applying the most effective de NO_x abatement technologies like SCR on all large point sources rather than only on the 26 sources we have considered here, limiting traffic through traffic demand management measures. Also one should consider how appropriate the air quality target for NO_x is and focus more on $N0_2$ rather than NO_x. This is obviously an issue of national concern since the criteria for classifying as an environmental model city is related to NO_x.

5.5 Particles/TSP-options

Options that will be examined for reducing TSP concentrations are the following:

- Low ash coal
- High efficiency electrostatic precipitators (ESP)
- Baghouse filters
- Street cleaning

We will first recall the costs and potential of options that already have been analyzed as SO_2 control options but which also will have an impact on emissions and concentrations of TSP.

5.5.1 Options already considered under SO_2 or NO_x but which also reduce TSP

Moving 20 factories

We concluded that the emission reduction potential was very limited and that the cost per ton TSP removed was RMB 109,500 per ton if all costs were allocated to TSP, and RMB 72,400 per ton if costs were spread on both SO_2, NO_x and TSP. We consider the last estimate as the most appropriate.

Close down small power plants

On this option we concluded that by closing down power plants with 200 MW or less installed capacity and instead increasing production in big plants and/or increasing imports from the regional network, TSP emissions could be reduced by 23-44%, or 27,000 – 52,000 tons, depending on how much is imported from the regional network. The cost effectiveness ratio varies between RMB 0 and RMB 4,250 if costs are allocated to all three air pollutants, depending on assumptions which have been explained under SO_2 (i.e. how much is imported from regional grid, remaining value of capital equipment in small plants, differences in thermal efficiencies and O&M costs between small and big plants, if extra investments in transmission and distribution are needed). We consider the estimate closer to zero as the best estimate.

We also concluded that - in the case where we assign a high remaining value to the equipment in power plants to be closed down - if only those plants with capacity of 150 MW or less are closed down, the cost effectiveness ratio would improve substantially. The high estimate for cost per ton TSP would fall from 4250 to RMB 2,050 per ton (assuming that costs are spread to SO_2, NO_x and TSP)[25]. The reduction potential of this option 21-33% of total particles emissions, or 25,000-39,000 tons (again depending on the share of increased imports from the regional grid). We will focus on the 150 MW variant in the following, due to its more favorable cost effectiveness and also because it is politically more feasible than the 200 MW option. The latter will eliminate a very high share of the installed capacity in Guangzhou[26].

Fuel switch taxis and buses

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[25] Again, the cost will approach 0 if the electricity from these plants instead is entirely imported from the regional grid and no new investment in transmission/distribution is needed, or if thermal efficiencies are substantially higher and O&M substantially lower in big plants than in small plants, and if the machinery in small plants is considered to be fully depreciated when plants are closed down.

[26] It should be kept in mind that if cogeneration is implemented as a SO_2 control option, the option of closing down small power plants should be redesigned so as to include fewer and partly different power plants than has been described here.

The TSP reduction potential of the fuel switch options for taxis and buses was found to be very limited, and the costs were also high. A major reason for this was the extra fuel consumption (and costs) for LPG buses compared to gasoline buses. For taxis the cost effectiveness ratio is RMB 17,000 per ton, and for buses: RMB 45,000, assuming that costs are divided between SO_2 and TSP. If costs are allocated to TSP only, the ratios will be significantly higher, but the estimate of 15,000 is the most relevant in our view.

Cogeneration in major industrial sources

The combined effect of replacing boilers and installing cogeneration units in 9 major industrial sources on SO_2 emissions from these sources was found to be almost 50%. The relative effect on particles emissions will be of the same magnitude (49%). As can be seen in Annex 5, installing cogeneration units and replacing boilers in the nine sources can reduce particles emissions by 16,500 tons. The costs of this option were found to be negative - meaning that there will be a net saving associated with each ton reduced particles emission. When savings are allocated to both reductions of SO_2 and particles emissions, the negative cost was found to be RMB 2550 per ton.

At this point, we may conclude that there are three options – cogeneration, shut down of small power plants and both have significant emission reduction potentials and reasonable cost.

5.5.2 Retrofit high efficiency ESP (99.5%) – 11 sources

There are two main technologies for removing particles from the flue gas: electrostatic precipitators (ESP) and baghouse filters. ESP is the most commonly used technology in power plants, while baghouse filters are dominant in industry. However, baghouse filters are popular in power plants in the USA.

In Guangzhou, some of the largest point sources (POI 50) of particles did have ESP with reported efficiencies of 95-98% in 1995, but a significant number of these sources had other cleaning devices with lower cleaning efficiencies, e.g. waterfilm with efficiency of 88%. One option to reduce emissions of particles may therefore be to retrofit high efficiency ESP on those large sources which do not have ESP today. By high efficiency ESP we mean 99% or more. This would constitute a group of 11 sources which are listed in Annex 7 The main advantage of ESP is the simplicity of the technology and relatively low O&M costs. Retrofitting ESP on existing plants requires that units are closed down temporarily for a period of 2-6 weeks.

Costs

We do not have local data from Guangzhou on capital costs for retrofit of ESP. According to World Bank (1997b), the cost for *upgrade* ranges between RMB 10-160 per kW, while costs for new ESPs are higher, between US$ 30-80 per kW depending on e.g. fly ash resistivity and other factors. Information gathered from one large supplier of ESPs (ABB) indicates that these numbers might be too high since this supplier estimated the investment costs for a new ESP to be US$ 25 per kW for a large plant (500 MW). For smaller plants, costs are higher. Takahashi (1998) reports that Chinese manufacturers can provide ESP for US$ 15 per kW, but these units are not able to meet an emission standard of 50 mg/Nm^3. A Norwegian plant with a 70 MW boiler[27] recently installed a new ESP with particles emissions less than 10 mg/Nm^3. This plant reported investment costs of US$ 10 per kW (excluding installation costs). Maintenance costs for ESP are zero or close to zero.

Box 5.11 Estimating ESP abatement costs for particles Yongda and Zini power plants.

> In order to calculate the cost effectiveness ratio of this option we will first take Yongda power plant as an example. Yongda power plant has an installed capacity of 61 MW. The annual emission of particles from Yongda is 8,900 tons (1995, all 6 stacks). The cleaning equipment currently in place is waterfilm with a cleaning efficiency of 88.4%. By retrofitting ESP with 99.5% efficiency, the particles emissions could be reduced 8,500 tons per year.
>
> Since unit costs for ESP are somewhat higher for small plants than large plants, we assume that ESP investment costs for Yongda is US$ 30 per kW, or RMB 240 per kW. The total investment costs would be 61,000 kW x RMB 240 = RMB 14.6 mill. On an annual basis, this would represent a cost of RMB 2.32 mill. (20 years depreciation, 8% interest rate).
>
> In addition there would be costs associated with the electricity needed for the ESP. World Bank (1997b) reports operation costs (basically electricity) to be approximately US$ 5 per kW per year, or RMB 40 per kW. For Yongda, this would be 2.44 mill. As maintenance costs are almost zero for ESP, they can be neglected. Total annual costs for Yongda power plant will be RMB 4.75 mill.
>
> Cost effectiveness ratio: RMB 4.75 mill. / 8,500 tons = RMB 560 per ton.
>
> Another plant like Zini Tangciang has an installed capacity of 45 MW, and reported emission of particles is 5060 tons per year (2 out of 6 stacks). The cleaning efficiency for particles is reported to be 88%. If we do the same calculation for Zini as we did for Yongda, total annual abatement costs are 3.5 mill. Emissions reduction resulting from ESP will be approximately 4,800 tons. Cost effectiveness ratio: RMB 3.52 mill / 4,800 tons = RMB 730 per ton.

Thus, it seems that installing highly effective ESP on the 11 high polluting plants that today do not have ESP will be both a very effective and cost effective option. Even if there are uncertainties about the investment costs per kW, this would not alter the conclusion that ESP seems to be a very attractive way of reducing particles emissions and concentrations.

Reduction potential

By examining the emissions inventory, one can find that 13 sources (stacks) together are responsible for 32% of total particles emissions registered in the inventory (selected on the basis of their concentrations contributions). In terms of their concentration contribution, their share is even higher (approximately 40%). Of these 13 sources, 11 have cleaning efficiencies for particles of 88%. The remaining 2 sources have cleaning efficiencies of 96-97% (ESP). If ESP is installed on the 11 sources, it is quite evident that both total emissions and concentrations will be reduced significantly, even though the 2 sources which already

[27] Saugbruksforeningen, Halden, Norway. Personal communication Jens Petter Dannevig.

have installed ESP are responsible for large emissions. A reduction of total emissions of 20% or 20,000 tons should be realistic.

5.5.3 Baghouse filters

Baghouse filters may not be very suitable for cleaning particles from combustion in Guangzhou. The material traditionally used in baghouse filters make them less suitable for removing dust from flue gas with high temperatures, but they are also less suited in areas with relatively high humidity such as in this part of China. For dust control in cement factories, however, baghouse filters may be feasible. The advantages of baghouse filters relative to ESP are first that the effectiveness of baghouse filters is independent of the sulfur content of the coals. Second, baghouse filters may enhance the capture of SO_2 when used in combination with sorbent injection or dry scrubbing.

Baghouse filters are reported to be more cost effective than ESP when the coal used has low sulfur content or has a high fly ash resistivity and when high collection efficiency is required. For coals with lower resisitivity and when lower collection efficiencies are required, baghouse filters are normally less cost effective than ESP (World Bank 1997b).

Materials withstanding higher temperatures with collection efficiencies of 99.99% have been developed but are very costly (World Bank 1997b).

5.5.4 Low ash coal

As an average, 90% of the total ash in the coal will come out as fly ash, which then could be cleaned, while only 10% comes out as bottom ash. Given the dominant role of coal in the energy supply in Guangzhou, one option of potential great importance for reducing TSP emissions and concentrations could be reducing the ash content of the coal used, particularly for the large consumers of coal, i.e. power plants and industry.

The ash content could be lowered either through some form of washing locally in Guangzhou, or alternatively, by importing coal with lower ash content than before. The imported coal may have been washed by the coal mine or may have a lower natural ash content than coal from other mines.

Reduction potential

According to World Bank (1997b) and other sources, roughly 90% of the ash in the coal will be emitted as fly ash in a plant with no dust cleaning equipment. The rest 10% will remain as bottom ash. In Guangzhou, the coal fired power plants mainly use bituminous coal, except Huangpu which use anthracite coal. Bituminous coal comes in different qualities (e.g. different ash contents) but all qualities have a higher ash content than anthracite. The price of bituminous coal is lower than the price of anthracite. Bituminous coal with lower ash content costs more than bituminous coal with higher ash content. One option for reducing TSP emissions and concentrations could be that power plants and other major industrial consumers of bituminous coal shift to either anthracite coal or to bituminous coal with lower ash content.

The coal consumption (1995) of all large point sources (POI 50) was approximately 7.7 mill. tons. Of this approximately anthracite accounted for 2.1 mill. tons. Hence consumption of bituminous coal in large point sources was about 5.6 mill. tons. The average ash content of bituminous coal used in Guangzhou is 32%. If average cleaning efficiency is 90% the emissions would be

5,600,000 tons x 32% (ash content) x 0.9 (90% of coal ash to flue gas) x 0.1 (90% cleaning of flue gas) = 161,000 tons.

If average cleaning efficiency is 95%, the emissions would be 50% lower: 80,000 tons. As can be recalled from the chapter on calculated 1995 emissions above, total particles emissions from large point sources were 99,000 tons. This points to an average cleaning efficiency of 94%. If all these large point sources using bituminous coal instead shifted to anthracite, the emissions would be:

5,600,000 tons x 22% x 90% (coal ash to flue gas) x 6% (94% cleaning) = 66,500 tons. Thus total emissions of fly ash would be reduced by 32,000 tons. This would mean a reduction of 27% for all large point sources, or 27% of all particles emissions from large point sources.

Costs

We will analyze an option where power plants and major industrial TSP sources shift from bituminous coal to anthracite. The average ash content of bituminous coal used in Guangzhou is 32%, while the average for anthracite is 22%, in other words a difference of 10 percentage points. The average price for anthracite is RMB 315 per ton, while the average price for 32% ash bituminous can be assumed to be approximately RMB 220 per ton. Thus, the price difference is approximately RMB 95 per ton[28].

The next question is how much a shift to anthracite will mean in terms of reduced emissions of fly ash. That will depend on two factors: the cleaning equipment for fly ash (particles) and the reduced coal consumption which can be expected to occur with a shift to anthracite (because anthracite has a higher energy content than bituminous coal). Based upon reported emissions, we may assume that average cleaning efficiency is 95% in the power plants presently using bituminous coal.

Burning 1 ton of bituminous will produce fly ash emission (actual emission) of:

320 kg x 0.9 x 0.05 = 14.4 kg.

Burning 1 ton of anthracite will produce 220 kg x 0.9 x 0.05 = 9.9 kg

The difference is 4.5 kg. Thus, if one burns 220 tons of coal, the emission of fly ash will be 1 ton less when burning anthracite compared to bituminous coal. 220 tons x price difference RMB 95 per ton coal = RMB 21,000 per ton fly ash «removed». However, coal consumption can be reduced by 5-10% if one shifts to

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[28] We do not have specific information on how coal prices depend on ash content. Part of the price difference above may also be attributed to other factors.

anthracite due to higher calorific value, so this should be taken account of: 220 tons – 7.5% = 204 tons. Thus, the real cost would be 204 tons x price difference (RMB 95) = 19,400. When comparing different options we will use RMB 20,000 per ton TSP as a cost effectiveness ratio for low ash coal.

The above estimate should be considered an upper range estimatedue to the fact that the price difference is also due to other coal quality differences. Anthracite has a lower average sulfur content than bituminous coals in Guangzhou, and part of the price difference should ideally be attributed to sulfur content. As we do not possess detailed data on this matter we have not considered it any further.

The ratio will of course be higher if cleaning efficiencies are higher than 95% and lower if cleaning efficiencies are lower than 95%. If cleaning efficiency is 80%, the cost will be RMB 5000 per ton removed, and if it is 90%, the cost will be RMB 10,000 per ton removed.

An average cleaning factor of 95% seems high. From the above, it can be seen that cost effectiveness ratio of this option is quite sensitive to the cleaning factor. Thus, further investigation of the actual cleaning efficiencies seems appropriate.

5.5.5 Street cleaning

Streets in Guangzhou are cleaned regularly by machines. The machines used are:

- Dry vacuum cleaning vehicles: 3 ton vehicles made in Sichuan Province and 6 ton vehicles produced locally in GZ.
- Water spray vehicles: 2 types, 5 and 8 tons respectively.

Cleaning is currently done regularly every morning, systematically through the city. Vehicle speed is 20 km/h, and they often work many vehicles together, so that the whole width of the street is cleaned. If 5 teams of 3 vehicles each work for 3 hours at 20 km/h, they are able to clean totally 150 km of street (counting that they have to clean both direction, one after the other).

Total street length of the main road network in Guangzhou is about 250 km, (or 500 km counting both directions). Thus, if the extent of cleaning as estimated above is a continuous activity, each street is cleaned approx. every 2^{nd} day.

We assume that this extent of cleaning is done by dry vacuum cleaning vehicles.

Reduction potential

There are no estimates available of the effectiveness of the street cleaning practice in terms of:

- how large part of the dust depot on the street is removed
- how much does this reduce the resuspension of TSP and PM_{10}

Also, we have no quantitative estimates of the actual contribution to TSP from street dust resuspension. At urban background stations in Guangzhou the TSP concentrations are typically 250 $\mu g/m^3$ (annual average), and the contribution from fuel combustion in Guangzhou (point sources and traffic) is about 100 $\mu g/m^3$

or less. Street dust resuspension contributes to part of the difference, i.e. part of 150 μg/m^3.

Cleaning is done to a large extent already. The potential to reduce the resuspension further by increasing the extent and frequency of cleaning, seems limited.

Resuspension of street dust could be reduced more effectively by the use of better equipment. Such equipment tends to be very expensive. It is necessary to improve the estimates of street dust contribution to TSP and the potential for better cleaning, before improved street cleaning through new equipment can be recommended. Our tentative conclusion is that it will neither be an effective nor a cost-efficient option for reducing particles emissions.

5.5.6 Comparison of options

Table 5.9 summarizes the estimates for abatement costs and emission reduction potential of the various TSP control options.

Table 5.9 Abatement costs and emission reduction potential of TSP control options.

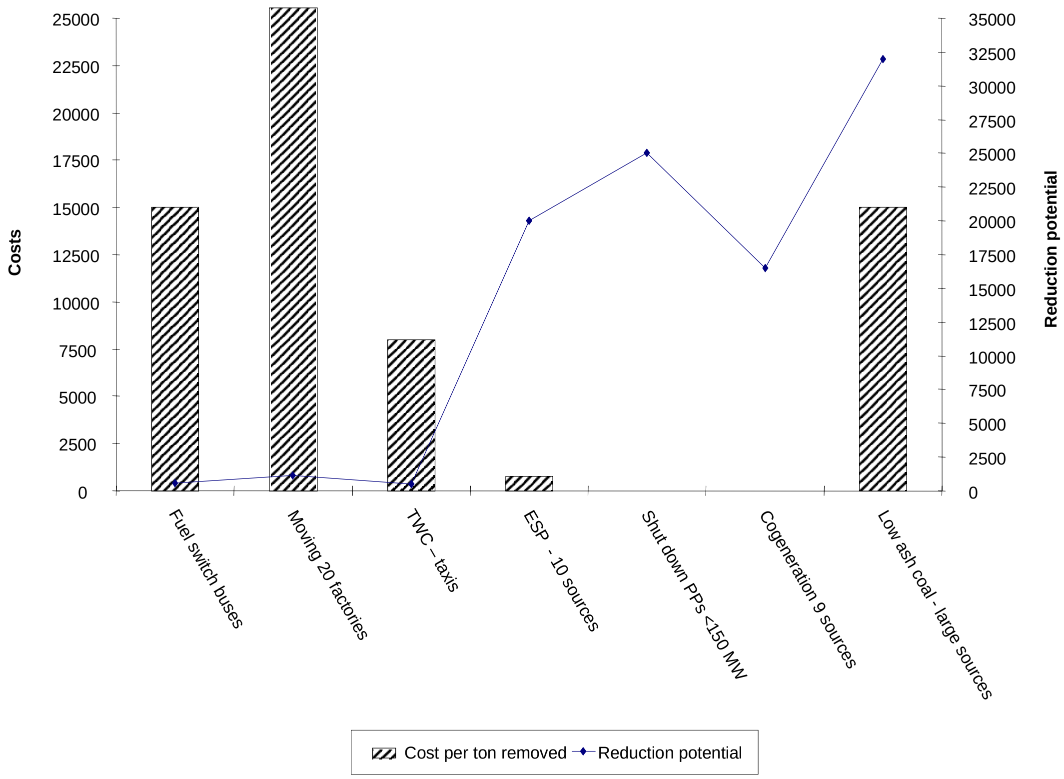
Option	Cost per ton removed	Reduction potential
Co-generation 9 sources	-2.550	16,500 tons
ESP - 11 sources	500-1000	20,000 tons
Shut down 13 power plants, 150 MW or less	0*	26,000 – 39,000 tons
TWC – taxis	8,000	500 tons
Fuel switch 1000 buses	45.000	110 tons
Low ash coal - all large point sources	10,000-20,000 (90-95% cleaning)	32,000 tons
Moving 20 factories	72,400	1,150 tons
Street cleaning	Probably low	Limited (0)

*: Lower range

Figure 5.5 provides an illustration of the costs per ton removed and emissions reduction potential of the various particles control options. Again, there is a strong tendency that the costly options have the smallest emission reduction potentials, while the least costly options have the largest reduction potentials. Low ash coal is an exception and has both relatively high costs and high emission reduction potential.

Among the control options listed above, there are none which are totally mutually excluding or overlapping. The four options that to a certain degree could overlap with each other are: i. cogeneration, ii. shut down of either 18 or 13 small power plants, iii. low ash coal for all large point sources, iv. ESP on 10 worst sources for particles.

Figure 5.5 Abatement costs per ton and abatement potential of TSP control options.



From table 5.9 and figure 5.5 above we can conclude that the options of ESP on 11 sources, shut down of small power plants and co-generation in main industrial sources have a combined reduction potential of roughly 60,000 tons. However, as they are partly mutually excluding, this estimate should be reduced to somewhere around 40,000-50,000 tons if all three options are implemented (and adjusted, cf SO_2). Such a reduction would represent a reduction of emission of 35-40%.

Both cogeneration and high effective ESP are well known technologies already in use in Guangzhou, and the total costs should be very moderate even if we apply the upper range cost estimate for the shut down option.

Since the target is defined for TSP and we only focus on combustion particles emissions (PM10), and since combustion particles only account for a fraction of TSP levels, these three options will not be able to make Guangzhou meet the TSP target, but they will imply a significant reduction of concentrations of the most harmful part of TSP.

6 Cost-benefit analysis

6.1 Introduction

Estimating the *benefits* of reduced air pollution is a difficult task, more so, usually, than estimating costs of certain pollution abatement measures. Environmental benefits are often directly related to the betterment of the quality of people's lives, a quality which is hard to define and measure in monetary terms. Nonetheless, analysis of benefits is an essential component of the basis for public decisions.

This chapter will firstly analyze potential health impacts of the nine proposed control options for SO_2 discussed in section 5.3 (table 5.4), and secondly, propose a tentative economic valuation of these impacts. A brief, and more qualitative, discussion of the reduced material damages in the city of Guangzhou will then be presented.

The costs of implementing control options can then be compared with the benefits to complete the *cost-benefit analysis* in the concluding section, 6.5.

The discussion of physical health impacts is based on GZAQMS task 6-1 (1999), while the methodology for valuation of these impacts is mainly taken from GZAQMS task 6-1 and task 9 (1998). The former report proposes specific exposure-response functions for Guangzhou which replace the more general functions that were used in the 1st sequence calculations.

Estimation of material benefits of reduced SO_2 pollution is based on a damage assessment in Guangzhou (GZAQMS task 6-2 1999).

6.2 Health effects

A complete assessment of health benefits of reduced air pollution involves five steps: (i) establishing a robust relationship (function) between emissions and the level of concentration of various air pollutants, (ii) calculating the exposure of people to the concentration of pollutants (population weighted exposure), (iii) estimating the relevant air pollution reduction from implementing control measures, (iv) estimating the exposure-response functions, i.e. the health impacts on humans, and finally (v) measuring (reduced) health effects in economic terms (health benefits).

Steps (i), (ii) and (iii) have been discussed in previous chapters, while the latter two steps will be treated here.

6.2.1 Exposure-response functions

The health damage assessment for Guangzhou is mainly based on Chinese epidemiological studies on exposure-response relationships between air pollutants and health effects. Some health end-points not covered by Chinese studies were analyzed by using studies carried out in Europe and the U.S. (e.g. for infant mortality, and some respiratory diseases). Most of the functions derived from these studies are rendered as so-called relative functions. This means that they give the percentage increase in the frequency of a given health effect per μm increase of a given air pollutant indicator. In table 6.1 these functions are combined with the observed or estimated frequency of the health effect end-points in Guangzhou to give «absolute functions», i.e. the absolute annual increase in cases per mill. inhabitants per $\mu g/m^3$. The details of these calculations are given in the above mentioned report (GZAQMS task 6-1 and 9, 1998).

Table 6.1 Exposure-response functions proposed for Guangzhou. Change in annual number of cases per mill. people (all ages) per 1 μg/m³ change in ambient concentration[1]. Uncertainty intervals represent tentatively ±1SD.

End-point	Indicator component	Period per case	Coefficient (uncertainty interval)
Deaths	PM_{10}		2.2 (0-4.1)
	SO_2		12 (9-15)
Infant deaths	PM_{10}		0.7 (0.4-0.9)
	SO_2		0.2 (-0.2-0.6)
Outpatient visits (OPV)	PM_{10}		4,670 (1,980-7,360)
	SO_2		1,800 (1,510-2,100)
Emergency room visits (ERV)	PM_{10}		55 (15-95)
	SO_2		186 (112-260)
Hospital admissions (HA)	PM_{10}	21 days	97 (65-121)
	SO_2	"	186 (89-302)
Respiratory hospital admission (RHA)	PM_{10}	14 days	56 (28-84)
(subgroup of HA)	SO_2	"	56 (28-84)
Hospital adm. For COPD (HA-COPD)	PM_{10}	18 days	5 (0-9)
(subgroup of RHA)	SO_2	"	3 (0-5)
Work day loss (WDL)	PM_{10}		18,400 (9,200-27,600)
Respiratory symptoms in children	PM_{10}	1 day	21,500 (14,190-32,470)
(ARS-Ch)	SO_2	"	2,830 (2,690-2,970)
Respiratory symptoms in adults	PM_{10}	"	28,320 (21,130-35,520)
(ARS-Ad)	SO_2	"	7,650 (7,270-8,030)
Chronic resp. Sympt. in children (CRS)	PM_{10}	~1 year	15 (13-18)
Chronic resp. Sympt. in adults (CRI)	PM_{10}	"	34 (29-39)
Asthma attacks	PM_{10}	1 day	1,770 (990-5,850)

1 The share of the population that is <14 y, is incorporated in the functions that applies to adults and children specifically. Thus, the functions can be applied to the total population in an area.

It is worth noting that some of the health end-points in the table, such as WDL and asthma attacks, are associated only with changes in the PM_{10} indicator (see below). The focus in the following will be on the concentration and exposure to people of SO_2. In China, several studies report a clear effect of SO_2 on various health end-points, as indicated in the table above.

6.2.2 Reduced health effects from implementing control options

We have used the exposure-response functions proposed in the Task 6-1 Technical Report, to estimate the reduced health damage that may be obtained by implementing the nine control options for SO_2 given in table 5.4. The calculated reduced damage applies to each control option implemented in the given sequence, i.e. starting with the most cost effective option (see section 5.3.13).

In the calculation we have assumed that the ratio between the reduced population weighted exposure to SO_2 in the 8 central districts *(ΔPWE)* and the concentration reduction in the central area of Guangzhou (ΔC) is the same as in the «1st sequence calculation» (the 1st sequence calculation is described in Technical Report B6). This is a reasonable assumption because the two sets of control options (1st and 2nd sequence) have a similar profile, i.e. they are mainly devised towards large point sources and will have only minor impacts on traffic and other sources. The obtained $\Delta PWE/\Delta C$, where ΔPWE is given in µg/m^3 and ΔC is given in percentage points, is used to calculate the health effects. The ΔPWE is calculated from the output of the KILDER model (run for the 1st sequence control options), whereas the concentration reduction in central areas of Guangzhou that may be achieved by implementing 1st sequence control options, is calculated by means of the function for source contributions (see footnote 21)

In the 1st sequence the KILDER model was run for three control options:

1. Removing point sources from three districts – 50% reduction of the emissions from large and small point sources within these districts;
2. 50% reduction of emissions from motorcycles;
3. Fuel switch to gas for buses.

The first measure would reduce the total SO_2 emissions in Guangzhou by about 3.5%, whereas the total reduction of SO_2 emissions from the three measures together would be about 4-5%[29].

According to the KILDER model, the population weighted exposure *(PWE)* for SO_2 is 61.4 µg/m^3 before the control options are implemented and 59.7 µg/m^3 after implementation. These figures apply to 1995 for the 8 central districts in Guangzhou (Dongshan, Liwan, Yuexiu, Haizhu, Tianhe, Fangchun, Baiyun, and Huangpu). Thus, implementation of these control options would reduce *PWE* with 1.7 µg/m^3 SO_2. As a comparison, *PWE* would be reduced from 72.3 µg/m^3 to 69.8 µg/m^3, i.e. with 2.5 µg/m^3, in the three central districts (Dongshan, Liwan, and Yuexiu), and with 1.5 µg/m^3 (from 55.9µg/m^3 to 54.4 µg/m^3) in the Guangzhou area as a whole. The first control option, «Removing point sources from three central districts», is the most effective in terms of reducing the population exposure. The highest *PWE* in any district (before abatement) was estimated to be 86 µg/m^3 (Fangchun).

The annual SO_2 concentration in the grids that have the highest level (before abatement) is approximately 100 µg/m^3, see 5.3.13. Applying the equation in footnote 21 we estimated that the concentration in these grids would be reduced to 94 µg/m^3 if the 1st sequence control options were implemented. (Because traffic sources contribute only 13% to the factor *b* in the equation the impact of the second and third control option are literally negligible[30]).

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29 Emissions from large point sources in the three central districts represent about 7% (10.3 ktons) of the total SO_2 emissions in Guangzhou. Emissions from small point sources in these districts represent about 0.8% (1.2 ktons) of the total SO_2 emissions.

30 The relative contribution to the aggregate factor *b* in the equation in section 5.3.13 from small point sources is 82%, whereas the relative contribution from domestic and commercial sources is 5%. We estimated that *b* was 0.90 for the 1st sequence control options. Factor *a* in the equation was estimated to be 0.95.

Thus, implementation of the 1st sequence options would reduce the SO_2-concentration in central Guangzhou by 6%, whereas the population weighted exposure is reduced by nearly 3%. Dividing the modelled ΔPWE in the 8 districts (1.7 μg/m^3) with 6 percentage points concentration reduction, we arrive at:

$$\Delta PWE \text{ per percentage point concentration reduction} = 0.3\ \mu g/m^3$$

The estimated ΔPWE for each of the nine control options are given in table 6.2. As seen from the table, the nine control options together reduce the population weighted exposure by 13.5 μg/m^3, which is a reduction of 22%.

The estimated reductions in *PWE* are used to calculate the reduced health damage for each control option (see table 6.4). As discussed in the Task 6-1 Technical Report, SO_2 is an indicator of the air pollution mixture in the functions that are applied here. This means that the observed effect is attributed to one component (SO_2), although it may also be related to other components. Since SO_2 for most end-points is a weaker indicator than PM_{10}, and SO_2-functions are not established for all end-points, the health benefit estimated from SO_2 reductions alone may be an underestimate. The reduction in particulate air pollution that would be achieved if Action Plan 2001 were implemented, would most likely entail additional health benefits.

To put the estimated reduced health damage into perspective, we may compare the figures in table 6.4 with the total number of cases for the various end-points. As seen in table 6.3 the estimated benefit constitutes from 0.3% to 2.8% of the baseline figures.

Table 6.2 Reduced population exposure (SO_2) estimated for each control option, given that the options are implemented in succession.

Control option no.	Red. Factor	Δ PWE (μg/m^3)
1	5.5	1.65
2	5.3	1.59
3	21	6.28
4	4	1.20
5	0.5	0.15
6	5	1.50
7	1.4	0.42
8	0.15	0.04
9	2.4	0.72
SUM	45.3	13.5

Table 6.3 Annual number of cases of various health end-points estimated for the 8 central districts of Guangzhou, and estimated percentage reduction in cases obtainable from implementation of nine control options in Action Plan 2001.

	Annual no. of cases	% reduction
Deaths	22,513	2.7
Infant deaths	463	2.2
Outpatient visits (OPV) (mill.)	30.1	0.3
Emergency room visits (ERV) (mill.)	1.9	0.5
Hospital admissions (HA) (mill.)	0.34	2.8
A/cute resp. Symptoms in children (ARS-Ch)(mill. sympt. Days)	14.9	1.0
Acute resp. Symptoms in adults (ARS-Ad)(mill. sympt. Days)	40.2	1.0
Chronic respiratory disease in adults (CRD-Ad) (cases)	138,000	0.5

Table 6.4 Estimated reduced number of cases obtained for each control option in Action Plan 2001, estimated for the 8 central districts in Guangzhou. OPV: Outpatient visits; ERV: Emergency room visits; HA: Hospital admissions; ARS-Ch: Acute respiratory symptoms in children; ARS-Ad: Acute respiratory symptoms in adults; CRD-Ad: Chronic respiratory disease in adults.

Control option	Deaths			Infant deaths			OPV (10^3)			ERV (10^3)			HA (10^3)			ARS-Ch (10^3)			ARS-Ad (10^3)			CRD-Ad[1]		
	Mean	low	high	Mean	Low	High	Mean	Low	High	Mean	low	high	Mean	low	High	Mean	low	high	Mean	Low	high	Mean	low	high
1	74	53	94	1	-1	4	10.0	8.7	11.4	1.2	0.7	1.6	1.2	0.6	1.9	17.6	16.7	18.4	47.5	45.1	49.8	82	16	147
2	72	51	91	1	-1	4	9.7	8.3	11.0	1.1	0.7	1.6	1.1	0.5	1.8	16.9	16.1	17.8	45.7	43.4	48.0	79	16	141
3	284	201	360	5	-5	14	38.3	33.1	43.6	4.4	2.7	6.2	4.4	2.1	7.2	67.0	63.7	70.4	181.2	172.1	190.3	311	62	560
4	54	38	69	1	-1	3	7.3	6.3	8.3	0.8	0.5	1.2	0.8	0.4	1.4	12.8	12.1	13.4	34.5	32.8	36.2	59	12	107
5	7	5	9	0	0	0	0.9	0.8	1.0	0.1	0.1	0.1	0.1	0.1	0.2	1.6	1.5	1.7	4.3	4.1	4.5	7	1	13
6	68	48	86	1	-1	3	9.1	7.9	10.4	1.0	0.6	1.5	1.0	0.5	1.7	16.0	15.2	16.8	43.1	41.0	45.3	74	15	133
7	19	13	24	0	0	1	2.6	2.2	2.9	0.3	0.2	0.4	0.3	0.1	0.5	4.5	4.2	4.7	12.1	11.5	12.7	21	4	37
8	2	1	3	0	0	0	0.3	0.2	0.3	0.0	0.0	0.0	0.0	0.0	0.1	0.5	0.5	0.5	1.3	1.2	1.4	2	0	4
9	32	23	41	1	-1	2	4.4	3.8	5.0	0.5	0.3	0.7	0.5	0.2	0.8	7.7	7.3	8.0	20.7	19.7	21.7	36	7	64
Total	613	434	776	10	-10	31	82.6	71.3	93.9	9.5	5.7	13.3	9.5	4.5	15.4	144.4	137.2	151.6	390.4	370.9	410.0	671	134	1208

1 To tentatively estimate the effect on this end-point we have used a preliminary function from the interview study (Task 6-1).

Discussion

Table 6.1, table 6.3 and table 6.4 give a mix of the two main categories usually considered in epidemiological studies on health effects of air pollution:

- *Biological end-points*, e.g. mortality or lost years of life, acute respiratory symptoms and chronic respiratory disease.
- *Social or consequential end-points*, e.g. hospital admissions, emergency room visits and outpatient visits.

These categories have different advantages and drawbacks when it comes to the economic valuation of health damage due to air pollution. Some of the biological parameters are assumed to be more reliable. Consequential end-points, like hospital admissions, are, on the other hand, in some ways easier to assess in monetary terms.

The end-points included in the above tables are regarded as relevant for the situation in Guangzhou, in that a relationship between SO_2 concentration and these end-points has been established. As mentioned above, not all health end-points can be related to SO_2 and to disentangle the direct effect of SO_2 (from other pollutants such as PM_{10}) is by nature a difficult task. A discussion of the academic basis for the estimation of the various end-points for Guangzhou and how the estimates have been derived from Chinese and US/European studies are given in chapter 5 in GZAQMS task 6-1 and 9 (1998).

It can be seen from table 6.4 that control options 1-3, if implemented, would give a total mortality reduction of 430 adults annually (mean values considered) . Similarly, for less serious health end-points, such as Acute Respiratory Symptom days, the total reduction of cases for adults and children would be 375.900, a considerable figure. We arrive at the mean figures in table 6.4 by multiplying the exposure-reponse coefficients (per *mill.* people) for SO_2 (table 6.1) by the ΔPWE for each control option (table 6.2) and the population number of central Guangzhou (3.7 mill.).

The figures in table 6.4 should be regarded as rough indications of the health effects of reduced air pollution in Guangzhou. The true effects are (of course) unknown so figures are presented with an uncertainty band. There are inherent difficulties in measuring health effects, since a whole range of background and health status variables need to be controlled for. Problems connected to transferring risk estimates from one population to another ad to this difficulty. For instance, the composition of the car fleet in Western Europe and the U.S., where most of the epidemiological studies have been performed, differs substantially from that in China. There are also fundamental differences in the use of coal, overall health status, age distribution in the population etc. between China and USA/Europe, as well as somewhat more negligible differences between the main study region in China (Beijing) and Guangzhou.

In the European ExternE program it was recommended that quantitative estimates of health effects of air pollution are more reliably transferable between locations if expressed as percentage change (per unit of exposure) rather than as absolute numbers (EC, 1995). This is to ensure that the calculated possible reduction in health damage from a reduction in the population exposure in the applied study is a function of the actual frequency before abatement takes place. This is also the approach taken in our study.

Despite these fundamental difficulties in estimating specific exposure-response functions for Guangzhou, we have reason to believe that the estimates can be seen as rather conservative. At least two factors indicate such a conclusion.

First, Chinese studies, on which a large share of the estimates are based, generally report lower coefficients for the exposure-response relationships than studies from Europe or the U.S. Problems related to possible confounding with indoor air pollution are indicated in most Chinese studies. We therefore regard the estimated benefit calculated by means of the functions based on Chinese studies as rather conservative, i.e. they may possibly understate the effect of air pollution abatement. This interpretation is more likely than that the more numerous Western studies systematically exaggerate exposure-response coefficients.

Second, few studies on the long-term effect of air pollution on mortality rates of populations have been carried out. Since some ailments last for a considerable number of years, the overall health effects can be hard to estimate. There is no consensus as to how to estimate this chronic effect of air pollution on mortality rates in a population, so we decided to omit this potential effect here.

6.3 Economic valuation of health effects

Having analyzed the potential health impacts from the reduced air pollution obtained from implementing the nine control options, the next step is to measure these in monetary terms. This step will enable a comparison of the control costs with the total health benefits.

The valuation of health impacts is difficult and controversial. One thing is to measure the ‘hard costs’ involved in hospital treatment for people (transport, medicines, doctor/nurse care etc.). Quite another is to find an estimate of the overall loss to society from illness and premature deaths.

As the case for epidemiological studies, most health valuation studies have been carried out in Europe and the U.S. Two different methodologies (approaches) for estimating the value of lives lost (and chronic diseases) have been identified in these studies, each of which will be briefly explained in turn here.

In many Western studies the willingness-to-pay approach (WTP approach) is the preferred methodology. This approach values the health impact as the monetary amount people are willing to pay for reduction of health risks, e.g. wage differentials between risky and similar non-risky jobs, or purchases of life saving equipment. A fundamental reason why economists prefer this approach is that the health valuation is based on people’s preferences, i.e. the value (of health) is determined in the market place.

Two common and related methodologies in the WTP category are the estimations of the value of a statistical life (VOSL) and the value of life years lost (VOLY).

VOSL generalizes individual willingness to pay to achieve a small reduction in the probability of death, to a collective good of group or societal willingness to pay for policies that reduce the risk of random death to one of its members. Heterogeneity in value of life assessments may arise from differences in wealth, risk preference, age, education, race, nature of risk incurred (voluntary versus involuntary) and initial probability of mortality, method of death, and latency, in the case of disease. To illustrate, a recent study by Feng (1999) reports VOSL estimates for the U.S. which range between USD 1.6 mill. and USD 8.5 mill. WB (1997a) reports an average estimate of USD 3 mill. per statistical life for the U.S. which adjusted to Chinese circumstances yields an estimate of USD 60.000 per statistical life in urban China.

The related methodology under the WTP heading, is as mentioned above, the VOLY approach. Estimating VOLY, as opposed to VOSL, has recently been recommended by the European Commission (EC, 1998). This methodology is a response to certain weaknesses attached to the VOSL approach. VOSL does not take into account that the willingness to pay (for reduced health risk) may be dependent on a person's life expectancy. For example, many people whose deaths are linked to air pollution may be suspected of having only a short life expectancy even in the absence of air pollution.

These two related approaches have, however, mostly been used in Europe and the U.S., so there are very few data on VOSL and VOLY in developing countries, which would be more directly relevant to the situation of Guangzhou (and China). The way around this dilemma is either to adjust and transfer Western WTP estimates to the specific economic circumstances prevailing in Guangzhou, or try and use adjusted estimates from the very few relevant WTP studies carried out in non-Western countries. We have in this study, as far as possible, tried to utilize the latter type of estimates, even though for some health end-points Western estimates had to be applied. The background calculations for various health end-points will be briefly explained below.

The second main methodology to measuring the value of lives lost, which has been widely used in China, is the human capital approach (HC approach). This approach values mortality and morbidity impacts simply as lost productivity (discounted lost wages) plus out-of-pocket expenditures (such as medical bills). The preferred approach to valuing environmental damages to health has shifted from the HC approach to the WTP approach. The HC approach generally yields a lower estimate, but continues to be widely applied because it is convenient and straightforward (e.g. wages are generally easily observed). In some cases the HC estimate is used to represent a lower bound on WTP. Another reason why HC is often used is that the method can be seen as less controversial (outside the field of economics).

The following analysis for Guangzhou includes estimates generated by using both the WTP and the HC approach. Estimates for the values per case of various health end-points are given in table 6.5. The assumptions underlying the calculations are explained below.

Table 6.5 Unit valuation of mortality and morbidity effects from reduced SO_2 pollution – 1994 prices.

Health impact	WTP approach: Task 9 estimates RMB per case	WTP approach: World Bank (1997) estimates RMB per case	HC approach: Adjusted WB (1997) estimates, and task 9 estimates RMB per case
Mortality, per death	620,288	517,200	77,321
Respiratory hospital admissions (HA)	5123	2448	5123
Work Day Loss for HA	252	-	252
Emergency room visits (ERV)	114	198	114
Outpatient visits (OPV)	114	-	114
Chronic bronchitis (CRD-Ad)	68,960	68,960	10,310
Respiratory symptoms (ARS)	8	5	8

Table 6.5 is taken from the 1st sequence health damage assessment report, only with an additional column showing corresponding estimates by using the HC approach.

The value of health impacts of SO_2 estimated for Guangzhou (column 1) is generally higher than the World Bank estimates (WB, 1997a) (column 2). The differences arise primarily because the income level in Guangzhou is higher than the average income level in China. The following paragraph gives a brief description of the calculations behind the estimates in column 1 and 2, and the specific estimates generated by using the HC approach (column 3).

Ad. Mortality:

The estimate for mortality is based on a study from Taiwan. Liu, et.al. (1997) has estimated the willingness to pay to save one statistical life in Taiwan based on labor survey data. In the estimate for Guangzhou it is assumed that the ratio of willingness to pay to save one statistical life to the total income in Guangzhou is the same as in Taiwan. Thus, when adjusting for different GDPs per capita, we arrive at RMB 620,288 per death (avoided).

Ad. Respiratory hospital admissions (HA):

The valuation of HA in Guangzhou (RMB 5123) is based on the average cost of seven respiratory diseases collected from one hospital in Guangzhou. An uncertainty of the estimate arises if the hospital is not representative. The figure seems to differ considerably from the World Bank which is only half of the estimate of Guangzhou.

Ad. Work day loss for HA:

When a patient is admitted to a hospital suffering from a disease associated with air pollution, time which could alternatively be used to work is generally lost. A rough estimate of this work day loss can be calculated as follows. The average daily wage in Guangzhou was reported to be (RMB 8831/365=) RMB 24/day in 1994 (Guangzhou Statistical Yearbook 1995). A conservative assumption to take account of people who do not work (i.e. children, elderly, disabled and unemployed), is that half of this daily wage is lost when a (random) person is admitted to hospital. Since a HA case on average lasts 21 days (confer table 6.1), we arrive at an estimate of RMB 252 per case of HA.

Ad. Emergency room visits (ERV):

Estimating ERV in Guangzhou (RMB 114) is done by calculating the cost of visiting a doctor when people catch a cold as a proxy because it is a fair representative of symptoms related to air pollution. The cost includes the following items: transportation fee (RMB 20 by taxi), registration fee (RMB 4) and medicine fee (RMB 90). The cost is somewhat lower than the World Bank estimate of RMB 198.

Ad. Outpatient visits (OPV):

The estimate for ERV is used for this category. It is likely that the cost of treating an emergency case is somewhat higher than the cost of a general polyclinical visit. This inaccuracy will not change the overall picture in the cost-benefit analysis.

Ad. Chronic bronchitis (CRD-Ad):

Chronic respiratory disease in adults is used as a proxy for the health end-point chronic bronchitis. The World Bank (1997) estimate is preferred because no cost studies for chronic bronchitis have been made for Guangzhou.

Ad. Respiratory symptoms (ARS):

The cost considered only includes medicine (RMB 8). People do not generally visit the doctor when feeling unwell from respiratory symptoms.

Ad.HC approach

The estimates in column 3 are naturally different from column 1 and 2 only for the health end-points, mortality and chronic bronchitis. World Bank (1997a)'s estimates for China are used unadjusted for Guangzhou. Age-specific mortality data for Beijing (1989) were used by the World Bank to calculate the HC estimate. It can be seen from the table that in this case the WTP approach yields estimates for mortality and chronic bronchitis which are around six and eight times higher, respectively, than the HC estimates.

To sum up, in order to calculate the value of the health effects associated with reduced SO_2 pollution from implementing the control options suggested in this action plan, the mean figures for different end-points in table 6.4 are multiplied with the corresponding values per case given in table 6.5. These total health benefit figures will be presented together with the respective costs of implementation in section 6.5.

6.4 Reduced material damages

Within the Guangzhou Air Quality Management System project, a damage assessment of the outer materials in Guangzhou was carried out. A thorough field study in the small smaller central part (14 km x 10 km) of the model area in Guangzhou was performed and the total amount of materials was distributed into the modelling grid squares. The average lifetime for the different materials can be calculated for each grid square based on existing lifetime equations. These lifetime equations describe the reduction of life for materials caused by air pollution in the area. With knowledge of the lifetime, the amount of materials and prices for repair and maintenance work in the area, the total cost for the yearly repair can be calculated. By using the same input parameters for an unpolluted situation, the part of the cost connected to the air pollution in the area has been calculated for the situation in 1995 (GZAQMS task 6-2 1999).

For this action plan a benefit calculation for materials (reduced damage costs) has been carried based on the data reported in GZAQMS task 6-2 (1999) and the changes in the SO_2 concentrations calculated for the different control options.

The calculations have been carried out using the following limitations and assumptions:

- The changes in the SO_2 concentrations were reduced with the same percentage as for the control option in all grid squares[31].
- Due to practical constraints, only the materials concrete and painted steel were selected. Concrete was selected as one of the materials that had a step function for the lifetime dependence for air pollution. Painted steel was a representative for the materials with a real lifetime equation and with a high percentage of material exposed (12.5%).
- The damage cost for painted steel was taken as representative for all materials with an established lifetime equation. The total damage cost was then calculated by extrapolating the damage cost up to 64.6% of the total amount of materials, since 64.6% of the materials have lifetime equations of the same type as painted steel.
- The materials excluded in this calculation of total damage costs were concrete, bricks, aluminium, stainless steel, and glass.
- The cost benefit for concrete and bricks would have been calculated separately if the control options had given changes in the lifetime for the materials. For this being the case, the SO_2 concentrations in the grid squares would have had to be lower than 15 µg/m3. To reach that concentration for the *square with the lowest concentration* in 1995 the reduction must be as high as 45%.
- All calculations are based on the results from the smaller grid (14 km x 10 km).

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[31] By using the CorrCost Excel v1.0 model given to GRIEP as a part of the co-operation project *Air Quality Management and Planning System for Guangzhou* (NORAD Project CHN 013).

In table 6.6 the results based on the 1995 pollution levels and reported in report (GZAQMS task 6-2 1999) are given. The damage cost for the materials sensitive to the SO_2 reduction produced by the control options (64.6% of the total amount of materials) is given both as extrapolated values according to the assumptions given above as well as the values calculated in the GZAQMS task 6-2 (1999). The difference between the two results is minor and indicates that the assumption used in this report will give data with sufficient quality.

The results based on the 1995 pollution levels are given in table 6.6. All calculations are based on the results from the smaller grid (14 km x 10 km) and *no extrapolation to the large grid (52 km x 56 km) has been done*. A rough estimate is that 50% of all materials in study area is within the inner area of 14 km x 10 km.

Table 6.6: Corrosion cost in Guangzhou with the pollution levels in 1995.

	Total cost, mill. RMB	Cost background pollutants, mill. RMB	Cost linked to pollutants, mill. RMB
Concrete	3.35	2.68	0.67
Painted steel	70.88	52.70	18.18
Cost of 64.6% materials based on extrapolation	366.3	272.4	93.9

Table 6.7 gives a first rough estimation of benefits from reduced material damage resulting from SO_2 control options 1-9 using the limitations and assumptions above. The benefits are calculated only for inner area (14 km x 10 km). A rough extrapolation to the large grid (52 km x 56 km) should double the benefits since half of the population is living outside the central part. This assumption is probably valid since the materials included in the calculation are standard materials. Expensive materials used in new commercial and institution buildings, which are more frequently seen in the central areas of a city, are not included in the extrapolation.

Table 6.7 Benefits for materials obtained by implementing the 9 pollution control options for SO_2 (mill. RMB).

Control option	Pollution reduction	Materials, total benefits
1	5.5%	7.6
2	5.3%	7.3
3	21%	29.1
4	4%	5.5
5	0.5%	0.7
6	5%	6.9
7	1.4%	1.9
8	0.15%	0.2
9	2.4%	3.5

The 64.6% of the materials included in the calculations represent more than 64.6% of the damage because the remaining materials (35.4%) are in large part materials with long lifetime and little sensitivity for air pollutants. There are however two materials that are sensitive to pollution but which are not included in the calculations: aluminium and glass. With time aluminium will have a reduced

esthetical value but the functional time will still be quite long. Cleaning of windows is the other esthetical value not taken into account.

6.5 Benefits and costs compared

This section will finalize the chapter by comparing the total costs and benefits of implementing the nine selected pollution control options.

The cost benefit analysis is presented in table 6.8 and table 6.9. The first table shows the total annual costs and benefits when the HC approach is applied, and table 6.9 uses the WTP approach. Thus, table 6.8 and table 6.9 differ in the estimates of the health end points, death and chronic disease, whereas the other estimates are common for the two approaches. If one prefers to look at the overall costs and benefits independently of the estimation approach chosen for deaths and CRD, such an estimate is given in the last row of table 6.8 (including total annual number of lives saved and break even value of mortality).

Table 6.8 Costs and benefits from the implementation of Action Plan 2001 estimated by using the human capital approach (mean values, mill. RMB).

Category/Control Option 1-9	1	2	3	4	5	6	7	8	9
Total Annual Costs	-30	0	101,2	120	11	170	36,2	6,3	1350
Health benefits									
Deaths (incl. infants)	5,9	5,6	22,4	4,3	0,5	5,3	1,5	0,2	2,6
Hospital Admissions (HA)	5,9	5,7	22,6	4,3	0,5	5,4	1,5	0,2	2,6
Work day loss for HA	0,3	0,3	1,1	0,2	0,0	0,3	0,1	0,0	0,1
Outpatient Visits (OPV)	1,1	1,1	4,4	0,8	0,1	1,0	0,3	0,0	0,5
Emergency Room Visits (ERV)	0,1	0,1	0,5	0,1	0,0	0,1	0,0	0,0	0,1
Acute Respiratory Symptoms (ARS)	0,5	0,5	2,0	0,4	0,0	0,5	0,1	0,0	0,2
Chronic Respiratory Disease (CRD)	0,8	0,8	3,2	0,6	0,1	0,8	0,2	0,0	0,4
Total Annual Health Benefits	14,7	14,2	56,1	10,7	1,3	13,4	3,7	0,4	6,4
Material benefits	7,6	7,3	29,1	5,5	0,7	6,9	1,9	0,2	3,5
Total Annual Benefits	22,3	21,5	85,2	16,2	2,0	20,3	5,6	0,6	9,9
Net benefits	***52,3***	***21,5***	***-16,0***	***-103,8***	***-9,0***	***-149,7***	***-30,6***	***-5,7***	***-1340,1***
Benefit-Cost Ratios	n/a	DIV/0	0,8	0,1	0,2	0,1	0,2	0,1	0,0
Net benefits (excl. Deaths and CRD)	45,6	15,1	-41,6	-108,7	-9,6	-155,8	-32,3	-5,9	-1343,0
Lives saved annually (# of people)	75	73	289	55	7	69	19	2	33
Break even value of mortality	n/a	n/a	0,1	2,0	1,4	2,3	1,7	3,0	40,7

Table 6.9 Costs and benefits from the implementation of Action Plan 2001 estimated by using the Willingness to Pay approach (mean values, mill. RMB).

Category/Control Option 1-9	1	2	3	4	5	6	7	8	9
Total Annual Costs	-30	0	101,2	120	11	170	36,2	6,3	1350
Health benefits									
Deaths (incl. Infants)	47,0	45,3	179,3	34,2	4,3	42,7	12,0	1,3	20,5
Hospital Admissions (HA)	5,9	5,7	22,6	4,3	0,5	5,4	1,5	0,2	2,6
Work day loss for HA	0,3	0,3	1,1	0,2	0,0	0,3	0,1	0,0	0,1
Outpatient Visits (OPV)	1,1	1,1	4,4	0,8	0,1	1,0	0,3	0,0	0,5
Emergency Room Visits (ERV)	0,1	0,1	0,5	0,1	0,0	0,1	0,0	0,0	0,1
Acute Respiratory Symptoms (ARS)	0,5	0,5	2,0	0,4	0,0	0,5	0,1	0,0	0,2
Chronic Respiratory Disease (CRD)	5,6	5,4	21,5	4,1	0,5	5,1	1,4	0,2	2,5
Total Annual Health Benefits	60,6	58,4	231,3	44,0	5,5	55,1	15,4	1,6	26,4
Material benefits	7,6	7,3	29,1	5,5	0,7	6,9	1,9	0,2	3,5
Total Annual Benefits	68,2	65,7	260,4	49,5	6,2	62,0	17,3	1,8	29,9
Net benefits (mill. RMB)	***98,2***	***65,7***	***159,2***	***-70,5***	***-4,8***	***-108,0***	***-18,9***	***-4,5***	***-1320,1***
Benefit-Cost Ratios	n/a	DIV/0	2,6	0,4	0,6	0,4	0,5	0,3	0,0

6.5.1 Discussion

It can be seen from table 6.8 that when the HC approach is used only control options 1 and 2 have positive net benefits (RMB 52,3 mill. and RMB 21,5 mill. respectively). This means that if the benefits given in the table represent the true benefits in a satisfactory way, only the control options 1 and 2 should be carried out. This is the normative guideline for public undertakings which follows from the cost benefit analysis. The first option is, as mentioned in chapter 4, a true ‘win-win’ option.

If one looks at the benefits independently of deaths and CRD the conclusion above still holds, i.e. only counting ‘hard costs’ saved from reduced air pollution gives positive net benefits. In *addition* comes the lives saved every year which for control options 1 and 2 are 75 and 73 respectively.

When marginal cases, such as option 3 in table 6.8 arise it is advisable to consider the valuation of mortality (and chronic disease) a bit more carefully. One way of doing this is to calculate the value per life saved when the options *break even*. Leaving CRD out, yields a break even value of mortality for option 3 of RMB 100,000. It must be noted here that since estimates of benefits from reduced CRD are left out, the break even values are somewhat higher than they otherwise would be. When general valuation methodologies are put aside, it is very much a normative decision which values of mortality should be set (accepted) in a given situation (e.g. is RMB 100.000 ‘reasonable’?).

As is evident from a whole range of evaluation studies, the HC estimate is often regarded as a lower bound on the WTP estimate, and as a relatively low estimate of what one would believe is the ‘true’ value of (reduced) frequency of illness and death. In order to complete the picture and bring our analysis in line with the general recommendations in the international scientific literature, the estimates from using the WTP approach are given in table 6.9.

The net benefits are all positive for control options 1 through to 3. Options 1 and 2 make an even stronger case, while option 3 now emerges as a beneficial control option (BC ratio of 2,6).

The single most important health end-point in the tables above is the reduction in the number of deaths. Whether control option 3 should be regarded as beneficial to society depends, thus, fundamentally on the point of view one chooses to have about estimation methodologies.

In completing this short discussion, there are a number of potential benefits from reduced air pollution that not yet have been treated explicitly in the preceding section. An important point in relation to the discussion of reduced air pollution is that our estimates above do not include potential synergy effects. We have analyzed SO_2 in particular and it is likely that reduced air pollution will also reduce the concentration of other damaging pollutants (such as PM_{10} and NO_x).

A second, and final, point mentioned here is that there are usually also many ecosystem benefits associated with reduced air pollution. As mentioned in the recent book by Feng (1999) these benefits may be expressed as increased agricultural yield, and generally cleaner terrestrial ecosystems (e.g. forests and rivers). Clean water and higher agricultural benefits carry obvious values to Man, while clean terrestrial environments in general may be important far beyond mere life support.

7 Conclusions

SO_2

The analysis in the preceding chapters have shown that the target for annual average for SO_2 can be met quite easily at low total annual costs. The least cost package consists of cogeneration in 8 industrial facilities, shut down of a group of small power plants and sorbent injection in all 55-60 large point sources. The net annual costs will be less than RMB 70 mill.

The technologies of cogeneration and sorbent injection are mature and well-known, and they are both used in Guangzhou already. This fact increases the feasibility of the options. Politically, the shut down of small power plants might run into problems on several fronts. First, it could be assessed to contradict national power sector policies for the short term. It could also conflict with the interests of local authorities which are financially responsible for the small plants and enjoy the income from them. However, these problems can most probably be solved. Further studies should be undertaken to identify how such hurdles might be overcome.

As for the maximum 24 hour target, it is quite clear that it will be quite more difficult and more costly to achieve, but far from impossible. It will probably require a somewhat different composition of the package of control options. Although we have not analysed this question in any depth, it seems likely that if this target is to be met, some of the most effective and more costly control options such as the wet or dry FGD needs to be applied on a larger number of large point sources.

NO_x

For NO_x we can conclude that the control options covered in this report will not be sufficient to meet the stated targets. There are two important reasons for this:

- background levels represent high shares of target concentration levels
- traffic also account for high shares of contributions to concentrations and the control options for traffic are not very effective.

From this, three different responses should be considered in terms of the targeted NO_x concentrations. *First*, Guangzhou should consider how it might help reduce out-of-area emissions that contribute to background levels. *Second*, Guangzhou should consider more aggressive or potent options towards emissions from traffic. One such measure could be emission standards that require TWC on all new gasoline (and LPG) fuelled vehicles. However, this will only produce significant reductions in a somewhat longer perspective, necessitating other measures in the short term. This could be non-technical options such as fuel taxes or limiting the total number of vehicles or other means to reduce the volume of road traffic. *Third*, Guangzhou might relax the NO_x target and instead focus on NO_2 as this compound is clearly the more significant one in terms of health effects. The NO_x target in China equals WHO's guideline for NO_2, while it may be assumed that 50% of NO_x concentrations is accounted for by NO_2. This implies that the Chinese NO_x target is approximately twice as ambitious as the WHO guideline and very ambitious by any international standard. This is even more so for the 2010 target.

Finally, it would probably pay off to apply the most effective NO_x control options on a larger number of sources than we have done here. The control options for point sources should not be associated with any major technical or political obstacles, even though some technologies such as SCR and SNCR are new in China. Internationally, all are well known technologies.

If the annual target is adjusted downwards by 50%, this would imply a required reduction of concentrations of 25 percentage points from 1995 levels in central Guangzhou (annual average). The total annual costs of achieving such a target would be in the order of RMB 250-300 mill. Achieving the current targets for NO_x could easily prove to be a rather costly affair with questionable health improvements.

TSP

As for TSP we concluded that three options – cogeneration, shut down of small power plants and high effective ESP on 11 sources – will reduce total emissions of combustion particles by 40,000-50,000 tons, or 35-40% from 1995 level. The total costs will be small, and all three options should be feasible. Cogeneration and high effective ESP are mature technologies which are also in use in Guangzhou. For those sources where ESP might pose technical problems, the alternative baghouse filters should be considered. Again, the shut down of small power plants could turn out to be politically controversial in the short term but not so much so slightly extended perspective.

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ANNEX 1

List of all large point sources for SO_2 ("POI 50" = sources with emissions larger than 50 kg/h)

Name	Contribution (ug/m3)	% of load	SO_2 emission (kg/h)	% of emission	X	Y	Emission t/year
Zini Sugar Refinery	154.23	1.48	130.00	1.03	26.16	2.77	1 139
Zini Sugar Refinery	97.18	0.94	128.58	1.02	26.05	2.76	1 126
Zini Sugar Refinery	97.81	0.94	129.41	1.03	26.05	2.76	1 134
Hengyun Dian Factory	267.87	2.58	210.32	1.67	45.26	21.20	1 842
Hengyun Dian Factory	200.68	1.93	182.67	1.45	45.26	21.20	1 600
Hengyun Group Factory	140.90	1.36	72.48	0.57	45.38	20.80	635
Hengyun Group Factory	120.98	1.16	61.41	0.49	45.38	20.80	538
Gz Yongda Group	101.01	0.97	30.63	0.24	34.00	17.30	268
Gz Yongda Group	356.90	3.44	112.15	0.89	34.00	17.40	982
Gz Yongda Group	273.25	2.63	234.39	1.86	34.00	17.40	2 053
Gz Yongda Group	81.67	0.79	56.33	0.45	34.00	17.40	493
Gz Danfei Factory	223.20	2.15	167.98	1.33	32.82	30.10	1 472
Gz Danfei Factory	387.28	3.73	135.03	1.07	32.82	30.10	1 183
Hp Power Plant	62.75	0.60	295.35	2.34	45.15	22.81	2 587
Hp Power Plant	52.22	0.50	245.77	1.95	45.15	22.81	2 153
Hp Power Plant	60.90	0.59	286.64	2.27	45.15	22.81	2 511
Hp Power Plant	64.63	0.62	304.18	2.41	45.15	22.81	2 665
Hp Power Plant	68.41	0.66	798.27	6.33	45.39	22.79	6 993
Hp Power Plant	52.35	0.50	610.86	4.84	45.39	22.79	5 351
Zj Rubber Tire Factory	62.54	0.60	41.10	0.33	3.76	55.41	360
Gz Weidagao Factory	204.71	1.97	99.80	0.79	21.75	22.78	874
Gz Shihuazong Factory	226.93	2.18	946.52	7.50	44.97	27.27	8 292
Gz Shihuazong Factory	126.97	1.22	90.06	0.71	44.69	28.11	789
Gz Shihuazong Factory	91.81	0.88	67.86	0.54	45.58	27.80	594
Gz Aosan Weijing Factory	168.16	1.62	115.63	0.92	21.17	22.30	1 013
Py Meishan Sugar Refinery	112.94	1.09	70.79	0.56	44.26	-5.03	620
Py Meishan Sugar Refinery	33.36	0.32	72.93	0.58	44.24	-5.02	639
Py Meishan Sugar Refinery	124.28	1.20	326.92	2.59	44.24	-5.03	2 864
Gz Zhujing Dian Factory	205.44	1.98	1021.85	8.10	51.70	-7.10	8 951

Gz Zhujing Dian Factory	204.65	1.97	987.11	7.83	51.70	-7.10	8 647
Gz Power Plant	317.99	3.06	1173.69	9.30	17.30	29.87	10 282
Gz Paper Making Factory	172.35	1.66	70.74	0.56	20.83	22.37	620
Gz Paper Making Factory	201.67	1.94	106.07	0.84	20.83	22.37	929
Gz Paper Making Factory	154.37	1.49	68.78	0.55	20.84	22.38	603
Gz Paper Making Factory	195.23	1.88	141.67	1.12	20.71	22.38	1 241
Gz Paper Making Factory	180.48	1.74	131.95	1.05	20.71	22.38	1 156
Gz Zj Cement Factory	6.74	0.06	24.16	0.19	9.00	51.30	212
Gz Zj Paper Making Factory	537.97	5.18	99.76	0.79	31.70	26.50	874
Gz Zj Beer Factory	80.06	0.77	35.58	0.28	28.50	25.83	312
Gz Huaxian Factory	339.12	3.26	85.49	0.68	32.82	27.18	749
Gz Steel & Iron Company	105.43	1.02	120.79	0.96	18.70	22.20	1 058
Gz Steel & Iron Company	141.27	1.36	53.23	0.42	18.98	21.32	466
Gz Steel & Iron Company	164.13	1.58	102.88	0.82	18.98	21.28	901
Gz Haotian Huaxue Group	392.14	3.78	82.73	0.66	36.33	25.26	725
Py Yuguotou Sugar Refinery	11.40		17.40		29.94	-19.16	152
Gz Huaqiao Sugar Refinery	124.37	1.20	66.48	0.53	15.90	32.10	582
Gz Huaqiao Sugar Refinery	123.79	1.19	64.78	0.51	15.90	32.12	567
Gz Youzhiqi Factory	343.43	3.31	126.79	1.01	37.90	28.12	1 111
Py Lianhuashan Zhi Factory	336.70	3.24	95.99	0.76	45.89	10.99	841
Py Lianhuashan Dianli	1630.24	15.70	356.72	2.83	45.80	11.00	3 125
Xinhua Cement Factory	9.67		10.24		16.12	55.87	90
Nh Dianhuaqiye Group Facto	150.28	1.45	486.99	3.86	11.85	31.78	4 266
NH DIANLISHIYE Group Facto	26.63	0.26	605.86	4.80	-16.13	-0.55	5 307
NH DIANLISHIYE Group Facto	16.17	0.16	118.36	0.94	-16.10	-0.56	1 037
NH DALI Power Plant	65.01	0.63	81.37	0.65	7.55	19.12	713
SD GD Guoyingsugar Refiner	29.14	0.28	58.72	0.47	19.97	-4.11	514
SD GD Guoyingsugar Refiner	20.56	0.20	60.60	0.48	20.07	-4.14	531
SD Power Plant	53.30	0.51	72.40	0.57	20.55	-4.44	634
SD Power Plant	52.37	0.50	89.14	0.71	20.57	-4.41	781

ANNEX 2

List of 17 largest SO_2 point sources

Stack name	Location (coordinates)		Emission (kg/h)	Concentration contribution (Ug/M^3)
	X	Y		
Hengyun Di	45.26	21.20	210.32	1060.18
Hengyun Di	45.26	21.20	182.67	794.44
Gz Yongda	34.00	17.40	112.15	1493.64
Gz Yongda	34.00	17.40	234.39	1102.39
Gz Danfeic	32.82	30.10	167.98	927.27
Gz Danfeic	32.82	30.10	135.03	1636.75
Gz Weidaga	21.75	22.78	99.80	859.83
Gz Shihuaz	44.97	27.27	946.52	896.54
Gz Aosan W	21.17	22.30	115.63	708.96
Gz Zhujing	51.70	-7.10	1021.85	842.41
Gz Zhujing	51.70	-7.10	987.11	837.82
Gz Fadianc	17.30	29.87	1173.69	1300.24
Gz Zaozhic	20.83	22.37	106.07	767.34
Gz Zaozhic	20.71	22.38	141.67	772.84
Gz Zaozhic	20.71	22.38	131.95	714.36
Gz Zj Zaoz	31.70	26.50	99.76	2154.57
Py Lianhua	45.89	10.99	95.99	1372.54

ANNEX 3

20 factories to be moved out of inner city. Emissions of SO_2, NO_x and particles

Firm name	SO_2 emission kg/yr	NO_x emission kg/yr	Part. emission kg/yr	Production value (RMB 10,000)
Yc Baojianshipin Gongsi	39424	11506.88	227525.76	709
Guangzhou Tongcaichang	53072	15490.39	306291.78	8323
	100590	23839.83	28165.2	
	6438.6	1073.1	2897.37	
Guangzhou Guolufujichang	80	21.45	323.2	600
Guangzhou Liusuanchang	8802.56	3396.18	46636.64	2102
Guangzhou Diyi Ranzhichang	64020	17285.4	8706.72	3945
	693	124.3	13.75	
Guangzhou Yuanneng Huagongchang	27509.7	7427.619	3741.3192	1490
Guangzhou Qianjin Xiangjiao	2464	719.18	14220.36	130
Guangzhou Jueyuan Cailiaochang	38400	11208	221616	2735
Gd Yueqichang	201.096	36.0696	3.99	1835
Guangzhou Changzheng Tiqinchang	0.065	3.9	2.73	350
Guangzhou Jichuangchang	453.6	81.36	9	7616
	640	161.6	2089.2	
Guangzhou Penqichang	30.24	5.424	0.6	
Guangzhou Chachachang	126	22.6	2.5	1535
Guangzhou Hongmian Baowenping	46416	13547.67	267878.34	
	103950	24636.15	29106	
Guangzhou Guanyueqichang	41.6	15.3	178.1	279
Guangzhou Yuansheng Yueqichang	0.6	36	25.2	19
Guangzhou Qinxianchang	0.65	39	27.3	633
Guangzhou Youmochang	302.4	50.4	136.08	1632
Pinganfu Suliao Gongsi	19080	5151.6	2594.88	476
Shizhengweixiuchu Jishan Liqing	7182	1197	3231.9	2630

ANNEX 4

Power plants smaller than 200 MW

Plant name	Capacity (MW)	Location (X)	Location (Y)	Annual SO_2-emission	Annual smoke-dust emission
Guangzhou Power Plant	200	17.30	29.87	10,282	8,572
Hengyuin A	24	45.38	20.80	1,173	1,213
Hengyuin B	150	45.26	21.20	3,443	2,870
Huaqiao Sugar	33	15.90	32.11	1,150	736
Sinopec	55	44.97	27.27	8,292	9,678
GZ Paper mill.	30	20.71	22.38	2,97	3,230
GZ Nitrogen fertilizer factory	24	32.82	30.10	2,654	3,785
GZ Steel plant	43	18.70	22.20	1,133	1,836
GZ People's Paper Making Factory	5	21.75	22.78	874	1,959
GZ Town gas company	9	37.90	28.12	1,111	2,489
Youngda PP	61	34.00	17.40	3,529	7,907
Zini Tangchang	45	26.04	02.76	2,260	5,064
Meishan Tangchang	105	44.23	-05.03	3,503	145
Lianhuashan PP	192	45.80	11.00	841	632
Mingzhu diesel PP	37			888	302
Xicsen Diesel PP	40			702	239
Guangsheng PP	151			2,174	741
HD Bajiang PP	189			1,617	551

Power plants in bold: included in revised close-down option if cogeneration is introduced on 9 industrial power plants (Huaqiao sugar – Meishan Tangchang above).

ANNEX 5

9 industrial sources suitable for cogeneration

Source	Boiler units. MW	Fuel type	Fuel consumption (tons)	SO_2 (tons/year)	Dust (tons/year)
Huaqiao Sugar plant	12x2+6+3	B	89 900	1 150	736
Guangzhou oil chemical plant	12x2+25+6	B	641 700	8 292	9 678
GZ Danfeichang chemical plant	12x2	B	177 200	2 654	3 785
GZ Gangtie Gufen. Makes steel	11+32	B	70 800	1 133	1 836
Remin Paper mill.	3+2	B	61 400	874	1 959
Guangzhou oil making gas plant	6+3	B	78 000	1 110	2 489
Panyu sugarcane chemical plant	25+12x2+6+3	B	178 800	3 529	7 907
Tini Tangchang sugarplant	12x3+16+3	B	158 700	2 260	5 063
Meishan sugar plant	6x3+12+25+5	B	218 900	3 503	145
Total			1 675 400	24 505	33 598
Reduction			820946	12 007	16 430

ANNEX 6

List of 26 large NO_x point sources

Stack Name	X	Y	Emission (kg/h)	Contribution (ug/m^3)
Zini Tangc	26.16	2.77	55.62	271.49
Hengyun Di	45.26	21.20	52.09	262.57
Gz Yongda	34.00	17.40	47.98	268.98
Gz Yongda	34.00	17.40	100.27	471.59
Gz Danfeic	32.82	30.10	71.86	396.67
Gz Danfeic	32.82	30.10	53.17	644.49
Gz Weidaga	21.75	22.78	42.70	367.88
Gz Shihuaz	44.97	27.27	234.43	222.05
Py Meishan	44.24	-5.03	128.73	201.61
Gz Zhujing	51.70	-7.10	253.09	208.65
Gz Zhujing	51.70	-7.10	244.49	207.51
Gz Fadianc	17.30	29.87	290.70	322.04
Gz Zaozhic	20.83	22.37	22.43	207.35
Gz Zaozhic	20.83	22.37	34.49	249.51
Gz Zaozhic	20.71	22.38	55.78	304.29
Gz Zaozhic	20.71	22.38	56.45	305.61
Gz Zj Zaoz	31.70	26.50	12.25	264.57
Gz Huaqiao	15.90	32.10	29.16	203.66
Gz Huaqiao	15.90	32.12	28.41	205.83
Py Lianhua	45.89	10.99	30.44	435.25
Gz Huaxian	32.82	27.18	30.70	484.00
Gz Haotian	36.33	25.26	26.20	494.80
Gz Youzhiq	37.90	28.12	54.24	569.58
Py Lianhua	45.80	11.00	96.31	1651.24
Hp Fadianc	45.39	22.79	232.83	81.5
Hp Fadianc	45.39	22.79	178.17	62.4
Sum			2462.99	9365.14

ANNEX 7

List of 11 large point sources with 88% dust removal

Stack Name	X	Y	Emission (kg/h)	Contribution to concentration (ug/m3)
Zini Tangc	26.16	2.77	291.3	1422
Gz Yongda	34.00	17.40	251.3	1409
Gz Yongda	34.00	17.40	525.2	2470
Gz Weidaga	21.75	22.78	223.6	1927
Py Meishan	44.26	-5.03	158.6	1035
Gz Zaozhic	20.71	22.38	295.7	1601
Py Lianhua	45.89	10.99	72.2	1032
Gz Danfeic	32.82	30.10	376.4	2078
Gz Huaxhian	32.82	27.18	140.0	2217
Gz Youzhic	37.9	28.12	284	2983
Gzhaotian	36.33	25.26	62.2	1173

ANNEX 8

Calculations behind results in table 4-4 (least cost package SO_2)

Control option	Total annual cost (mill. RMB)	Concentration reduction potential – additional reduction from 1995 level	Annual cost per % point reduced SO_2 concentration
1. Cogeneration – 9 industrial sources	-73	5.5%	-11.6 mill.
2. Shut down 9 power plants	0 *	5.3%*	0
3. Sorbent injection, 60 large sources	101.2	21%	4.8 mill.
4. Fuel switch – 1,000 buses	1.75	0.15%	11.7 mill.
5. Shift to low sulfur coal, 60 large sources	120	4%	30 mill.
6. Fuel switch – 15,000 taxis	11	0.5%	23 mill.
7. Wet FGD, 13 largest point sources[32]	170	5%	34 mill.
8. Moving 20 factories	36.2	1.4%	26 mill.
9. Fuel switch third industry	1,350	2.4%	560 mill.
Total, options 1-3	37.2	31.8%	1.2 mill.
Total, options 1-6	170	36.5%	4.6 mill.
Total, options 1-8	1,726	45%	38 mill.

*: Lower range

Option 1. Cogeneration will bring down SO_2 emissions from power generating units in 9 industrial facilities particularly suited for cogeneration with 12,000 tons which is equivalent to 5.5% reduced concentrations in Central Guangzhou. The abatement costs per ton reduced of this option – applied on the 9 industrial facilities – has been estimated to ÷64 mill., that means annual savings of RMB 64 mill., or a saving of RMB 5300 per ton SO_2 avoided (64 mill./12,000 tons). The cost effectiveness ratio in terms of costs per percentage point reduced concentration in central Guangzhou is RMB 11,6 mill. per unit concentration reduction from 1995 level in central Guangzhou.

Option 2: Shut down of 13 power plants and increasing production in big power plants would *initially* produce a net reduction of SO_2 emissions of 16,500 tons, which would bring down SO_2 concentrations in central Guangzhou with 8% compared to the level in 1995 (using transformation formula in footnote 21).

[32] The 17 sources have become 13 because 4 are eliminated in the first option (13 power plants).

Since the cogeneration option is applied to many of the power plants suggested for shut down, however, it does not make sense to close these sources after installing new boilers with cogeneration. Therefore, the shut down option is restricted to 8 power plants smaller than 200 MW that are not suited for co-generation. These nine sources have combined SO_2 emissions of 21,200 tons. If big power plants are to compensate for the loss of production from these sources, it would entail a net reduction of 21,200 – 10,000 = 11,200 tons. This is equivalent to a reduction of SO_2 concentrations in central Guangzhou of 5.3% from the level in 1995.

In line with the reasoning in chapter 5, we assume the cost of this option to be zero (lower end).

Option 3: The next step is to apply sorbent injection on the 60 largest point sources for SO_2 emissions. Initially the SO_2 emissions from these sources were 111,200 tons per year. Through option 1, the emissions were brought down to 111,200 – 12,000 = 99,200 tons. Through option 2 the emissions are brought down to 99,200 – 11,200 = 88,000. On this amount of SO_2 we apply sorbent injection with an abatement rate of 50%. The control option will produce an additional emission reduction of 44,000 tons, which is equivalent to a concentrations reduction of 21% in central Guangzhou.

Costs: As we have seen, abatement costs are basically a function of installed capacity in each source and will therefore remain unchanged, except that we apply this control option on somewhat fewer sources (not on the 9 power plants). Total annual abatement costs are thus ½ (111,200 tons – 21,200 tons) x RMB 2250 per ton (CE ratio, emissions) = RMB 101.2 mill. The new cost effectiveness ratio in terms of concentrations reduction is RMB 101.2 mill. / 21% = RMB 4,8 mill. per unit (percentage point) reduction.

Option 4 remains unchanged from previous analytical step.

Option 5: The next step is to apply low sulfur coal on the 60 largest point sources for SO_2 emissions. However, this control option was only relevant to sources burning bituminous coal. We need to find the initial emissions of these particular sources and how they are affected by the previous options:

The combined initial emissions from the bituminous coal fired part of POI50 were roughly 75,000 tons SO_2. All sources selected for cogeneration in option 1 burn bituminous coal while their initial combined annual SO_2 emissions were approximately 24,500 tons before cogeneration and 12,500 after cogeneration is installed. Thus after option 1, the emissions for bituminous fired POI50 are 63,000 tons. In option 2 we close down a set of small power plants but most of them burn heavy oil and diesel. Only Guangzhou Power Plant and Hengyuin A and B burn bituminous coal. Their combined annual SO_2 emissions are 15,000 tons. After these are shut down, new emissions from bituminous coal fired POI50 sources will be 48,000 tons. Through option no.3 (sorbent injection) the emissions would have come down by 50% to 24,000 tons. Applying low sulfur coal on these sources would mean a further reduction of 33%, or 8,000 tons, which is equivalent to 4% reduction of SO_2 levels from 1995 in central Guangzhou.

Costs: Costs for this option are given by the price difference between different coal qualities. Thus we need to know the new total bituminous coal consumption among POI50 sources excluding those sources that were eliminated in option 2. We have estimated *initial* bituminous coal consumption to be 5.6 mill. tons per annum. Through cogeneration in 9 sources, this is reduced by 0.8 mill. tons to 4.8 mill. tons. Option 2 (shut down) will not include any reduction in coal consumption since consumption will only be shifted from smaller to bigger plants (which all are among POI50 sources). If 0.75% sulfur coal is RMB 25 more expensive per ton than 0.5% sulfur coal, the total costs will be RMB 25 x 4.8 mill. tons = RMB 120 mill., and the adjusted cost effectiveness will be RMB 30 mill. per percentage point reduced SO_2 concentration from 1995 level in central Guangzhou.

Option 6 remains unchanged from previous analytical step.

Option 7: Wet scrubbing 17 sources. The 17 largest source for SO_2 concentrations initially had a combined emission of 52,300 ton. Some of these 17 sources will have their emissions reduced by 49% through the cogeneration option, since their overall thermal efficiency will improve with 49%. Those among the 17 sources that are candidates cogeneration have a combined SO_2 emission of 17,250 tons. This will be reduced by 49% through cogeneration, or 8450 tons. Next, four of the nine power plants that we close down in option 2, are also among the 17 sources. The annual emissions of these four plants are 14,500 tons, which should be subtracted in order to find the new reduction potential: 52,300–8,450–14,500=29,350 tons. On this amount of SO_2 we first apply sorbent injection, bringing emissions down by 50% to 14,700 tons, and then low sulfur coal will bring them further down by 30% (assuming that most of the 17 minus 4 plants burn bituminous coal) to 10,300 tons. This is the emission that are exposed to wet scrubbing with an effectiveness of 95%, meaning that wet scrubbing in 13 sources (17-4) will produce an additional reduction of SO_2 emissions of 9,800 tons, or 5% percentage points reduced SO_2 concentration from 1995 level in central Guangzhou.

Costs may be calculated from initial emissions from the 13 (17-4) sources multiplied by the initial abatement costs per ton. Such a calculation gives (52,300 – 14,500 tons) x RMB 4500 per ton = RMB 170 mill. The adjusted cost effectiveness ratio will be RMB 170 mill. / 5% = RMB 34 mill. per percentage point reduced SO_2 concentration in central Guangzhou from 1995 level.

As is quite evident from the analysis above, it does not make much sense to apply this option this late in the sequence. Instead, it should probably be applied before both sorbent injection and low sulfur coal, but after cogeneration and shut down of power plants. In this case, the option would have rendered sorbent injection and fuel switch in these 9 sources unnecessary, bringing the total costs of these options further down as well. It may be estimated that the concentration reduction potential of this option if implemented after cogeneration and shut down, is 15% from 1995 level in central Guangzhou. This would have implied a cost effectiveness ratio of RMB 170 mill. / 15% = RMB 10.5 mill. per percentage point reduction.

ANNEX 9

Calculations behind results in table 4-8 (least cost NO_x package)

Option 1: Shut down 13 power plants will bring a *net* emissions reduction of 3,300 tons NO_x, equivalent to 4% concentration reduction in central Guangzhou. Costs: same as before.

Option 2: LNB/OFA in 26 sources: All 13 plants in option 1 are among the 26 sources selected for LNB/OFA. Since Huangpu is also among the 26 and since Huangpu is assumed to compensate for the production eliminated in the 13 plants, the new total emissions after close down 13 power plants will be 21,900-3,300= 18,600 tons. LNB/OFA will reduce this by 45%, or 8,370 tons, equivalent to 9,25% concentrations reduction.

Costs: Reduction multiplied with RMB 4000 per ton: 4000 x 8500 = 34 mill.

CE: RMB 34 mill./9.25% = 3.7 mill. per % point.

Option 3: SNCR 26 sources. After option 2 is implemented, the new combined emissions of the 26 is 21,900-3,300-8,370=10,230 tons. SNCR will reduce this to 50% or 5,115 tons which is equivalent to 5.6% concentrations reduction.

Costs: Emissions originally: 22,000 tons – 3000 tons (option 1) = 19,000 tons. Reduction 50% ⇨ 9,500 tons. Costs: 9,500 x 6000 = 57 mill.

CE: 57 mill./5.6%=10 mill.

Option 4: The reduction potential of retrofitting TWC on 7,500 taxis remains unchanged, 1350 tons, which is equivalent to a concentrations reduction of 1.5%.

Option 5: SCR on 26 sources. After option 3 is implemented, the combined NO_x emissions of the 26 sources are 5,115 tons. SCR removes 80% of this, or 4100 tons which is equivalent to a concentrations reduction of 4.5% in central Guangzhou.

Costs: 22,000-3,000=19,000 tons. 80% reduction = 15,200 tons. Costs: 15,200 x RMB 10,000 per ton = 150 mill.

CE: 150 mill./4.5% = 33 mill. per % point.

The abatement potential and concentrations reduction potential of the three remaining options will not be affected by the implementation of the first five options.

ANNEX 10

Sorbent injection - all large point sources

GZ Power Plant		GZ Power Plant	
Chinese data			
Capacity	200000	Capacity	200000
Unit investment cost	212	Unit investment cost	212
Total investment	42400000	Total investment	42400000
Annual investment cost (8%, 20 yrs)	6741600	Annual investment cost (5%, 20 yrs)	5724000
O&M pr kW	91	O&M pr kW	91
Annual O&M costs	18200000	Annual O&M costs	18200000
Total annual abatement costs	24941600	Total annual abatement costs	23924000
1995 SO_2 emission	10281	1995 SO_2 emission	10281
Emission reduction 50%	5140,5	Emission reduction 50%	5140,5
Emission reduction 70%	7196,7	Emission reduction 70%	7196,7
Cost effectiveness (50%)	4852	Cost effectiveness (50%)	4654
Cost effectiveness (70%)	3466	Cost effectiveness (70%)	3324

International data I (WB 1997)

Capacity	200000	Capacity	200000
Unit investment cost	800	Unit investment cost	800
Total investment	160000000	Total investment	160000000
Annual investment cost (8%, 20 yrs)	25440000	Annual investment cost (5%, 20 yrs)	21600000
O&M pr kW	48	O&M pr kW	48
Annual O&M costs	9600000	Annual O&M costs	9600000
Total annual abatement costs	35040000	Total annual abatement costs	31200000
1995 SO_2 emission	10281	1995 SO_2 emission	10281
Emission reduction 50%	5140,5	Emission reduction 50%	5140,5
Emission reduction 70%	7196,7	Emission reduction 70%	7196,7
Cost effectiveness (50%)	6816	Cost effectiveness (50%)	6069
Cost effectiveness (70%)	4869	Cost effectiveness (70%)	4335

International data II (ABB)

Capacity	200000	Capacity	200000
Unit investment cost	240	Unit investment cost	240
Total investment	48000000	Total investment	48000000
Annual investment cost (8%, 20 yrs)	7632000	Annual investment cost (5%, 20 yrs)	6480000
O&M pr kW	88	O&M pr kW	88
Annual O&M costs	17600000	Annual O&M costs	17600000
Total annual abatement costs	25232000	Total annual abatement costs	24080000
1995 SO_2 emission	10281	1995 SO_2 emission	10281
Emission reduction 50%	5140,5	Emission reduction 50%	5140,5
Emission reduction 70%	7196,7	Emission reduction 70%	7196,7
Cost effectiveness (50%)	4908	Cost effectiveness (50%)	4684
Cost effectiveness (70%)	3506	Cost effectiveness (70%)	3346

Guangzhou Nitrogen Fertilizer Factory

Chinese data

Capacity	24000	Capacity	24000
Unit investment cost	212	Unit investment cost	212
Total investment	5088000	Total investment	5088000
Annual investment cost (8%, 20 yrs)	808992	Annual investment cost (5%, 20 yrs)	686880
O&M pr kW	91	O&M pr kW	91
Annual O&M costs	2184000	Annual O&M costs	2184000
Total annual abatement costs	2992992	Total annual abatement costs	2870880
1995 SO_2 emission	2654	1995 SO_2 emission	2654
Emission reduction 50%	1327	Emission reduction 50%	1327
Emission reduction 70%	1857,8	Emission reduction 70%	1857,8
Cost effectiveness (50%)	2255	Cost effectiveness (50%)	2163
Cost effectiveness (70%)	1611	Cost effectiveness (70%)	1545

International data I (WB 1997)

Capacity	24000	Capacity	24000
Unit investment cost	800	Unit investment cost	800
Total investment	19200000	Total investment	19200000
Annual investment cost (8%, 20 yrs)	3052800	Annual investment cost (5%, 20 yrs)	2592000
O&M pr kW	48	O&M pr kW	48
Annual O&M costs	1152000	Annual O&M costs	1152000
Total annual abatement costs	4204800	Total annual abatement costs	3744000
1995 SO_2 emission	2654	1995 SO_2 emission	2654
Emission reduction 50%	1327	Emission reduction 50%	1327
Emission reduction 70%	1857,8	Emission reduction 70%	1857,8
Cost effectiveness (50%)	3169	Cost effectiveness (50%)	2821
Cost effectiveness (70%)	2263	Cost effectiveness (70%)	2015

International data II (ABB)

Capacity	24000	Capacity	24000
Unit investment cost	240	Unit investment cost	240
Total investment	5760000	Total investment	5760000
Annual investment cost (8%, 20 yrs)	915840	Annual investment cost (5%, 20 yrs)	777600
O&M pr kW	88	O&M pr kW	88
Annual O&M costs	2112000	Annual O&M costs	2112000
Total annual abatement costs	3027840	Total annual abatement costs	2889600
1995 SO_2 emission	2654	1995 SO_2 emission	2654
Emission reduction 50%	1327	Emission reduction 50%	1327
Emission reduction 70%	1857,8	Emission reduction 70%	1857,8
Cost effectiveness (50%)	2282	Cost effectiveness (50%)	2178
Cost effectiveness (70%)	1630	Cost effectiveness (70%)	1555

Wet FGD - 17 sources

Guangzhou power plant

Capacity	200000	Capacity	200000
Unit investment cost	1040	Unit investment cost	1040
Total investment	208000000	Total investment	208000000
Annual investment cost (8%, 20 yrs)	33072000	Annual investment cost (5%, 20 yrs)	28080000
O&M pr kW (fixed)	96	O&M pr kW (fixed)	96
Annual O&M costs	19200000	Annual O&M costs	19200000
O&M pr kWh (variable)	0,012	O&M pr kWh (variable)	0,012
Annual variable O&M	13200000		
Total annual abatement costs	65472000	Total annual abatement costs	47280000
1995 SO_2 emission	10281	1995 SO_2 emission	10281
Emission reduction 95%	9766,95	Emission reduction 95%	9766,95
Cost effectiveness (95%)	6703	Cost effectiveness (95%)	4841

Guangzhou SINOPEC Petrochem

Capacity	55000	Capacity	55000
Unit investment cost	1040	Unit investment cost	1040
Total investment	57200000	Total investment	57200000
Annual investment cost (8%, 20 yrs)	9094800	Annual investment cost (5%, 20 yrs)	7722000
O&M pr kW (fixed)	96	O&M pr kW (fixed)	96
Annual O&M costs	5280000	Annual O&M costs	5280000
O&M pr kWh (variable)	0,012	O&M pr kWh (variable)	0,012
Annual variable O&M	3630000		
Total annual abatement costs	18004800	Total annual abatement costs	13002000
1995 SO_2 emission	8291	1995 SO_2 emission	8291
Emission reduction 95%	7876,45	Emission reduction 95%	7876,45
Cost effectiveness (95%)	2286	Cost effectiveness (95%)	1651

Fuel switch 3rd industry

Total investment	200000	Total investment	200000
Annual capital costs (8%, 20 years)	31800	Annual capital costs (5%, 20 years)	27000
Additional fuel costs	26160	Additional fuel costs	26160
Total abatement costs	57960	Total abatement costs	53160
SO_2 reduction	0,107	SO_2 reduction	0,107
Cost effectiveness	541682	Cost effectiveness	496822

Low NOx burners + Over fire air

Guangzhou Power Plant

Capacity	200000	Capacity	200000
Unit investment cost	120	Unit investment cost	120
Total investment	24000000	Total investment	24000000
Conventional burner costs	1400000	Conventional burner costs	1400000
Additional capital costs	22600000	Additional capital costs	22600000
Annual investment cost (8%, 3 yrs)	16272000	Annual investment cost (5%, 3 yrs)	15820000
O&M pr kW	0	O&M pr kW	0
Annual O&M costs	0	Annual O&M costs	0
Total annual abatement costs	16272000	Total annual abatement costs	15820000
1995 NOx emission	2546	1995 NOx emission	2546
Emission reduction 50%	1273	Emission reduction 50%	1273
Cost effectiveness (50%)	12782	Cost effectiveness (50%)	12427

Guangzhou SINOPEC Petrochem

Capacity	55000	Capacity	55000
Unit investment cost	120	Unit investment cost	120
Total investment	6600000	Total investment	6600000
Conventional burner costs	385000	Conventional burner costs	385000
Additional capital costs	6215000	Additional capital costs	6215000
Annual investment cost (8%, 3 yrs)	4474800	Annual investment cost (5%, 3 yrs)	4350500
O&M pr kW	0	O&M pr kW	0
Annual O&M costs	0	Annual O&M costs	0
Total annual abatement costs	4474800	Total annual abatement costs	4350500
1995 NOx emission	2050	1995 NOx emission	2050
Emission reduction 50%	1025	Emission reduction 50%	1025
Cost effectiveness (50%)	4366	Cost effectiveness (50%)	4244

SNCR - 20 sources

Guangzhou Power Plant			
Capacity	200000	Capacity	200000
Unit investment cost	180	Unit investment cost	180
Total investment	36000000	Total investment	36000000
Annual investment cost (8%, 20yrs)	5724000	Annual investment cost (5%, 20yrs)	4860000
O&M pr kWh	0,012	O&M pr kWh	0,012
Annual O&M costs	13200000	Annual O&M costs	13200000
Total annual abatement costs	18924000	Total annual abatement costs	18060000
1995 NOx emission	2546	1995 NOx emission	2546
Emission reduction 60%	1527,6	Emission reduction 60%	1527,6
Cost effectiveness (60%)	12388	Cost effectiveness (60%)	11822

Guangzhou SINOPEC Petrochem

Capacity	55000	Capacity	55000
Unit investment cost	180	Unit investment cost	180
Total investment	9900000	Total investment	9900000
Annual investment cost (8%, 20yrs)	1574100	Annual investment cost (5%, 20yrs)	1336500
O&M pr kWh	0,012	O&M pr kWh	0,012
Annual O&M costs	3630000	Annual O&M costs	3630000
Total annual abatement costs	5204100	Total annual abatement costs	4966500
1995 NOx emission	2050	1995 NOx emission	2050
Emission reduction 60%	1230	Emission reduction 60%	1230
Cost effectiveness (60%)	4231	Cost effectiveness (60%)	4038

SCR - 20 sources

Guangzhou SINOPEC Petrochem			
Capacity	55000	Capacity	55000
Unit investment cost	1000	Unit investment cost	1000
Total investment	55000000	Total investment	55000000
Annual investment cost (8%, 20yrs)	8745000	Annual investment cost (5%, 20yrs)	7425000
O&M pr kWh	0,024	O&M pr kWh	0,024
Annual O&M costs	7260000	Annual O&M costs	7260000
Total annual abatement costs	16005000	Total annual abatement costs	14685000
1995 NOx emission	2050	1995 NOx emission	2050
Emission reduction 85%	1742,5	Emission reduction 85%	1742,5
Cost effectiveness (60%)	9185	Cost effectiveness (85%)	8428

Retrofit ESP - 10 sources

Yongda Power Plant

Capacity	61000	Capacity	61000
Unit investment cost	240	Unit investment cost	240
Total investment	14640000	Total investment	14640000
Annual investment cost (8%, 20yrs)	2327760	Annual investment cost (5%, 20yrs)	1976400
O&M pr kW	40	O&M pr kW	40
Annual O&M costs	2440000	Annual O&M costs	2440000
Total annual abatement costs	4767760	Total annual abatement costs	4416400
1995 particles emission	8900	1995 particles emission	8900
Additional emission reduction (88% to 99,5%)	8500	Additional emission reduction (88% to 99,5%)	8500
Cost effectiveness	561	Cost effectiveness	520

Zini

Capacity	45000	Capacity	45000
Unit investment cost	240	Unit investment cost	240
Total investment	10800000	Total investment	10800000
Annual investment cost (8%, 20yrs)	1717200	Annual investment cost (5%, 20yrs)	1458000
O&M pr kW	40	O&M pr kW	40
Annual O&M costs	1800000	Annual O&M costs	1800000
Total annual abatement costs	3517200	Total annual abatement costs	3258000
1995 particles emission	5060	1995 particles emission	5060
Additional emission reduction (88% to 99,5%)	4800	Additional emission reduction (88% to 99,5%)	4800
Cost effectiveness	733	Cost effectiveness	679