Journal of Environmental Sciences Vol. 15, No. 3, pp. 401—412, 2003 ISSN 1001—0742 CN11—2629/X

Article ID: 1001-0742(2003)03-0401-12 **CLC number**: X32 **Document code**: A

Marginal cost pricing for coal fired electricity in coastal cities of China: The case of Mawan Electricity Plant in Shenzhen City, China

ZHANG Shi-qiu, DUAN Yan-xin

(Center for Environmental Sciences, Peking University, Beijing 100871, China. E-mail: zhangshq@ces.pku.edu.cn)

Abstract: By developing a GDMOD model to estimate the environmental externalities associated with electricity generation, this project provides a detailed analysis of the damages and costs caused by different pollutants at varying distances from the Mawan Electricity Plant in Shenzhen, China. The major findings of this study can be summarized that (1) environmental damages caused by electricity production are large and are mainly imposed on regions far away from the electricity plant; (2) air pollution is the most significant contributor to the total damages, and SO_2, NOx, and particulate matter are the three major pollutants with highest damages; (3) the damages caused per unit of particulate, NOx, and SO_2 emissions are much higher than pollution treatment and prevention costs. The research results of this project showed that China needs to have a more effective levy system on SO_2, and a more manageable electricity tariff mechanism to internalize the environmental externalities. The results have also implications for pollution control strategies, compensation schemes as well as emission trading arrangements.

Keywords: marginal cost pricing; environmental damages; environmental policy

1 Issues and problems

China is currently in the process of transition from a planned to a market economy. In a market economy, the allocation of scarce resources between competing uses is a problem that is solved through market pricing of resources. A precondition for the optimal functioning of this allocation process is that the market prices reflect all costs involved in production (Pearce, 1993). The market mechanism cannot secure an optimal macroeconomic allocation if substantial costs of production are not reflected in the market price because they are passed on to third parties not involved as consumers or producers of a product(in the instance of external or social costs).

China has experienced remarkable economic growth in recent years. China's struggle to meet its enormous energy needs is a key element of the nation's development strategy and is perhaps the single most important variable shaping the future of China's environment. Given the government's plans to continue depending heavily on coal to meet the increasing demands for power, it is unlikely that coal's use in the power sector will be declining. As a consequence, it is expected that China's air pollution will increase substantially.

China has made progressive steps towards the liberalisation of electricity prices, which has created a pricing structure that more accurately reflects the production costs(although not the externalised environmental costs). However, further measures to rationalise energy prices and reform product markets are still needed. The major problems related to electricity price in China can be summarized as follows:

First, the current price system is the result of a number of incremental *ad hoc* changes instead of being the product of a well-designed long-term price reform program. The electricity pricing system remains too complex and cumbersome in spite of the major reforms initiated in 1993. Pricing policies vary by region, supplier, and customer. Furthermore, municipal, provincial, and county governments frequently impose added fees to raise funds for electricity development, and cost classifications are poorly defined(Yang, 1991; ADB, 1994).

Second, there is an internal distortion of electricity pricing. The price for commercial industries, service sectors, and hotels is set too low. Preferential prices for industry and agriculture are also too low. Furthermore, the current prices poorly reflect differentiation in peak-load use.

Foundation item: The Environmental Economy Program of South East Asia (EEPSEA) and Trans-century Training Program Foundation for the Talents in China by Ministry of Education

Third, there is a problem with inefficient management in the electricity sector. The roles of the various administrative departments (agencies) are not clearly defined which is a major obstacle to co-ordinating efforts between different departments. As a result, there is not a very strong scientific basis behind the calculation and classifications of electricity prices or in the determination of rational profit rates.

Fourth, electricity prices do not reflect the full social cost, such as environmental damages produced by electricity generation. This tends to discourage firms from adopting efficient pollution prevention and treatment measures.

In sum, the current price system is still very much a product of central planning. Such a price distortion sends misleading signals to producers and consumers which leads to lower investments in alternative energy, improved efficiency in electricity production, the installation of environmental pollution prevention facilities, and the use of clean inputs (such as cleaner coal with lower sulphur and ash content).

2 Definition of marginal opportunity cost (MOC) pricing for this study

2.1 Definition of coal fired electricity price

In this study, the electricity price is defined as **the firm-gate price of electricity** produced by the coal fired power plants.

2.2 Components of the electricity price at firm gate

The price that leads to a more efficient allocation is the one that reflects not only the production costs, but also the environmental and user costs. Therefore, the electricity price (MOC at firm-gate) should include MPC, MUC and MEC.

MPC (marginal production cost) is the cost of production for an incremental unit of electricity (capital investment and operating cost).

MUC (marginal user cost) is the depletion cost of the coal that is used as fuel. In theory, either the domestic marginal opportunity cost (MOC) price of coal or world market price of coal can be used as the cost of coal, which means the MUC will be considered in the MPC.

MEC (marginal external cost) is the external costs related to the production and consumption of electricity. It consists of MEC1, the external (environmental) costs (damages) caused by electricity generation, and MEC2, the external (environmental) costs (damages) associated with electricity consumption. Since the electricity price for this study is the firm gate price, the MEC used here includes only the external costs of production, MEC1.

Thus the electricity price at firm gate for this study can be described as:

$$P = MOC = MPC + MEC = MPC + MEC1. \qquad (1)$$

3 Methodology used

The major focus of this study is the estimation of the environmental costs (MEC1) associated with coal-fired electricity production. To do this we first identify the environmental stressors and then use dispersion and transformation models to estimate the possible environmental changes caused by the different stressors. The physical impacts and damages caused by these changes are assessed and quantified, and finally monetary values are assigned to the damages. The steps involved in this process of MEC1 estimation are illustrated in Fig. 1.

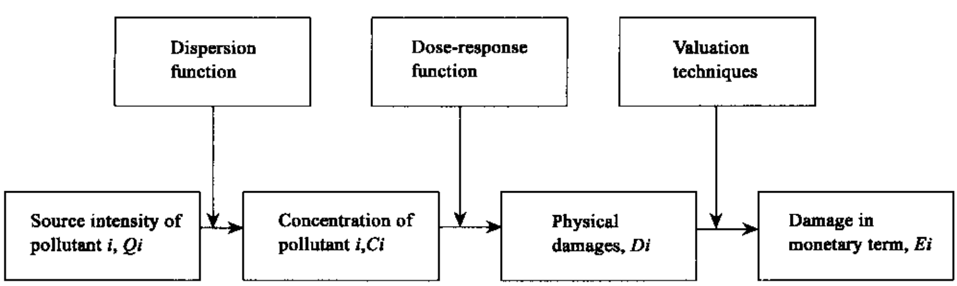

Fig. 1 Process of damage valuation for estimation of MEC1

4 Develop the GDMOD model to estimate the MEC1

Since the production processes used in the electricity industry vary little, coefficients of pollution emission and the environmental damage functions from other models can be used. This allows for the use of computer programs to calculate the damages and determine the monetary value the damages. Based on the program EXMOD* created for the "New York State Environmental Externalities Cost Study", we developed a GDMOD, which is a computer model to estimate the environmental costs produced by the Mawan Electricity Plant in Shenzhen. The model was developed based on the characteristics of pollution produced by coal-fired electricity plants.

4.1 Scope of the analysis

The analytical parameters for GDMOD are defined as: (1) the regional focus of this study is Guangdong Province, though areas on the border of Guangdong are also included in the analysis; (2) 1992 was selected as the base year for the study and all data was converted into 1992 values using a discount rate of 12%; (3) the model developed here only considers the environmental damages produced by electricity generation and does not include the external costs associated with the transportation of coal and consumption of electricity.

4.2 Receptor cell definition

The model uses spatial units called **receptor cells**. These are the basic units for calculation. The affected area is divided into 139 receptor cells that are categorised based on their distance from the facility site. The four geographic classifications used are: (1) local community: locations in Guangdong within 30 km of the facility site; (2) rest of the region: locations in Guangdong between 30 and 80 km from the facility site; (3) rest of province: locations in Guangdong more than 80 km from the facility site; (4) out of province: locations in provinces neighbouring Guangdong.

Each receptor cell is assumed to be internally undifferentiated vis-a-vis pollution levels, population density and the relevant economic indicators. For each cell, the central point is used for distance from source measurement.

4.3 Air quality models used in GDMOD

Air quality models are used to calculate changes in ambient air quality and pollution deposition using stack emissions data. This study uses the same air quality models used in EXMOD, though they have been adjusted based on related parameters in Guangdong Province. The following major models are used: (1) ISC2LT model: Used for short range modelling, to calculate the air quality changes with 50 km of the power plant. This model can be used to calculate the incremental concentration of SO_2, NOx, TSP and other pollutants; (2) SCREEN2 model: It is used to calculate the short-term average concentration of PM10 for a maximum of 24 hours and NOx (an O_3 precursor) for a maximum of 1 hour; (3) SLIM2 model: this model is used to calculate annual average impacts at long range(greater than 50 km from the power plant); (4) OLM: It is used to calculate changes in ambient ozone concentrations resulting from power plant emissions of NOx.

4.4 Case creation

With this model, it is necessary to specify the facility location(including elevation), production specifications (type of plant and production process), as well as the characteristics of the receptor cells.

For the facility, the emissions and concentration amounts are determined based on information regarding the production process, facilities and operation parameters as well as the pollution prevention measures for the Mawan Electricity Plant. The electricity generating equipment used at the Mawan Electricity Plant is a pulverised steam boiler with a capacity of 2 × 300 MW. The plant uses high quality domestic and imported coal. Pollution prevention measures taken at the plant include the use of high stack (210M) emissions, low NOx emission boilers, electrostatic dust precipitators with 99% dust removal efficiency, and wastewater treatment facilities.

For the receptor cells, the data inputted include: (1) information for each receptor cell, such as place name, latitude, longitude, altitude, area, population, sex and age structure of the population; (2) environmental concentration monitoring data in each receptor cell (collected prior to plant operation); and (3) meteorological data (joint frequency distribution of wind speed and direction).

Once the characteristics of the facility and receptor cells have been established, the dose-response functions must be specified. By modifying the parameters used for the EXMOD, appropriate functions for the GDMOD can be produced for the

* For detail, see Robert D. Rowe *et al.*, The New York electricity externality study, Oceana Publications Inc. 1995

region being studied. The monetary value for physical damages must also specify before the model can be run.

4.5 The output of calculation results

Using the above mentioned data for the facility, surrounding regions, pollution characteristics and effects, the GDMOD will generate the following information: (1) value of damages based on regional proximity; (2) value of damages for each major type of pollutant; (3) value of damages within environmental category(such as air, water, land, etc.); (4) value of damages per unit of each major pollutant.

5 Estimation of marginal environmental cost

5.1 Identification and classification of pollution damages produced by Mawan Electricity Plant: potential stressors and impacts screening

Coal-fired electricity plants emit various pollutants that when released into the environment impacts the health and well being of humans and other forms of life. The major impacts can be summarised as: (1) impacts on human health; (2) impacts on human welfare; (3) impacts on environmental resources; (4) impacts on global change.

Based on data collected for this study and on results from previous research, the different stressors can be identified, which was reviewed and categorized in terms of their potential impacts. Through this screening process, each stressor was assigned one of four classifications. These classifications are used to select the applicable externalities for the study. The criteria used in assigning categories were: (1) the impact can be mitigated, which has or will be included in calculations of pollution prevention cost (P_e); (2) the impact is relatively small, which will be deleted from further analysis; (3) there is not enough scientific information available for a quantitative assessment, which will be qualitatively assessed and analysed separately; (4) a quantitative assessment can be completed, which subject to be assigned full or partial economic valuation.

5.2 Estimation of dose-response function and monetary valuation parameters for pollutants

5.2.1 Human health effects of air pollutants

5.2.1.1 Human health effects of PM10

Many studies showed that PM10 is the major factor causing health problems, since they are small enough to enter into the airways of the lungs. Therefore, PM10 is more accurate to indicate the dose for damages. In the model we run, we use PM10 instead of TSP. Abbey and others(Abbey, 1993) studied the conversion factor for TSP and PM10, and use a factor of 0.5—0.6. Brook(Brook, 1997) studied data collected over a 10-year period from 19 monitoring stations and also determined the conversion coefficient for PM10 and TSP to be 0.5—0.6. These studies are consistent with the research findings of the New York Study(Rowe, 1995). In this model we use 0.55 as the conversion factor. Therefore

$$C_{PM10} = 0.55 \times C_{TSP}. \tag{2}$$

The human health effects of PM10 include mortality and respiratory disease. Studies showed that the health problems and impacts related to PM10 includes: chronic bronchitis(CB), respiratory hospital admissions(RHA), asthma(AA), restricted activities days(RAD), acute respiratory symptoms(ARS), emergency room visits(ERV), and asthma for children. Formula (3) is used to calculate the dose-response of health effects of PM10.

$$\Delta D_a = R \times \Delta PM10 \times POP \times N. \tag{3}$$

In which, ΔD_a is the annual incremental cases of disease due to PM10; R is the dose-response coefficient (case/(d·μg/m); $\Delta PM10$ is the annual concentration change of PM10, POP is the affected population; N is the days of PM10 exceeding standards in one year.

The dose-response coefficient estimation is therefore the key issue for estimating the health effects. Given the similarities, we decided to use the dose response functions developed for the New York Study(EXMOD)* . These functions were developed based on the most comprehensive review of related research conducted in the US during the 1990's(Table 1).

Since some double counting may exist between the indicators shown in Table 2, we adjust the functions in the GDMOD as followis:

The average days for staying in hospital for a RHA case are 9.5 days(China's health statistical year book, 1996);

* There have been a number of studies conducted by Chinese researchers (Wang, 1989; 1993; Zhang, 1994; Chu, 1993), and there appears to be no significant difference from findings of studies conducted in other countries

$ERV_{adjusted} = ERV - RHA$,

$RAD_{adjusted} = [RAD - (r \cdot 9.5d \cdot RHA) - (r \cdot ERV_{adjusted}) - r \cdot AA]$,

in which, r refers to the proportion of population over age 18; $ARS_{adjusted} = ARS - RAD$.

Table 1 Damage functions of health effects of PM10

Effects	Unit	Damage function					
		L	P	C	P	H	P
Mortality(≥65)	case/d·person·1 μg/m³	10.1×10^{-8}	33	16.9×10^{-8}	34	25.4×10^{-8}	33
Mortality(<65)	case/d·person·1 μg/m³	0.14×10^{-8}	33	0.23×10^{-8}	34	0.35×10^{-8}	33
CB (≥25)	case/a·1 μg/m³	3.0×10^{-5}	25	6.1×10^{-5}	50	9.3×10^{-5}	25
RHA	case/d·1 μg/m³	1.8×10^{-8}	25	3.3×10^{-8}	50	4.8×10^{-8}	25
ERV	case/d·1 μg/m³	3.2×10^{-7}	25	6.5×10^{-7}	50	9.7×10^{-7}	25
AA	day/d·1 μg/m³	0.9×10^{-4}	33	1.6×10^{-4}	50	5.4×10^{-4}	17
RAD (≥18)	day/d·1 μg/m³	0.8×10^{-4}	33	1.6×10^{-4}	34	2.5×10^{-4}	33
ARS	day/d·1 μg/m³	2.2×10^{-4}	25	4.6×10^{-4}	50	7.0×10^{-4}	25
Asthma for children (<18)	case/a·1μg/m³	0.8×10^{-3}	25	1.6×10^{-3}	50	2.4×10^{-3}	25

Notes: L refers to low value; C refers to central value; H refers high value; P refers to probability (%); source: A. D. Rowe, 1995; Schwardz, 1992

5.2.1.2 Human health effects of ozone

Ozone has some obvious impacts on human health, including morbidity, respiratory hospital admissions(RHA), asthma (AA), minimum restricted activities days(MRAD), and acute respiratory symptoms(ARS). Formula (4) is used to calculate the human health effects of ozone.

$$\Delta D_a = R \times \Delta O_3 \times POP \times N. \tag{4}$$

In which, ΔD_a is the annual incremental cases of disease due to PM0; R is the dose-response coefficient(case/(d·μg/m³)); ΔO_3 is the annual average of daily changes in high-hour ozone; POP is the affected population; N is the days of ozone exceeding standards in one year.

Since there is no study on human health effects by ozone available in China, we use the functions used in EXMOD, which are shown in Table 2. Due to the possibility of double counting, the following adjustments were made:

$$MRAD_{adjusted} = MRAD - AA; \ ARS_{adjusted} = ARS - MRAD.$$

Table 2 Dose-response functions of human health effects of O_3

Effects	Unit	Dose-response					
		L	P	C	P	H	P
Mobility	case/d·1 ppm	0.0	33	3.3×10^{-6}	34	6.6×10^{-6}	33
RHA	case/d·1 ppm	8.4×10^{-6}	33	13.7×10^{-6}	34	19.0×10^{-6}	33
AA	case/d·1 ppm	1.06×10^{-1}	33	1.88×10^{-1}	50	5.20×10^{-1}	17
MRAD	day/d·1 ppm	1.93×10^{-2}	25	4.67×10^{-2}	50	7.40×10^{-2}	25
ARS	day/d·1 ppm	0.73×10^{-2}	25	1.37×10^{-2}	50	2.04×10^{-2}	25

Notes: L refers to low value; C refers to central value; H refers high value; P refers to possibility (%)
Source: A.D. Rowe, 1995; Schwardz, 1992

5.2.1.3 Human health effects of lead and mercury

Lead and mercury are emitted into the air with soot produced during coal combustion. Exposure can occur through breathing and ingestion. Epidemiological studies have found that PbB levels can lead to higher rates of hypertension, nonfatal heart attacks, nonfatal strokes and risks of premature death for adult men. Effects of mercury exposure are quite complex and difficult to quantify. As a result, we use the damage value per unit of pollutant used in the New York Electricity Externality Study, after adjusting for per capita GDP values, to directly calculate the damages (Table 3).

Formula (5) and (6) are used to calculate the human health effects of lead and mercury.

$$E_{il} = R_{jl} \cdot POP \cdot C_{il}, \tag{5}$$

in which, E_{li} is the damages due to health effects of lead; *POP* is the population exposed to lead; C_{il} is the incremental lead level produced by electricity plant; R_{il} is the damage function of lead.

$$E_{ik} = R_{jk} \cdot C_{ik}, \quad (6)$$

in which, E_{ik} is the damages due to health effects of mercury; C_{ik} is the incremental mercury level produced by electricity plant; R_i is the damage function of mercury.

5.2.1.4 Human health effects of radiation

Radiation can cause various health effects, which can be estimated by Formula (7). The dose received by an individual can be used as an indicator of the damage caused by radiation.

$$E_R = R \cdot r \cdot POP/1000, \quad (7)$$

Table 3 Damage functions for human health effects of lead and mercury

Effects	Unit	Damage function					
		L	*P*	*C*	*P*	*H*	*P*
Health effects of lead	\$ /person·μg/dl	0.531	33	1.614	34	8.600	33
Health effects of mercury	\$ /kg	0.35	25	6.95	50	41.00	25

Notes: 1. *L* refers to low value; *C* refers to central value; *H* refers high value; *P* refers to probability (%); 2. the value here is subjected to adjust by GNP ratio; source: Rowe, 1995; Schwardz; 1992

in which, E_R is the value of damages caused by radiation; *R* is the value of damages per unit radiation; *r* is the radiation exposure/(person·a) due to 1000 MW electricity plant; *POP* is the affected population.

It is estimated in the EXMOD model that the incremental radiation produced by a 1000 MW coal fired electricity on local area is

$$1.33 \times 10^{-3} \text{rem/(person} \cdot \text{a} \cdot 1000 \text{ MW)}.$$

5.2.1.5 Human health impacts of air toxics

Air toxics included here are the suspected carcinogenic air emissions such as As, Be, Cd, Cr, Ni and POMs(BaP). Uptake of these pollutants can happen through breathing and ingestion. According to the USEPA's Integrated Risk Information System(IRIS) (USEPA, 1992), the dose response functions of air toxics are:

$$\Delta D_i = POP_i \cdot \Delta C_i \cdot RF_i/70, \quad (8)$$

in which, ΔD_i is the incremental case of cancer by pollutant *I*; ΔC_i is the incremental concentration of pollutant *I*; RF_i is the cancer risk factor for inhalation for chemical *i* (which refers to 1 incremental concentration exposure in one's life time, 70 years); *POP* is the affected population.

The value we used of RF_i is shown in Table 4(Chen, 1992).

Table 4 Damage functions of selected toxic chemicals

Pollutants	Damages	RF_i, μg/m^3
As	Respiratory	0.0043
Cd	Respiratory	0.0018
Cr	Lung	0.012
Ni	Respiratory	0.00024
BaP	Respiratory	0.017

Source: USEPA 1992

5.2.1.6 Valuation for human health effects

There are several different ways to estimate the economic costs of human health effects. The Willingness to Pay (WTP), Cost of Illness (COI) and Human Capital Approaches are three common methods. However, given the difficulties associated with data and information collection, for this study we use the technology transfer methodology to estimate the human effects in monetary terms.

Usually, the estimation based on WTP is much higher than on COI(Pearce, 1989; Rowe, 1995). According to research conducted by the Chinese Academy of Social Sciences, the monetary value assigned to human life in 1992 for China was about 160000 RMB Yuan (World Bank, 1997). In the affected areas of the Mawan Electricity Plant, the per capita GDP is higher than the national average. We therefore adjust the average life value using GNP ratios and values calculated in other countries to assign life values for the areas around the Mawan Plant (Table 5 and Table 6). Given the arguments for and against benefit transfer approach as well as the value of human life approach, we present

Table 5 The estimation for life value (converted by GNP ratio)

Effects	Population	Life value (10000 RMB Yuan/person, 1992)		
		L	*C*	*H*
Mortality	> age 65	23	47	94
Mortality	< age 65	31	62	126
Mortality	All population	29	58	106
Mortality	Children	31	62	126
Probability	weight, %	33	50	17

Sources: calculated based on Cropper 1991; Fisher 1989; Miller 1989; Moore 1988 final results two ways——once with costs of deaths included in total damages and once with deaths left out of the cost calculation.

Table 6 The cost estimation for illness (converted by GDP)

Illness	Unit	RMB Yuan, 1992			Primary resource	Type of estimate
		L	C	H		
CB (adult)	RMB Yuan/person	1980	3309	5200	Cropper, 1991; Miller, 1989	WTP
RHA	RMB Yuan/case	1100	2200	3300	Viscusi, 1991	Adjusted COI
ERV	RMB Yuan/case	42	83	125	Krupnick, 1992	Adjusted COI
CB (children)	RMB Yuan/case	21	42	64	Viscusi, 1991	Adjusted COI
RAD (≥18)	RMB Yuan/case	5.5	11	16.5	Abbey, 1993	WTP & adjusted COI
AA	RMB Yuan/d	1.90	5.3	8.7	Loehman, 1979	WTP
MRAD	RMB Yuan/d	2.4	3.8	6.5	Abbey, 1993; Rowe, 1986	WTP
ARS	RMB Yuan/d	0.8	1.6	2.4	Abbey, 1993; Rowe, 1986	WTP
Probability weight, %		33	34	33		

5.2.2 Damage to crops by SO_2 and acid deposition

Studies on the dose-response functions for SO_2 and acid deposition for agricultural crops have been done in China (Cao, 1991; Zhang, 1997). Cao *et al*. focused on Guangdong and Guangxi Province, making their results most appropriate for use in this study. Given that there is a direct relationship between SO_2 emissions and acid deposition, we use the following formula to calculate the damages to various crops. The calculated results are shown in Table 7.

$$\Delta Q_i = \sum R_i \cdot \Delta C_{SO_2 j} \cdot Q_{ij};$$

$$\Delta V_i = \Delta Q_i \cdot P_i = P_i \cdot \sum R_i \cdot \Delta C_{SO_2 j} \cdot Q_{ij} = \sum R_i \cdot \Delta C_{SO_2 j} \cdot V_i. \tag{9}$$

In which, ΔV_i is the losses to crop I; ΔQ_i is the production loss of crop i; P_i is the market price of crop I; R_i is the damage functions for crop i; $\Delta C_{SO_2 j}$ is the incremental value of SO_2 at region j; Q_{ij} is the total production of crop i at region j; V_{ij} is the total output value of region j.

5.2.3 Material damages by acid deposition

An empirical study conducted by Yang Zhiming *et al*. (Yang, 1997) provided dose-response functions for various materials, such as covering materials, marble, galvanized steel, and steel. Formula (10) is used to estimate the cost of materials damages caused by acid deposition.

Table 7 Damage functions for agricultural losses caused by SO_2 and acid deposition

Crops	Unit	Damage function					
		L	P	C	P	P	P
Rice, soy beans, ground nuts, etc.	%/(μg/m³)	0.018	33	0.021	34	0.025	33
Wheat, fruits, etc.	%/(μg/m³)	0.025	33	0.029	34	0.033	33
Vegetables	%/(μg/m³)	0.038	33	0.048	34	0.063	33

Source: calculated based on Cao *et al*. 1991

$$E = \sum R \cdot \Delta C_{SO_2 i} \cdot HH_i, \tag{10}$$

in which, E is the material damages cost by SO_2 and acid deposition; R is the damage function; $\Delta C_{SO_2 i}$ is the incremental concentration of SO_2 at receptor cell k; HH_i is the number of households at receptor cell k.

Yang (Yang, 1997) developed the following dose-response functions that we used as the input for R in Formula (10).

For covering materials: $R = 5.61 + 2.84SO_2 + 0.74 \times 10^4[H^+]$.

For marble: $R = 14.53 + 23.81SO_2 + 3.8 \times 10^4[H^+]$.

For galvanized steel: $R = 0.43 + 4.47SO_2 + 0.95 \times 10^4[H^+]$.

For steel: $R = 39.28 + 81.41SO_2 + 21.2 \times 10^4[H^+]$.

In which, R refers to the speed of the corrosion (μm/a); SO_2 refers to the concentration of the SO_2; $[H^+]$ refers to the concentration of $[H^+]$ of rainfall (mol/L).

5.2.4 Estimation of damages by waste water pollution

The wastewater discharged by the Mawan Electricity Plant includes mainly domestic wastewater; cleaning wastewater, wastewater from ash flushing, and thermal wastewater. The wastewater has been treated primarily before discharging. However, the heavy metals and toxics in cleaning wastewater and wastewater from ash ponds may have an impact on the environment and it is difficult to quantify these impacts. Large amounts of thermal water discharged may also have impacts on the ocean ecological system.

We use the cost for water treatment (outside of the plant) to estimate the environmental cost of wastewater pollution. Specifically, we use the secondary treatment cost for urban wastewater to calculate the losses produced by the wastewater released by the Mawan Plant. Based on Shanghai Monitoring Institute (1996), the treatment costs are: 1.2 RMB Yuan/t for domestic wastewater, 2 RMB Yuan /t for rinsing water, 1 RMB Yuan/t for ash flushing water and 0 RMB Yuan for thermal water* . Table 8 shows the treatment costs of wastewater.

Table 8 Wastewater discharges and treatment costs

	Annual discharge, 1000 tons	Treatment cost, RMB Yuan/t	Total loss, RMB Yuan1000
Domestic waste water	14.4	1.2	17.3
Rinsed water	24.0	2	48.0
Ash sewage	3600.0	1	3600
Thermal water	13000.0	0	0
Total			3665

6 Environmental impacts valuation results for the Mawan Electricity Plant

6.1 Damages based on geographic division

Table 9 summarizes the annual average total costs, and the annual average externality cost per kWh of power generation, calculated for each environmental externality group, broken down into 4 sub-regions. The total environmental externalities produced annually, if mortality valuation is included, are USD 3.8 million to USD 6.7 million. The results also show that pollution produced by the Mawan Electricity Plant imposed significant impacts on remote areas (rest-of-province and out-of-province). These remote areas account for 78.4% to 84.1% of the total environmental damages. Such a situation is perhaps due to the use of high stacks for emissions, which will increase pollution dispersion towards more remote regions. The environmental cost for generating one kWh of electricity ranges from USD 1.028×10^{-3} to 1.832×10^{-3} (1992 prices). Converted to 1997 prices, the cost would be USD 1.8117×10^{-3}/kWh to USD 3.2286×10^{-3}/kWh, which is 0.015 RMB Yuan/kWh to 0.027 RMB Yuan/kWh. Currently, the electricity price at firm gate is 0.52 RMB Yuan/kWh. Therefore, the costs associated with environmental damages range from 2.9% to 5.2% of the current price of electricity.

6.2 Damages produced by each major pollutant

By breaking down the external costs in terms of pollutant type, the environmental costs imposed by each major pollutant can be compared and the key pollutants and environmental impacts can be identified. The annual average externalities and the present value of total externalities of major pollutants are presented in Table 10, which one will find that air pollutants are the major sources of environmental externalities. They account for 86.0% to 91.9% of the total damages, while SO_2, NOx, and particulates (PM10), the three major pollutants, alone account for 80.5% to 90.0% of the total damages. SO_2 is the largest contributor among the air pollutants, with the damages accounting for 66.6% to 70.3% of the damages caused by air pollution and accounts for 56.4% to 64.0% of total damages. The second largest contributor is NOx, with the damages accounting for 22.2% to 22.7% of the damages caused by air pollution and 19.5% to 20.4% of total damages; the third largest contributor is PM10, which accounts for 5.2% to 5.3% of the damages by air pollution and 4.6% to 4.8% of the total damages.

6.3 Damages per physical unit of emissions

Table 11 summarises the total emissions and damages per unit emissions of major pollutants. Although the particulate emissions is not much in comparison with SO_2, it has the highest damages per unit at USD 592/ton to USD 1040/ton; while SO_2 damages per unit emission is from USD 106.24/ton to USD 173.50/ton. The treatment cost for SO_2 in China is currently estimated to be less than USD 100 per ton. This difference between damage and treatment costs for SO_2 should provide further evidence in support of increasing levels of SO_2 levies or charges to encourage polluters to reduce SO_2 emissions. Further efforts to control pollution is cost effective since the marginal cost of damages is higher than the marginal treatment cost.

* The Environmental Impact Assessment Report for the Mawan Plant states that the thermal water will not produce significant impacts

Table 9 Annual average total externalities and per kWh generated by geographic divisions

Geographic division	Externality group	Annual average total externalities Damages (USD 1000) *			Annual average externality per kWh generated Damages (USD mills/kWh) **		
		Low, 20%	Central, average	High, 80%	Low, 20%	Central, average	High, 80%
Local							
	Air	17.171	31.514	48.234	0.005	0.009	0.013
	Water	287.946	575.893	863.839	0.078	0.157	0.235
	Land/waste	22.500	52.200	81.300	0.006	0.014	0.022
	Other	0.000	0.000	0.000	0.000	0.000	0.000
	Local subtotal	327.618	659.607	993.373	0.089	0.179	0.270
Rest-of-region							
	Air	272.579	369.900	462.832	0.074	0.101	0.126
	Water	0.000	0.000	0.000	0.000	0.000	0.000
	Land/waste	0.000	0.000	0.000	0.000	0.000	0.000
	Other	0.000	0.000	0.000	0.000	0.000	0.000
	Rest-of-region subtotal	272.579	369.900	462.832	0.074	0.101	0.126
Rest-of-province							
	Air	1268.054	1695.433	2102.519	0.345	0.461	0.571
	Water	0.000	0.000	0.000	0.000	0.000	0.000
	Land/waste	0.000	0.000	0.000	0.000	0.000	0.000
	Other	0.000	0.000	0.000	0.000	0.000	0.000
	Rest-of-province subtotal	1268.054	1695.433	2102.519	0.345	0.461	0.571
Out-of-province							
	Air	1914.204	2563.237	3179.375	0.520	0.697	0.864
	Water	0.000	0.000	0.000	0.000	0.000	0.000
	Land/waste	0.000	0.000	0.000	0.000	0.000	0.000
	Other	0.000	0.000	0.000	0.000	0.000	0.000
	Out-of-province subtotal	1914.204	2563.237	3179.375	0.520	0.697	0.864
Total externalities		3782.455	5288.177	6738.100	1.028	1.437	1.832

Notes: * Low and high totals may not sum because of Central Limit Theorem; ** 1 mill = USD 0.001

Table 10 Annual average and present value of total externalities of major pollutants

Externality group	Annual average Damages (USD 1000)			Present value Damages (USD 1000)		
	Low, 20%	Central, average	High, 80%	Low, 20%	Central, average	High, 80%
Air						
Greenhouse gas/CO_2	N/A	N/A	N/A	N/A	N/A	N/A
Lead	48.900	148.000	231.000	398.697	1206.692	1883.417
Mercury	0.158	0.406	0.626	1.288	3.310	5.104
Nitrogen oxides	755.000	1060.000	1330.000	6155.758	8642.522	10843.919
Particulates (PM10)	177.000	248.000	312.000	1443.138	2022.024	2543.837
Radioactivity	0.002	0.010	0.017	0.016	0.082	0.139
Sulphur dioxide	2388.409	3136.474	3898.750	19473.467	25572.683	31787.767
Toxics	28.000	58.500	84.500	228.293	476.969	688.956
Air subtotal	3397.469	4651.390	5856.893	27700.658	37924.281	47753.139
Water						
Sewage	287.946	575.893	863.839	2347.714	4695.427	7043.141
Toxics in ash	0.000	0.000	0.000	0.000	0.000	0.000
Water subtotal	287.946	575.893	863.839	2347.714	4695.427	7043.141
Land/waste						
Land use/noise/terrestrial	13.100	25.000	36.500	106.808	203.832	297.596
Volume/land use	0.000	27.200	53.900	0.000	221.770	439.463
Land/waste subtotal	13.100	52.200	90.400	106.808	406.602	737.058
Total externalities	3698.515	5279.483	6811.133	30155.187	43045.325	55533.359

Note: Due to the arguments and large uncertainty related to the damages of climate change, we did not include the CO_2 effects

6.4 Summary

Table 12 summarizes the life cycle damages and damages per physical unit of emissions for each major pollutant. The present value of damages for SO_2 is clearly the most significant one, with about USD 25.6 million in total damages. NOx ranks as second with a total present value of USD 8.6 million and particulates rank third with a total present value of USD 2.0 million.

The major conclusions that can be drawn from the analysis presented in this section are as follows: (1) The regions over 80 km away from the electricity plant suffer most of the damages, about 78.4% to 84.1% of the total; (2) air pollution is the most significant contributor to the total damages, with 86.0% to 91.9% of the externalities resulting from atmospheric pollutants; (3) SO_2, NOx, and particulate matter are the three major pollutants with highest damages. Together they account for 80.5% to 90.0% of the total damages, while SO_2 accounts for 56.4% to 64.0%, NOx for 22.2% to 22.7%, and particulates for 4.6% to 4.8% of the total environmental costs; (4) damages produced per unit of particulates, NOx, and SO_2 are significant with the values of USD 830/t, USD 226/t, and USD 139.7/t respectively; (5) total environmental cost of electricity generation accounts for 2.9% to 5.2% of the current electricity price at firm gate.

Table 11 Annual damages per physical unit emissions

Air pollutant	Annual emissions	Damages			
		Unit	Low, 20%	Central, average	High, 80%
Particulates	299.00 tons	$ /ton	592.000	830.000	1040.000
Nitrogen oxides	4710.00 tons	$ /ton	160.000	226.000	282.000
Sulphur dioxide	22500.00 tons	$ /ton	106.240	139.670	173.500
Lead	1010.00 lbs	$ /lb	1.460	4.410	6.910
Mercury	340.00 lbs	$ /lb	15.400	39.800	61.400
Arsenic	693.00 lbs	$ /lb	0.060	0.200	0.310
Beryllium	69.50 lbs	$ /lb	0.020	0.040	0.040
Chromium	208.00 lbs	$ /lb	0.070	0.180	0.270
Nickel	243.00 lbs	$ /lb	0.000	0.000	0.000
POMs	104.00 lbs	$ /lb	13.200	32.000	48.000

Table 12 Ranking of damages by major pollutants

Total damages in present value (in central value term)		Annual emission	Damage per physical unit (in central value term)	
Rank	$ 1000		Rank	$ /unit
Sulfur dioxide	25572.683	22500 tons	Particulates (PM10)	830 $ /ton
Nitrogen oxides	8642.522	4710 tons	Nitrogen oxides	226 $ /ton
Particulates (PM10)	2022.024	299 tons	Sulfur oxides	139.7 $ /ton
Lead	1206.692	1010 lbs	Mercury	39.8 $ /lb
Mercury	3.310	1409 lbs	Lead	4.41 $ /lb

7 Policy implications of this study

In most cities of China the concentrations of particulate matter and SO_2 far exceed WHO guidelines of 70 $\mu g/m^3$ and 50 $\mu g/m^3$ respectively (Sunman, 1998). The results of this study suggest the importance and cost-effectiveness of increased control of TSP and SO_2 emissions.

7.1 A more effective pollution levy system on SO_2 is needed to internalize the externalities

The analysis above shows that the costs of environmental damages is the main factor leading to price distortion and accounts for 2.9% to 5.2% of the current firm gate price of electricity. Taking into account the current production cost of electricity generation at the Mawan Plant, which is about 0.31 RMB Yuan/kWh, if the environmental costs are internalised then the cost of electricity generation should be increased from 0.325 RMB Yuan/kWh to 0.337 RMB Yuan/kWh, which is an increase of 4.8% to 8.7% of the current production cost.

Levies or charges on pollutant emissions are necessary, especially for SO_2. This study shows that SO_2 emissions produce environmental costs of USD 106.24/t to USD 173.50/t (or about 881.8 RMB Yuan/t to 1440.1 RMB Yuan/ton), while the SO_2 mitigation cost is about USD 100/t (830 RMB Yuan/t). China introduced a SO_2 charge in 1992 on a trial basis at a rate of only 200 RMB Yuan/ton emissions. This rate is well below the damage costs of SO_2, covering only 13.9% to 22.7% of the damages caused. If the levy or charge on SO_2 were to reflect the full damage costs, they would help to encourage electricity producers to better mitigate the pollution and would bring greater environmental gains for the whole of society.

7.2 More manageable electricity tariffs are needed

An important obstacle to the effective internalization of environmental externalities is the current electricity tariffs structure. More manageable electricity tariffs should be set up which would not only take into account the price at firm gate, but also demand-related issues such as user price, different end-uses and timing (e.g., peak versus off-peak use). A significant problem related to electricity tariffs in Shenzhen (and Guangdong Province) is that, the consumer price of electricity is already very high, with some users paying 1 RMB Yuan/kWh to 2 RMB Yuan/kWh, which is about 2—4 times the firm gate price, At the same time, the producers complain they earn very their low profits (some even operate at a deficit). The problem is due in part to the complicated and irrational price system, and to the fact that most of the profits are collected by those responsible for the distribution and transmission of electricity.

7.3 Other implications

This study showed that the environmental damages produced by the Mawan Electricity Plant have greater effects on regions further from the plant. This finding has a number of important policy implications. When one includes all of Guangdong Province and surrounding regions into the damage valuation analysis, it may be necessary to re-examine whether the high stack is the best choice for mitigating pollution or whether other options might be better. Where the high stack strategy is used, a compensation scheme should be considered. If a compensation policy is needed, then the results in Table 10 and 11 provide a reference baseline rate for the policy design.

The results of this study also have implications for emissions trading of SO_2. SO_2 emissions have long distance transport characteristics and may affect more than one air shed. With a permit trading scheme, the quota being treated should not only take into account the total emission, but also the geographic location of emissions as well as the potential damages per unit emission.

Acknowledgements: The authors wish to acknowledge the research grant extended by EEPSEA; and thankful for the valuable comments of Jeremy Warford, Stein Hansen, David Glover and Hermi Francisco, as well as other members of the advisory group.

References:

Abbey D E, Petersen F, Mills P K *et al*., 1993. Long term ambient concentrations of total suspended particulates, ozone and sulfur dioxide and respiratory symptoms in a non-smoking population[J]. Archives of Environmental Health, 48(1): 33—46.

Asian Development Bank, Office of Environment, 1994. National response strategy for global climate change: People's Republic of China[Z]. Prepared by the East-West Centre, Argonne National Laboratory, and Tsinghua University.

Cao H F, Shu J M, Liu Y J, 1991. Study on economic losses of crops in Guangdong and Guangxi areas[J]. Research of Environmental Sciences, 4(2):29—33.

Chen B Y, 1992. Study on concentration of benzo(a) pyrene[J]. Journal of Environment and Health, 9: 245—247.

Chestnut L G, Rowe R D, 1990. Economic valuation of changes in visibility: A state of the science assessment for NAPAP[R]. Acidic deposition: State of science and technology report 27 (Brown Jr. G. M, Callaway. J. M. ed.). National Acid Precipitation Assessment Program, Washington, D.C. October.

China State Statistical Bureau, 1994; 1995; 1996; 1997. Statistical yearbook of China[M]. Beijing: China Statistical Publishing House.

Cropper M L, Freeman Ⅲ A M, 1991. Environmental health effects[M]. Measuring the demand for environmental quality (Braden J. B, Kolstad C. D ed.). New York: North - Holland.

Fisher A, Chestnut L G, Violette D M, 1989. The value of reducing risks of death: A note on mew evidence[J]. Journal of Policy Analysis and Management, 8(1):88—100.

EPA, 1990. Methodology for assessing health risks associated with indirect exposure to combustor emissions[R]. Interim final. Prepared by Office of Health and Environmental Assessment. Washington, D.C. EPA/600/6-90/003.

Jeffrey R B, Dann T F, 1997. The relationship among TSP, PM10, PM2.5, and inorganic constituents of atmospheric particulate matter at Multiple Canadian Locations[J]. J Air & Waste Manage Assoc, 47(January): 2—19.

Krupnick A J, 1986. A preliminary benefits analysis of the control of photochemical oxidants[R]. Report prepared for the U.S. EPA, Washington, D.C. September.

Krupnick A J, Cropper M L, 1989. Valuing chronic morbidity damages: medical costs, labor market effects, and individual valuations[R]. Final report to U.S. EPA, Office Policy Analysis.

Krupnick A J, Cropper M L, 1992. The effect of information on health risk valuations[J]. Journal of Risk and Uncertainty, 5: 29—48.

Loehman E T, Berg S V, Arroyo A A *et al*., 1979. Distributional analysis of regional benefits and cost of air quality control[J]. Journal of

Environmental and Economic Management, 6: 222—243.

Miller T R, 1989. Willingness to pay comes of age: will the system survive? [J]. North-western University Law Review, 83:876—907.

Pearce D, Warford J, 1993. World without end: economics, environment, and sustainable development[M]. New York: Oxford University Press.

Pearce M, 1989. The benefits of environmental policy: monetary valuation[Z]. Paris: OECD.

Rowe, Lang C M, Chestut L G *et al*., 1995. The New York electricity externality study[M]. Oceana Publications Inc.

Sun B Y, 1997. Estimation for economic losses by TVIE pollution in Ba County of Chongqing. China's Environmental Economics in Practice [M]. Beijing: China Environmental Sciences Press.

Sunman H, Munasinghe M, Zhang S Q, 1998. Economics and environmental management for industry in China[R]. A report submitted to China Council for International Cooperation on Environment and Development (CCICED), Beijing.

USEPA, 1986. Guideline on air quality models (Revised) [R]. Prepared by the Office of Air Quality Planning and Standards. Research Triangle Park, North Carolina. EPA-450/2-78-027R.

USEPA, 1992. Integrated risk information system (IRIS) [R]. Office of Research and Development, Office of Health and Environmental Assessment, Washington, D.C.

Viscusi W K, Magat W A, Huber J, 1991. Pricing environmental health risks: survey assessments of risk-risk and risk-dollar trade-offs for chronic bronchitis[J]. Journal of Environmental Economics and Management, 21(1): 32—51.

Wang J Q, Luo D Y, 1989. Study on air pollution and residents' health in Chengdu City[J]. Journal of Environment and Health, 6(2):1—4.

Wang R H, 1993. Discussion on the relations between bronchial asthma of children and the air quality, meteologic factor in Chongqing City [J]. Journal of Environment and Health, 10(5): 205—206.

Yang L, Tian Y, 1991. The strategy choice ford development and reform of the power industry in China[M]. Beijing: China Price Publishing House.

Yang Z M, Wang W X, Zhang W H, 1997. Study on estimation of economic loss of materials by acid deposition[J]. Chongqing Environmental Sciences, 19(1): 11—16.

Zhang C Q, Li Q, 1994. Analysis for air pollution and mortality of lung cancer in Chongqing urban area[J]. Journal of Environment and Health, 3.

Zhang H Q, 1995. Analysis for environmental benefits of thermal power development in China[J]. Energy of China, 3:47—49.

Zhang Y M, Wu L Y, 1997. Impacts on seeds quality and crops by acid rain[J]. Agricultural Environmental Protection, 16(1): 1—10.

(Received for review January 9, 2002. Accepted February 26, 2002)