Policy Analysis of Energy-related Environmental Pollution in China[*]

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1 Introduction

China's economic growth and industrialization has been spectacular over the past thirty years. This has global implications because China is the world's most populous country with over 1.3 billion people. China's growth has been fueled by energy use, especially from fossil fuels, which have had serious environmental impacts on both China and the world. China's energy related environmental issues such as the emissions of carbon dioxide (CO2), sulfur dioxide (SO2), nitrogen oxides (NOx), and total suspended particulates (TSP), etc and associated health damages have attracted increasing concern in recent years. As a result, a growing number of theoretical and empirical studies have emerged concerning how to address the energy related environmental problem facing China and to seek an optimal way to control the emissions.

To identify the underlying mechanisms in resource use and economic growth is a starting point to understanding this issue. Firstly, the environment provides inputs of energy resources and material resources for the economic system as basic factors of economic output, together with labour and capital. The growth of inputs and the productivity of the inputs results in economic growth. Secondly, emissions like CO2, SO2 and TSP are generated during the combustion of energy, particularly coal and oil, and during production process. The accumulated emissions increase the concentration in the atmosphere and inhalation of the pollutants causes health damage to people, for example, chronic bronchitis, premature mortality and respiratory symptoms, etc. People are familiar with these two links between the environment and the economy and many relevant studies can be found in literature (see below).

However, there exists a third link between environmental degradation and the economy, called the feedback effect, which has been largely ignored by economists. This effect refers to the fact that environmental damages may lead to substantial costs, such as a rise in sea level, loss of harvest in agriculture, accelerating the rate of capital depreciation, increasing sick leave and reducing labour productivity, etc. The costs of emissions and the benefits of emission reduction are two sides of the same issue. Neglecting these costs means the benefits of control emissions may be underestimated and thus may affect optimal policy decisions.

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Williams (2002) is one of the few analytical studies that take into account the feedback effects of environmental damages on the economy. He develops an analytical general-equilibrium model that considers several potential benefits from reduced pollution, including improved health or productivity, and draws an instructive conclusion that the overall interaction effects of environmental regulation may be ambiguous depending on the way that pollution affects labour supply.

There is no doubt that estimating the extent of the overall feedback effects is an empirical issue. In this paper, a dynamic intertemporal general equilibrium (CGE) model, the G-Cubed model, is modified to study this issue for China by incorporating environmental feedback effects on economic activity. Several questions will be addressed: How serious is the health damage caused by each pollutant emissions in China? What difference will be made when considering the feedback effects on the economy? Will China's economic performance be affected substantially by imposition of carbon tax policies? What will be the optimal tax level to control emissions in China? To this end, a base case simulation is performed within our model specification and the overall economic and environmental impacts of various environmental policies are evaluated at both the sectoral and national level.

The rest of the paper is organized as follows. Section 2 gives a brief survey of environmental CGE modeling applications of China. Section 3 describes the structure, the data used and parameter estimation of the modified G-cubed model with environmental feedback. The simulation results under different policy scenarios are presented and discussed in Section 4, followed by sensitivity analysis in Section 5. The final section concludes.

2 Previous Literature

Computable general equilibrium (CGE) models have been used extensively to study environmental issues, especially for evaluating the causal relationship between a proposed policy change and its potential economic, environmental, and social impacts. The models construct the behavior of economic agents based on microeconomic principles and simulate markets for products, production factors, and foreign exchange, with equations that specify supply and demand behavior. The models are solved for a set of wages, prices, and exchange rates to bring all of the markets into equilibrium. The improvements in computer technology and numerical algorithm methods have triggered the development of large-scale dynamic computable general equilibrium models.

Among the environmental CGE models in China, Xie (1995) simulates the impacts of pollution emission taxes, subsidies, and household waste disposal taxes; Zhang (1998) uses a recursive CGE model to analyze the economic effects of China's reducing carbon emissions in 2010 by 20 per cent and 30 per cent below baseline, respectively; Glomsrod and Wei (2005) analyze the environmental implications of coal washing; He (2005) evaluates the economic costs of trade policy and de-sulfur policy considering SO2 emission directly linked to energy input consumption in production (see Table 1 for a brief comparison of these models).

However, these models of China lack the associated environmental dimensions in the sense that the ancillary benefits from reducing carbon emissions have been largely neglected. Ancillary benefits refer to the co-benefits gained from a policy to mitigate climate change, such as better health for its citizens leading to higher labour productivity. For example, sulphur dioxide and particulates emissions can cause serious health damage to people. They are mainly emitted from burning high sulphur content coal, so a carbon control policy can reduce the emissions of these pollutant as well as carbon dioxide emissions. Therefore, the total benefits or costs of a climate policy may be under-estimated or over-estimated without considering these ancillary effects. To assess greenhouse gas policies comprehensively, these impacts should be allowed for at both the national and sectoral levels. The internalization of these effects could further motivate the implementation of GHG reduction policies.

Garbaccio et al. (2000) is the first study to estimate the reduction in health damages from a 5, 10, 15 percent reduction of carbon emissions in China and find that 'double dividend' may exists by imposing a carbon tax; O'Connor et al. (2003) integrates an analysis of both the health and agricultural productivity effects of a carbon tax and find that the inclusion of agriculture makes an important difference to the assessment of abatement options; Aunan et al. (2007) evaluates the welfare changes from China's taking on a climate commitment when allowing for the improvement of public health and increase in agricultural yields; Ho and Jorgenson (2007a) uses the intake fraction method to estimate health damages caused by SO2 and PM and analyzes the effects of output taxes and fuel taxes based on damages .

In the above models and even many current ones, the feedback effect of environmental quality on economic behaviour has not been allowed for. How do the feedback impacts of the damages influence the economic agents' decisions on consumption and investment? To what extent do these effects change the relative price consequences and dynamics of adjustment to the policy? Will the optimal level of environmental policy be different? In addition, these studies are based on standard time-recursive growth models, where agents are myopic, basing decisions on current prices rather than expected future ones. Furthermore, they are all calibrated to 1997 China input-output data which can be improved by updating a more recent available dataset to better reflect the economic structure of China.

This paper modifies the G-cubed model. This model is a multi-country, multi-sector, intertemporal general equilibrium model, which includes detailed energy, material production sectors and financial sectors and allows for international trade and capital flows between different countries and regions. To assess the feedback effects of environmental policy, new features are included into the model with particular reference to the two-way link between environmental quality and economic agents' behavior by explicitly incorporating estimates of the value of benefits of the improved health and agriculture productivity from carbon abatement. The model is calibrated using Chinese energy and environmental data in 2002 to reveal the magnitude of environmental impacts such as health damage and capital depreciation caused by energy use in production.

3 A Dynamic Intertemporal Computable General Equilibrium Model with Environmental Feedback

3.1 The Economic Model

The G-cubed model is a multi-region, multi-sector intertemporal general equilibrium model of the world economy, consisting of eight countries and regions which are linked through trade and financial markets. A full theoretical description of the model is contained in McKibbin and Wilcoxen (1999). Because the focus of this paper is on China, the model used in this paper, the G-Cubed-T version, is aggregated into four regions: the United States (US), the rest of the OECD, China, and all other developing countries (LDCs). Production in each region is divided into twelve sectors. There are five energy sectors (electric utilities, natural gas utilities, petroleum processing, coal extraction, and crude oil and gas extraction) and seven non-energy sectors (mining, agriculture, forestry and wood products, durable manufacturing, non-durable manufacturing, transportation and services). This disaggregation enables us to capture the sectoral differences in the impact of alternative environmental policies.

Each economy or region in the model consists of several economic agents: households, the government, the financial sector and firms in the 12 production sectors listed above. The behavior of each type of agent is modeled.

Each of the twelve sectors in each country in the model is represented by a single firm in each sector which chooses it inputs and its level of investment in order to maximize its stock market value subject to a multiple-input production function and a set of prices it takes as given. For each sector, output is represented by a constant elasticity of substitution (CES) function of inputs of capital, labor, energy and materials (Figure 1). Similarly, energy and materials are CES aggregates of inputs of intermediate goods and these intermediate goods are, in turn, aggregates of imported and domestic commodities which are taken to be imperfect substitutes.

The capital stock in each sector changes according to the rate of fixed capital formation and the rate of geometric depreciation. Following the cost of adjustment models of Lucas (1967), Treadway (1969) and Uzawa (1969), it is assumed that the investment process is subject to rising marginal costs of installation.

In addition to the twelve industry sectors, the model also includes a special sector that produces capital goods. This sector supplies the raw investment goods produced by combines labor and the outputs of other industries. The production functional form and the optimization problem are identical to those of the twelve production sectors.

Households consume a basket of composite goods and services in every period and also demand labor and capital services. Household capital services consist of the service flows from consumer durables plus residential housing. Households receive income by providing labor services to firms and the government, and from holding financial assets and receiving transfers from the government. The household maximizes its intertemporal utility subject to the constraint that the present value of consumption be equal to the sum of human wealth and initial financial assets.

Each region's real government spending on goods and services are assumed to be exogenous and allocated among inputs in fixed proportions in the base year input-output table for each country. The government spending includes purchases of goods and services plus interest payments on government debt, investment tax credits and transfers to households. It is financed by levying taxes on households, firms, imports, and externalities such as carbon dioxide emissions, as well as issuing new government bonds.

Labor is assumed to be perfectly mobile among sectors within each region but is immobile between regions. Thus, wages will be equal across sectors within each region, but will generally not be equal between regions. In the long run, labor supply is completely inelastic and is determined by the exogenous rate of population growth. In the long run, wages adjust to move each region to full employment. In the short run, however, nominal wages are assumed to adjust slowly according to an overlapping contracts model where wages are set based on current and expected inflation and on labor demand relative to labour supply. This can lead to short-run unemployment if unexpected shocks cause the real wage to be too high to clear the labour market.

The four regions in the model are linked by flows of goods and assets. Flows of goods are determined by the import demands. Trade imbalances are financed by freely mobile flows of assets between countries. Each region with a current account deficit will have a matching capital account surplus, and vice versa.

The demand for real money balances is assumed to be a function of the value of aggregate output and the short term nominal interest rate.

3.2 Calibration

The elasticities (the ease to which inputs and final demand can be substituted) for China are adopted from US values which are econometrically estimated using data from the detailed benchmark US input output transactions tables produced by the Bureau of Economic Analysis for the years 1958, 1963, 1967, 1972, 1977 and 1982.

The shares and weights of different goods used in each sector are calculated from the 2002 input-output China data (SSB, 2007), which includes 42 sectors. Some parameters used in the dose response function, intake fractions and monetary value on health effects are collected from Ho and Jorgenson (2007a) and World Bank (2007). For the other parameters related to environmental emissions, such as emission coefficients, are calibrated to China's environmental yearbook data, energy statistic yearbook data and International Energy Agency (2005) data after some appropriate adjustment. The estimation process of the emission coefficients and damage elasticities on productivity is discussed in the next section.

3.3 Modeling Environmental Feedback in the G-cubed

Since our analysis is focused on the environmental implications of energy use in a general equilibrium framework, three types of linkages between the economic system and environment are explicitly addressed. These linkages are shown in Figure 2 which gives a more comprehensive evaluation if the feedback effects of environmental variables.

The first is the linkage between the economic variables and emissions, where the inputs of energy and materials, fossil fuels in particular, generates growing emissions of carbon dioxides (CO2) and other pollutants like sulfur dioxides (SO2) and total suspend particulates (TSP). These emissions occur during the industrial production process as well as household coal consumption for the purpose of heating and cooking in rural China.

Second, the emissions are then related to the ambient concentrations in China causing environmental damages such as lowering productivity, especially in agriculture sectors, inducing health damages for people and accelerating capital depreciation, etc. These damages are measured by using the Intake Fraction method and Dose Response Coefficients and then applying a Monetary Valuation.

The final linkage is the feedback effects of the damages on the economic system, which is largely ignored in most of the other environmental CGE models for China and which this study attempts to make a first step to incorporate the environmental feedback effects in the G-cubed model. Three channels are considered: productivity loss, medical expenditure and capital depreciation.

3.3.1 Linking Economic Variables to Emissions: Emission Coefficients

Total emissions are principally determined by consumption of energy inputs, mostly fossil fuels, by both industry sectors and household. Additionally, for some pollutants, such as sulphur dioxide (SO2) and total suspended particulates (TSP), emissions are attributed to pure production process besides combustion of energy inputs. Therefore, in order to reduce sectoral emissions, one can either alter the input mix by substituting consumption of low-polluting energy for high-polluting energy, or control the pollutants through abatement technology. The former is captured in the Constant Elasticity of Substitution (CES) functional form of production in the G-cubed model. The latter is incorporated in the model by assuming a certain exogenous rate of reduction in the pollution-intensity of the economy, so called autonomous energy efficiency improvement (AEEI). This exogenous rate of pollution reduction assumption implies a non-price induced energy conservation over time.

There are three types of emissions considered in the analysis of environmental policy and its ancillary benefits: carbon dioxide (CO2) — the main greenhouse gas; total suspended particulates (TSP); and sulphur dioxide (SO2). The total amount of each emission is generated from three sources: emissions from energy and materials inputs, from production processes and from household consumption of fossil fuels (mainly coal and gas for cooking and heating) and biomass fuel (for cooking and heating in rural areas), which can be represented by the following equation:

$$EM_x = \sum_i \sum_j \alpha_{jx} \cdot INP_{ij} + \sum_j \beta_{jx} \cdot OUP_j + \sum_h \gamma_{hx} \cdot CON_h$$

$$\text{where } x = \mathrm{CO2, TSP, SO2}, \quad i,j,h = 1,2,...12$$

Let i denote the index of the twelve production sectors, j the product index and h the index of the products for household final consumption.

EM_x denotes the total emissions of pollutant x. They are comprised of emissions from product inputs ($INP_i, i = 1,2,...12$) and from production process in proportion to the output of each sector ($OUP_i, i = 1,2,...12$), as well as those from household consumption of goods ($CON_h, h = 1,2,...12$), mainly coal use and burning of biomass like crop residues, fuel wood and marsh gas in rural areas. The biomass fuels are considered as the inputs of agriculture goods ($h = 7$) and forestry goods ($h = 8$) in this model.

The emissions and each source of emissions are linked by the coefficients: α, β and γ. α_j indicates the direct relationship between energy or material use and the setoral emissions. The other part of emissions from industry are indirectly related instead to their output levels by the coefficients β_j, which is derived by dividing the official emissions by the value of gross output in the input-output table. Additionally, the coefficients γ_h link the emissions from household sector to their consumption of fossil and biomass fuels. It is assumed that the contribution of emissions by each type of fuel in each sector is proportional to those in the whole country. All the coefficients are scaled evenly to fit the 2002 China national account data and the estimated sectoral emission data. Since the emissions mainly come from the use of energy, the coefficients are zero in most other sectors. Detailed coefficients are contained in Appendix A which if not attached to this paper is available from the authors upon request. The procedure of estimating sectoral emission data are discussed in the next section.

The unit of the emission coefficients needs to be clarified here. The emissions of each pollutant EM_x are in effect pollution intensity, measured by million metric tons per real US dollar GDP for each country. The product input (INP_i), output (OUP_i) and household consumptions (CON_h) are measured in real US dollars and also normalized by the country's ral US dollar GDP in the G-Cubed database. Therefore, the unit of the emission coefficients α_j should be million metric tons divided by million real dollars and can be taken as the amount of emissions due to per real dollar of energy or material input; β_j indicates the amount of emissions due to per real dollar of sectoral output; and γ_h is that due to per real dollar of final consumption.

These emission coefficients obviously depend on the technology employed and will change as new investments are made. A more complete study should take into account the costs of these new technologies and how much they reduce emissions and energy use. However, estimates of these factors have not yet been assembled for many industries in China and we ignore these effects and leave it to future work.

3.3.2 Linking Emissions to Damages: Intake Fractions and Monetary Valuation

In this section, we estimate the health damage due to the emissions of pollutants in each sector of the economy as well as the household. We concentrate on two pollutants: TSP and SO2. There are two alternative methods of estimating health damage applied in conjunction with CGE models. One is by using an air dispersion model which expresses concentration as a linear function of industry emissions classified by three emission heights: low, medium and high. This method has been used in a number of studies, such as Lvovsky et al. (2000) for six major cities in developing and transition economies, Garbaccio et al. (2000) and World Bank (2007) for China, and O'Connor et al. (2003) for Guangdong. However, this method attributes all observed Particulate Matter (PM) concentrations to primary emissions and damages due to SO2 emissions are ignored (Ho and Jorgenson, 2007b). The other method is called the intake fraction (iF) which is simpler and summarizes the relationship between the emissions of a pollutant and the subsequent exposure to that pollutant or a secondary by-product. As discussed in Ho and Jorgenson (2007b), the use of national average intake fractions is highly simplified, but it is nerveless a methodological advance compared to the previous approach. Therefore, the iF method is employed in our analysis for simplicity following their approach.

- ***Intake Fraction method***

According to the definition proposed by Bennett et al. (2002), the term "intake fraction", designated iF, is defined as the integrated incremental intake of a pollutant, summed over all exposed individuals, and occurring over a given exposure time, released from a specified source or source class, per unit of pollutant emitted. This can be expressed as formulas below:

$$iF_{ix} = \frac{\sum Population \times Concentration \times Breathing\ Rate}{\sum Emissions} = \frac{\sum_d POP_d \times C_d \times BR}{EM_{ix}}$$

Where iF_{ix} is the intake fraction from a source x in sector i, POP_d is the population at location d, C_d is the change in concentration at d, EM_{ix} is the emissions form a given source x in sector i, and BR is a normal population-average breathing rate, used to yield a unitless measure. Breathing rates vary substantially across individual and their activities.

For simplicity, researchers generally use a nominal constant value of twenty cubic meters per day (20 m^3/day), which is used in our study as well. The summation is over all locations. The concept has been discussed in the scientific literature for decades, though with an array of different names (including exposure efficiency, committed dose, exposure commitment, exposure factor, exposure effectiveness, inhalation transfer factor, exposure constant, potential intake, population based potential dose, and fate factor).

The calculation of iF requires some modeling to be conducted in a relevant geographic area, or else the incremental concentration changes per unit emissions cannot be determined. As defined above, an iF implicitly assumes that the health effect has a linear dose-response function, that is, a linear relationship between emissions and total population intake, although this is not always correct for some secondary pollutants Levy and Greco (2007).

It would be easier to understand the way we estimate the health impacts of polluted air (e.g. the number of cases of chronic bronchitis, premature mortality, or other health endpoint) by rearranging the above equation as below. Note that the health effects of TSP is believed to be primarily from very fine particles and studies often use PM_{10}, so we convert the TSP emissions into PM_{10} emissions by taking a proportion of 0.54, as used in Ho and Jorgenson, (2007b).

$$\sum_d C_d \times POP_d = \frac{EM_{ix} \times iF_{ix}}{BR}$$

The number of cases of health effects HE_x due to the pollutant x is derived by multiplying the concentration C by the dose-response (or exposure-response) coefficient DR and population POP:

$$HE_x = DR_{nx} \times \sum_{d=1} C_d \times POP_d$$

Thus combined with the previous equation, the health effects HE_x can be rewritten as:

$$HE_x = DR_{nx} \times \sum_{d=1} C_d \times POP_d = \sum_n HE_{nx} = \sum_n DR_{nx} \cdot \frac{\sum_{i=1}^{12} iF_{ix} \cdot EM_{ix}}{BR}$$

where $x = \text{PM, SO2}$

In this equation, n represents the types of health effects caused by air pollution. Eight heath effects (including mortality) due to emissions of PM and three health effects (including mortality) due to SO2 are considered in our model. They are listed below.

- Health effects due to PM
  - mortality
  - respiratory hospital admissions
  - emergency room visits
  - restricted activity days
  - lower respiratory infection/children (asthma)
  - asthma attacks
  - chronic bronchitis
  - respiratory symptoms
- Health effects due to SO2
  - mortality
  - chest discomfort
  - respiratory symptoms in children

It is obvious that the health effects can be estimated as long as the dose-response coefficient DR_{nx} and intake fraction iF_{ix} estimates are available. In the past two decades, a large number of studies have reported dose-response relationship between air pollution exposure and human health (See World Bank (2007) for a systematic review of epidemiological evidence). A series of studies has also calculated iFs from a sample of emission sources for each of the highly polluting industries: electricity, chemicals, nonmetal minerals products (cement), metals smelting (iron and steel), and transportation (see Wang et al. (2006), Liu and Hao (2007), and Zhou et al. (2003)). In our model we calculated the values of the dose response coefficients and intake fractions based on the study of Ho and Jorgenson (2007b), shown in Table A-4 and A-5. The national average intake fractions for PM that we use are reproduced in the first column and the national average intake fractions for SO2 in the second. It can be seen from the equation that iF depends on the population in the vincity of the emission sources, and we thus projected that the intake fractions are proportional to the urban population. The iF shown in Table A-5 are derived from those for China in 1997 used in Ho and Jorgenson (2007b) and then scaled by the ratio of China's urban population in 2002 to that in 1997.

- ***Monetary valuation***

Health effects are physical measurement indicators of the costs of environmental degradation. Valuing environmental damages requires a valuation of health effects or health end-points, that is, we need to put a monetary value to the health effects to obtain the health damage associated with the pollutant emissions.

Let v_{nt} denote the value of one case of health effect n. The national value of damage D_x from all cases of n due to pollutant x is given by

$$D_x = \sum_n v_n \cdot HE_{nx}$$

Valuing Mortality:

Various approaches have been used to value these damages. In benefit-cost analyses of environmental programs conducted in the United States and the European Union, mortality risks are typically valued using the value of a statistical life (VSL) --- the sum of what people would pay reduce their risk of dying by small amounts that, together, add up to one statistical life. When estimates of the VSL are unavailable, the human capital approach (foregone earnings) is often used to place a lower bound on the VSL. In valuing the health damage associated with environmental degradation in China, we used the estimates extracted from World Bank 2007, which employs both approaches.

In practice, how do we know what people are willing to pay for a 1-in-10,000 risk reduction? Internationally, this is usually estimated from compensating wage differentials in the labor market, or from contingent valuation surveys in which people are asked directly what they would pay for a reduction in their risk of dying. Empirical estimates of the value of a statistical life based on compensating wage studies conducted in the U.S. lie in the range of \$0.6 million to \$13.5 million (1990 USD) (Viscusi (1993); U.S.EPA, (1997). For Taiwan, Liu et al. (1997) estimate a range for VSL of \$413,000 - \$624,000 US 1990 Dollars. However, similar studies have not been conducted in mainland China. For the contingent valuation methods, four studies conducted in China have been found in literature to value quantitative reductions in risk of death: Hammitt and Zhou (2006); Wang and Mullahy (2006); Zhang, (2002); and Krupnick et al. (2006). The VSLs obtained in these studies, based on mean WTP, range from 250,000 to 1.7 million Yuan, depending on the study and model used to fit the data.

In our model, following World Bank (2007) we use the preferred VSL reported by Krupnick et al. (2006), 1.4 million Yuan, based on pooled data from Shanghai and Chongqing, but adjusted to reflect differences in income between Shanghai, Chongqing, and the rest of China. Once the income adjustment is made, the Krupnick et al. (2006) figure is approximately 1 million Yuan. We note that this falls within the range of values reported in the other studies between 250,000 and 1.7 million Yuan. Following the practice used in the U.S. and Europe, we apply the same value to all lives lost due to different air pollution, regardless of location.

Valuing Morbidity:

In principle, economists value avoided morbidity by the amount a person will pay to avoid (the risk of) an illness, just as the risk of death is valued by what people will pay to reduce it. In the case of morbidity, Willingness To Pay (WTP) should capture the value of the pain and suffering avoided, as well as the value of time lost due to illness (both leisure and work time) and the costs of medical treatment. If some of these costs are not borne by the individual, and are therefore not reflected in his willingness to pay, the value of the avoided costs must be added to WTP to measure the social benefits of reduced morbidity.

In cases where WTP estimates are not available, analysts often rely on cost-of-illness (COI) estimates as a lower bound to the theoretically correct value of avoiding illness. Cost-of-illness studies estimate the lost earnings associated with chronic illness that result both from reduced labor force participation and lower earnings conditional on participation (Bartel and Taubman (1979); Cropper and Krupnick (1999)), and add to these medical costs associated with the disease.

The Cost-Of-Illness is a lower bound to WTP because it ignores the value of pain and suffering associated with illness and the value of lost leisure time. In regulatory impact analyses of air pollution regulations published by the U.S. Environmental Protection Agency U.S.EPA (1997), it is often the case that coronary heart disease and stroke are valued using cost-of-illness estimates, as WTP estimates are unavailable.

In our analysis, we follow the approach used in World Bank (2007) to approximate WTP for chronic bronchitis and rely on cost-of-illness estimates for hospital admissions. But the WB study only provided the estimates for WTP to avoid chronic bronchitis, and COI for hospital admissions for respiratory and cardiovascular diseases. For the other seven health effects, we adopt the estimates from Ho and Jorgenson (2007b), in which the willingness to pay method is used. The valuation of these damages is a controversial and difficult exercise, with arguments over the idea itself (Heinzerling 1999), whether the contingent valuation method works (Hammitt and Graham, 1999), and how to aggregate the willingness to pay (Pratt and Zeckhauser, 1996). They follow Lvovsky and Hughes (1997) and use estimates for willingness to pay in the U.S. and scale them by the ratio of per capita incomes in China and the U.S assuming a linear income effect. The values associated with each health effect in China are given in Table A-4.

3.3.3 Linking Damages to the Economic Model

The particular feature of modification of the G-cubed model is to incorporate environmental feedback on the economy. That is, the environmental damage affects the economy through three channels of lowering productivity, increasing medical expenditure, and accelerating capital depreciation.

- ***Productivity***

Carbon dioxide (CO2) is a basic building block for crop growth. Rising concentrations in the atmosphere will have effects on agriculture depending on their physiology and other prevailing conditions. Parry et al. (2004) examined the impacts of increasing global temperatures on cereal production and found that higher temperatures are likely to become increasingly damaging to crops, as droughts intensify and critical temperature thresholds for crop production are reached more often. In addition, vegetation damages may be caused by soil acidification indirectly. Direct damage from SO2 emissions is very likely in some regions Therefore, carbon dioxide and sulphur dioxide emissions have an effect on the productivity of the agriculture sector.

Besides the agriculture sector, the health damage that we estimated in the previous section also influences the productivity of other industry sectors. It is argued that reduced air quality increases sick leave and firms will have to spend on improving the working environment to avoid workers being infected by the polluted air. This input cost is calculated as a loss in the overall productivity of the industry sectors. We assume an exponential functional form with negative exponents ($-\theta_i \leq 0$) indicating the reduced productivity due to emissions. The modified production function takes the form of:

$$Y_i = D^{-\theta_i} \cdot A_i \cdot \left(\delta_L^{\sigma_o} L^{\frac{\sigma_o - 1}{\sigma_o}} + \delta_K^{\sigma_o} K^{\frac{\sigma_o - 1}{\sigma_o}} + \delta_E^{\sigma_o} E^{\frac{\sigma_o - 1}{\sigma_o}} + \delta_M^{\sigma_o} M^{\frac{\sigma_o - 1}{\sigma_o}} \right)^{\frac{\sigma_o}{\sigma_o - 1}}$$

$$D^{-\theta_i} = D_{CO_2}^{-\theta_{Ci}} \cdot D_{PM}^{-\theta_{Pi}} \cdot D_{SO_2}^{-\theta_{Si}}$$

where $D_{CO2}, D_{PM}, and\ D_{SO2}$ represents the atmosphere concentration of CO2, the emissions of pollutant PM, and SO2, respectively. A set of θ, called the damage elasticity, are non-negative constants, so the term $D^{-\theta_i}$ would be between 0 and 1, illustrating the negative feedback effect of environmental damage on productivity and thereby affect firms' decision on production. The higher the value of θ, the larger the feedback effects. Note that θ takes different values in each sector due to different pollutant emissions. The demand for labour (L), energy (E) and materials (M) are therefore given by:

$$L_i = \delta_L \cdot \left(\frac{P^Y}{W_i} \right)^{\sigma_o} \cdot Y_i \cdot D^{-\theta_i (\sigma_o - 1)}$$

$$E_i = \delta_E \cdot \left(\frac{P^Y}{P^E} \right)^{\sigma_o} \cdot Y_i \cdot D^{-\theta_i (\sigma_o - 1)}$$

$$M_i = \delta_M \cdot \left(\frac{P^Y}{P^M} \right)^{\sigma_o} \cdot Y_i \cdot D^{-\theta_i (\sigma_o - 1)}$$

It can be seen that the demand for production factors becomes lower when the environmental feedbacks are considered, since the term $D^{-\theta_i (\sigma_o - 1)}$ is between 0 and 1.

The estimates of the damage elasticity θ for each pollutant in each sector are shown in Table A-6 and the procedure of estimating is as follows. Firstly, we allow for the environmental damage caused by CO2 emissions only in the agricultural sector. Therefore, the set of θ_{CO2} are all zeros except in agriculture. Jiang (2003) reviews a number of empirical studies on estimating the impact of climate change on agriculture and takes the value of θ_{CO2} in the agricultural sector as 0.17788 in his model. We follow this estimate in our model as well.

Secondly, using the method discussed in the previous section, we are able to estimate the sectoral health damage due to PM in terms of the sectoral emission data for China in 2002. As mentioned before, the damage costs are considered as an input cost to industry sectors of improving the working environment for the sake of avoiding the infection of workers by polluted air. This is believed to be the loss in the overall productivity of the each sector. Then by taking logarithm and rearranging the production equation, the values of θ_{PM} in each sector can be calculated as shown in Table A-6. Note that we assume that emissions of PM in rural areas are less damaging and can be ignored. Therefore, the estimate of θ_{PM} in agricultural sector is specifically set to be zero.

Lastly, there are two damage effects of SO2 emissions considered in the model. One is the health damage caused by SO2 and θ_{SO2} in each sector which can be calculated using exactly the same method in estimating θ_{PM}. The other effect is that SO2 emissions together with acid rain reduce the crop (agricultural product) output. According to the study of World Bank (2007), it is estimated that crop losses due to SO2 and acid rain accounting for about 30 billion RMB in 2003. Then we treat the amount of crop losses as the damage effect on agriculture productivity due to SO2 and calculate θ_{SO2} taking the value of 0.0034 after adjustment based on the 2002 national account data in China.

- ***Medical Expenditure***

Another feedback from the environmental damage to the economy is the effect on household's medical expenditure due to polluted air. An increased risk of illness or death raises people's medical expenditure by more relative to a cleaner environment. Increased expenditure reduces their disposable income on consumption which means a loss of human wealth.

$$H_t = \int_t^{\infty} (1-\tau_1)\left[W\left(L_s^G + L_s^C + L_s^I + \sum_{i=1}^{12} L_s^i \right) + TR - m_P \cdot D_{PM} - m_S \cdot D_{SO2} \right] e^{-(R(s)-n)(s-t)} ds$$

where $m \cdot D$ represents the medical expenditure by the household. It is obvious that the household's consumption function will vary correspondingly. The increased medical expenditure is measured by the health damage of PM and SO2 caused by household consumption of fossil fuels and biomass fuels. The proportion rate, m_P and m_S , are calibrated using health damage in household sector in 2002, estimated to be 11.27 and 0.57, respectively.

- ***Capital Depreciation***

Air pollution, particularly SO2 and O3, causes material damage by corroding and deteriorating materials in southern China, where dry sulfur dioxide deposition corrodes a variety of materials, mainly building structures. There is also the impact of traffic on road depreciation. Heavy traffic wears down the roads and increases the need for road maintenance. This feedback is expressed as the link from environmental damage to the (industry specific) rates of capital depreciation as shown below:

$$\dot{K} = J_i - \delta_i K_i - \delta_i' K_i$$

where $\delta_i' K_i$ represents the accelerated capital depreciation due to pollutant emissions, especially SO2.

A study by the World Bank (2007) reported on findings in 14 municipalities and provinces in southern China, and estimated the economic cost of this damage to be about 6.7 billion RMB in 2003. Again, our estimation of δ_i' is based on their results after calibration to fit the 2002 data in China, equal to approximately 0.0011 in our model.

4 Results and discussion

4.1 The baseline simulation

This section describes our baseline simulation run from the modified G-cubed model which considers the environmental feedback on the economy. The baseline scenario is intended to reflect a plausible grow path of the Chinese economy and trends in energy use, pollutant emissions and damages in the absence of climate or environmental policies over time. This provides a reference for comparison with both the non-feedback scenario and the environmental policy scenarios in the next two sections. The baseline simulation is therefore called the "feedback scenario" hereafter, so as to be distinguished from the baseline simulation when no environmental feedback is included, called "non-feedback scenario" in the next subsection.

In the baseline, three sources of economic growth are considered. The first is population growth, which is exogenously set to be consistent with the UN mid range projections. The second is the productivity growth rate. The productivity growth of each sector in the US is assumed to be a particular rate over the next century. The three regions, China, OECD and the rest of the world start in 2002 with some proportion of the US's productivity level in each equivalent sector. It is then assumed that each sector catches up to the US sector (i.e. closes the initial productivity gap) over time as a predetermined rate. The rates of catching up to the US are exogenously determined, e.g. the catch up rate of 0.02 in China's energy sectors and that of 0.04 in China's material sectors over the simulation period are used in our model. Lastly, an autonomous energy efficiency improvement (AEEI) factor of 0.5 per cent per annum in all countries is assumed. The historical growth record of China shows a trend increase in energy efficiency (e.g., Fisher-Vanden and et al. (2004). Our assumption of the AEEI factor is low compared to the trend. This means the estimates of environmental pollution will be smaller if higher energy efficiency is achieved.

Table 2 presents the main variables from the baseline scenario and Figure 3 shows baseline trends in GDP, consumption, investment and energy consumption from 2002 to 2100. The 5.98% average annual growth rate of GDP over the next twenty eight years is derived from our simulation together with a higher rate of investment growth at 7.12% and a lower consumption growth at 4.54%. These growth rates start much higher in the early years and then decline over time as sectors "catch up" to the US sectors. These growth rates are slightly less optimistic than that projected by the World Bank, due to our conservative assumption of productivity growth and autonomous energy efficiency improvement. Even under these assumptions, China's ratio of energy to GDP is predicted to fall steadily from 3.70% in 2002 to 2.82% in 2030.

Figure 4 gives the time paths of CO2, TSP and SO2 emissions and damage due to TSP and SO2 generated from baseline simulation. It shows a rising trend towards the end of the century, however, the time paths differ significantly over time. CO2 emissions are expected to grow at a rate of 5.19% reaching 17062 million tons in 2030. TSP emissions will increase at a high rate of 5.63% and SO2 at a lower rate of 4.99% (Table 2). This is because a larger proportion of TSP emissions than that of SO2 emission are generated from production process, which is directly related to output of each sector, especially the fast-growing durable manufacturing sectors. Focusing on the sectoral emission projections, the electric utilities sector and other durable manufacturing sectors continue to be the largest contributors to the emissions of CO2, SO2 and TSP emissions. It is also worth noting that emissions from the residential sector take are the third main source of CO2 and SO2 emissions in the future.

The associated damage caused by the pollutant emissions can be estimated from our G-cubed simulation (see Table 2). The total value of health damage accounts for 6.75% of China's real GDP in 2002, of which 63.34 US 2002 billion dollars are due to TSP and 8.52 US 2002 billion dollars are due to SO2. Obviously, the damage from TSP is almost eight times that of SO2 despite their similar amount of emissions. It indicates that benefits from TSP abatement would be higher than those from SO2 abatement if they are reduced by the same amount. In conjunction with the growing economy, the total damage continues to rise sharply, although the percentage of damage to GDP declines a little to 5.75% in 2030.

4.2 Comparison with non-feedback scenario

In addition to predicting pollutant emissions and the associated damages in China, this section estimates the feedback effects of the environmental damage on the economy so that we can get a better understanding of how the feedback makes a difference in household and production firms decision making and to what extent it varies the outcomes of output, consumption, investment and economic growth. In so doing, the base case simulation (feedback scenario) presented in the previous section is treated as a reference and then compared with a non-feedback scenario baseline simulation that is run without environmental feedback. The difference of the predicted results in the two simulations illustrates the impact of environmental feedback.

In the non-feedback scenario simulation, all the parameters indicating the feedback relation between environmental damage and the economy are set to be zeros, such as $\theta_i, i = 1,2,......12$, med_p and med_s reflecting the output loss in industrial sectors, and medical expenditure in household sectors due to the health damage from TSP and SO2, and α representing the accelerated capital depreciation rate because SO2 emissions cause erosion of materials.

Table 3 shows the quantitative impacts of the environmental feedback on selected variables. It is found that most economic variables, such as real GDP, consumption, investment and energy consumption are lower, but only by a small amount. This is an interesting finding that the overall loss of GDP caused by damages may not very large, only -0.54% in 2030, when the feedback effect of the damages is considered by the firms and household. This is because firms will adjust their energy inputs when they are aware energy use may damage the productivity and capital depreciation and households reduce their energy use, which degenerates people's health. The substitutability between energy and non-energy composites partly offset the negative effects on the total output. Total energy consumption is 3.24% lower in the feedback scenario than in the non feedback scenario. Their corresponding emissions and health damages are also between 2-3% lower.

From the results comparison, it is concluded that including environmental feedback in the CGE modeling does not have a large impact in the future projections of the Chinese economy although there is some effect. This does not mean that it does not affect the payoff from different policy interventions which will be explored in the next section.

4.3 Carbon Tax Scenario

This section describes the simulations of imposing a carbon tax equivalent to 10 US dollars per ton of carbon on sector output based on their carbon content to reduce CO2 emissions in China. The additional carbon tax revenue is used to reduce the existing lump sum taxes so that real government spending and public deficit are kept the same as the baseline.

The impacts of the carbon tax on some important variables are presented in Table 4 and the percentage changes relative to the baseline are graphed in Figures 5 (a) through (d). In the first year of the imposition of the carbon tax, the CO2, SO2 and TSP emissions are reduced substantially by 32.66%, 38.82% and 26.75% compared to the baseline, respectively. As a consequence, the health damages related to SO2 and TSP emissions are also lower by 39.62% and 32.46%. These percentage reductions decline over time but are still all over 15% twenty years later, showing an effective role played by the carbon tax policy.

The imposition of the carbon tax raises energy prices and in turn leads to increases in the prices of other goods relative to the nominal wage rate (see Table 5). The prices of output in energy intensive sectors, such as electric utilities, gas utilities, and petroleum refining, are 4%-9% higher than in the baseline in the first year and even increase by 7%-12% twenty years after the carbon policy. In contrast, the prices in the non energy sectors increase only by less than 1% compared to the baseline in the twentieth year.

As a result of the higher producer prices in energy intensive sectors and relative lower prices in non energy sectors, demand for energy goods including coal, petroleum and gas is reduced by 27.56% (Table 4). Accordingly, the output in energy sectors falls significantly in contrast to slight changes in output of non-energy sectors. The output of the coal mining sector falls most by around 29.71% in the first year and 19.71% in the twentieth year. The agriculture sector output rises most among the non energy sectors. The overall effect is an increase of 0.60% and 1.05% in the producer price index and a slight decrease of 0.37% and 0.25% in the total output in industry sectors in the first year and the twentieth year, respectively (Table 4 and 6).

By imposing a carbon tax, the government uses the additional revenue to offset the lump sum tax and therefore increase the household disposable income. In addition, the reduction of carbon emissions shifts household medical expenditure on health damages to consumption. As a result, household consumption rises by 0.43% in the first year and 0.63% in the twentieth year. On the production side, given our specification, the imposition of the carbon tax reduces the enterprises' after-tax income significantly, this lead to a fall of 0.80% in investment and thus a fall of 0.09% in real GDP (Figure 5). Lower investment over time leads to lower capital stock overtime.

To estimate how the environmental feedback affects the effectiveness of a carbon tax policy, we also run the simulation in the non-feedback scenario. It is found that the investment and GDP falls by 2.81% and 0.87%, respectively, when the carbon tax is imposed. These changes are larger than the results in the feedback scenario. This is because negative effects of carbon taxes on production sectors are partly offset by the benefits gained in improved productivity due to carbon reduction when considering environmental feedback. Thus the output loss from imposing a carbon constraint is partly reduced through lowering the negative feedback of environmental damage on the economy when emissions are reduced.

4.4 Emissions Target Scenario

The consequences of imposing targets on Chinese CO2 emissions are estimated in this section. This is modeled as a carbon tax calibrated to achieve a given target of percentage reductions in Chinese CO2 emissions from baseline levels. After the optimal level of carbon tax to achieve the target is determined endogenously such that emissions in each period are 5%, 10% or even 30% less than in the base case, it is then treated as an exogenous shock to the economy. The rest of work on simulation and analysis will be similar to that in the carbon tax scenario and there is no need to repeat here.

Carbon tax rates under different emission targets

Unlike the constant unit carbon tax over the simulation period, the endogenously determined carbon tax in the emissions target scenario varies over time, which increases relatively sharply in the first few years and then levels off in later years (Figure 6). This is largely due to the assumption of autonomous energy efficiency improvement (AEEI) which contributes to lower emissions from energy use and is exogenously determined to increase every year.

Several experiments are undertaken for the cases where targets are designated at 5% CO2 reduction up to 30% reduction relative to the baseline at increasing stringency in our modified G-cubed model separately. Figure 7 shows the carbon tax rates to attain different emission targets. It is clear that the carbon tax rises at an increasing rate as the constraint on carbon emissions becomes more stringent. At the 10 percent abatement scenario, the carbon tax approaches US $2.98/ton in the initial year.

Optimal tax comparison

Concerning the specific feature of incorporating environmental feedback into the modified G-cubed model, it is of interest to see whether this modification influence the optimal level of carbon tax in the emissions target scenario. For this purpose, two experiments are performed where target is designated at 5% CO2 reduction relative to the baseline in the feedback and non-feedback scenarios separately.

Figure 6 gives a comparison of carbon taxes that are required to attain a 10% reduction in CO2 emissions from baseline in the feedback and non-feedback scenario. It is found that the optimal carbon tax in the feedback scenario is approximately 2-5% higher than that in the non-feedback scenario in various years. This finding is consistent with our expectation that a more stringent carbon control policy would be required when environment pollution causes damage on the economy. This is because the feedback effects captured in the production function, household budget constraint and capital accumulation result in higher prices of energy and related products, and then a higher tax is required to internalize the externality of environmental damage generated from the energy consumption.

The outcome resultant from the policy scenario simulations has important implications. First, including environmental feedback in the CGE modeling is a crucial part in predicting the health and non-health damage caused by pollutant emissions. Second, the overall costs (benefits) of a climate policy would be overestimated (underestimated) without considering the feedback effects. Third, it leads to a lower level of emissions and better environmental quality if the decision making process takes into account the environmental feedback on the economy. As a result, the cultivation of public awareness of the environmental damage and consciousness of environmental protection would be eventually beneficial to the economic development of the country.

5 Sensitivity Analysis

We vary some key parameter values used to derive the baseline results. The parameters that are expected to affect the results strongly are the elasticity of substitution between energy and non-energy inputs in the top tier as well as among energy and non-energy composites in the second tier in the production of gross output. These elasticities are econometrically estimated using data from the detailed benchmark US input output transactions tables produced by the Bureau of Economic Analysis for the years 1958, 1963, 1967, 1972, 1977 and 1982 in the G-cubed model (McKibbin and Wilcoxen, 1999). For sensitivity, we produce one simulation when halving the top tier elasticities and another simulation when harving the second tier elasticities.

Table 7 gives the results for sensitivity analysis in several scenarios. The first column shows the results in the base case (Column A), and the other columns show the results in the scenarios where the elasticities between energy and non-energy inputs (Column B), between energy inputs (Column C) and between both energy and non-energy inputs (Column D), respectively. It is expected that halving the elasticities reflects a less substitutability between the inputs and thus lead to a lower GDP impact. The GDP results range from -0.06% in column A to -0.19% in column D. Investment changes in the same direction and similar magnitude. The effects on consumption are even smaller, ranging from 0.62% in column A to 0.48% in column B. Due to the imposition of carbon tax, the less substitutability make the firms harder to substitute energy for non energy inputs and therefore the changes in energy consumption are smaller when the elasticities are lower. The impacts in emissions and health damage are also smaller in the less substitutability scenarios.

Comparing the results in the column B, C and D where the elasticities are lower, it is found that the elasticity of substitution between energy and non-energy composites in the second tier affects the results more strongly than that in the top tier in most variables such as GDP, investment, consumer price index, producer prices index and all emission and damage variables. Therefore, changing these parameters in the second tier has a major impact on energy use and thus damages.

6 Conclusions

Little empirical work has been found in the literature estimating the feedback effects of environmental damage on the economy. This implies the overall economic costs of environmental pollution or benefits of pollution control may be over- or under-estimated and thus there may be a lack of quantitative and reliable analysis for policy formulation.

This paper is a first step at integrating environmental damages from energy use into a dynamic intertemporal general equilibrium model, the G-Cubed model, with a focus on the Chinese economy. After incorporating the environmental dimensions into the model, the time paths of several types of energy related emissions and health damages can be predicted as well as the trends of macroeconomic variables. More importantly, we can derive how the feedback effects affect the economic performance and the outcome of various environmental policies. We should caution that these initial results are very preliminary.

Under a business as usual projection, CO2, SO2 and TSP emissions caused by energy use in China and the related environmental damages are estimated to continue to rise in the coming decades. The damages due to TSP emissions are much higher than that due to SO2 emission. The total damage is estimated to be 72 US 2002 billion dollars in 2002, equivalent to 6.75% of China’s GDP in the same year.

Comparing the results of a projection that includes feedback with that of a projection that does not take into account the effect of environmental damages on economic activities, it is found that total energy consumption is 3.24% lower and their associated emissions and health damages are also between 2-3% lower, while the effect on real GDP is much smaller. This is because that the overall loss of GDP caused by damages is partly offset by the substitution effect between energy and non-energy composites when the feedback effects do influence the decision making by firms and household.

In the carbon tax and emissions target scenario, it is found that whether to consider the feedback effects does change the simulation results under various environmental policies. For example, the negative effects of lower investment and lower GDP due to a carbon tax policy are overestimated if feedback effects are neglected; to attain a certain carbon emissions target, the optimal carbon tax required is between 2-5% higher in various years in the feedback scenario than in the non feedback scenario.

To include environmental damages on the economic activity in a dynamic intertemporal G-cubed model is a useful contribution to the empirical analysis of the environmental feedback effects. Three types of effects are considered in our model: lower productivity, increased medical expenditure and accelerated rate of capital depreciation. However, future studies can be extended to incorporate the labour productivity loss and treat the health of workers as a factor of effectiveness of labor input. In addition, since it is assumed that emissions in rural areas are less damaging and negligible, the estimation may be improved if urbanization can be modeled explicitly.

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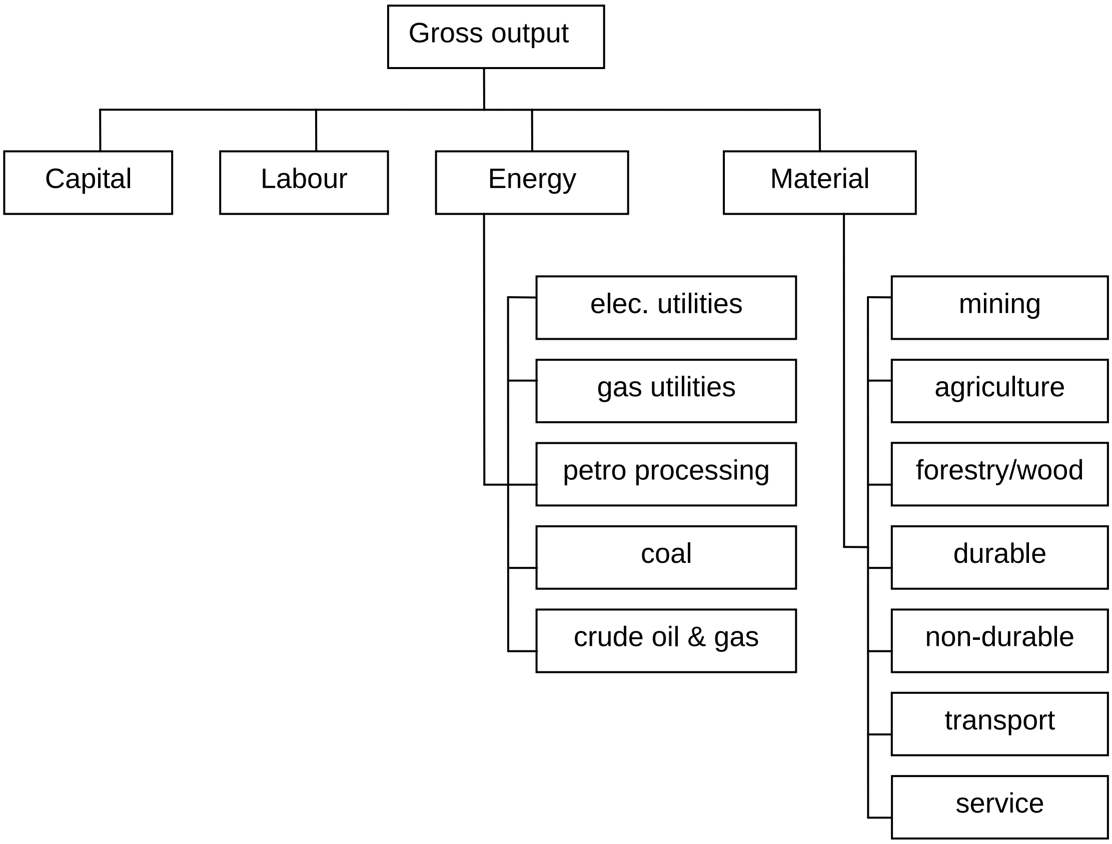


Figure 1 Nesting structure of production in the G-Cubed

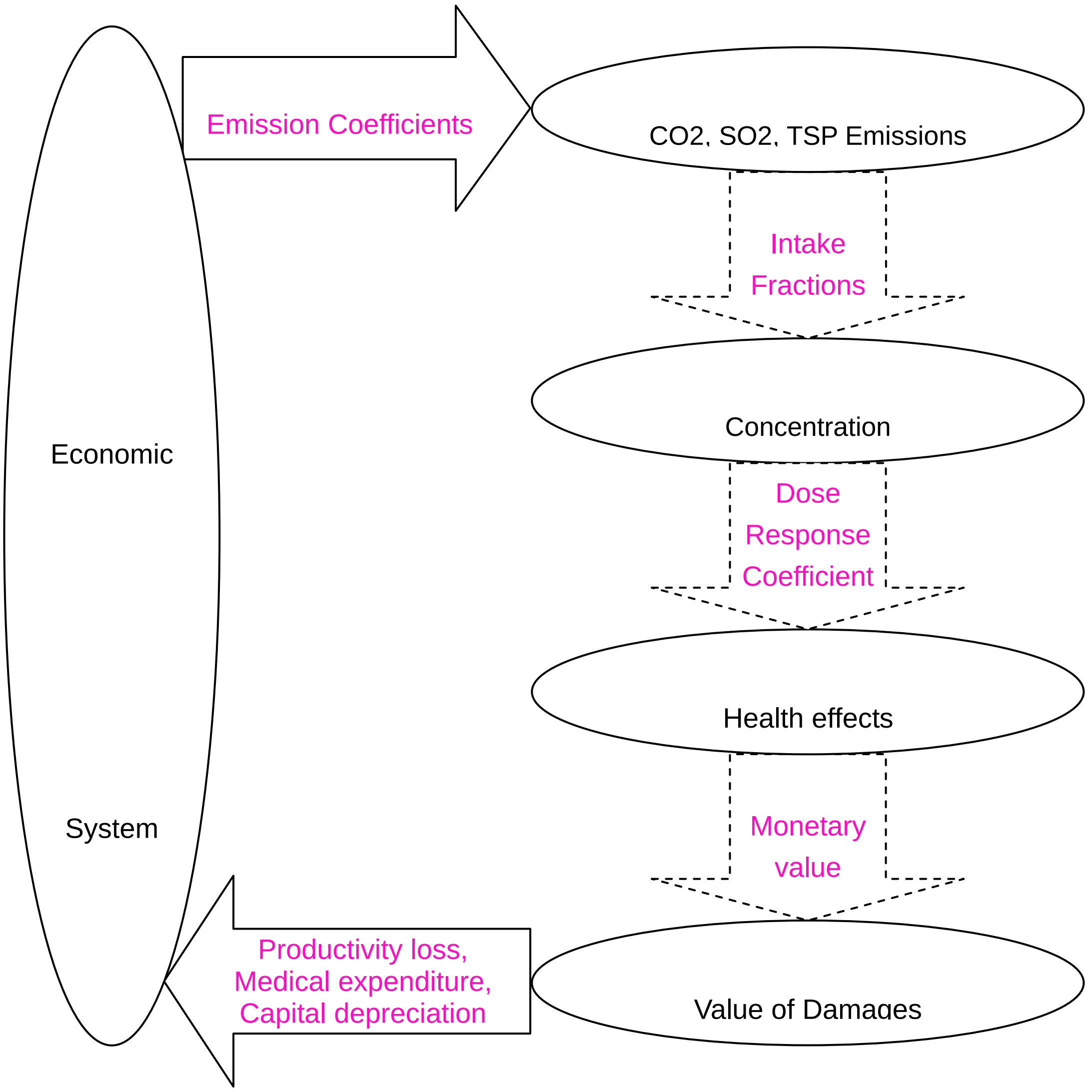
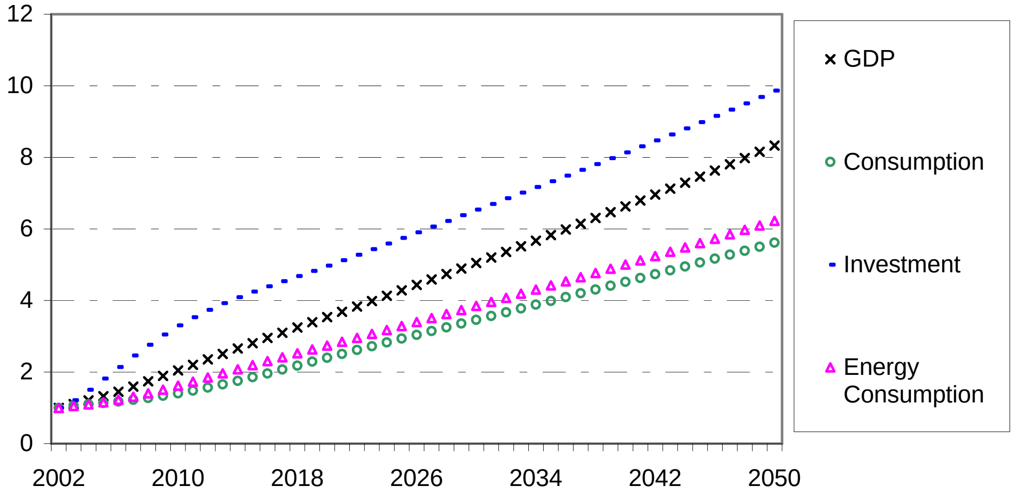


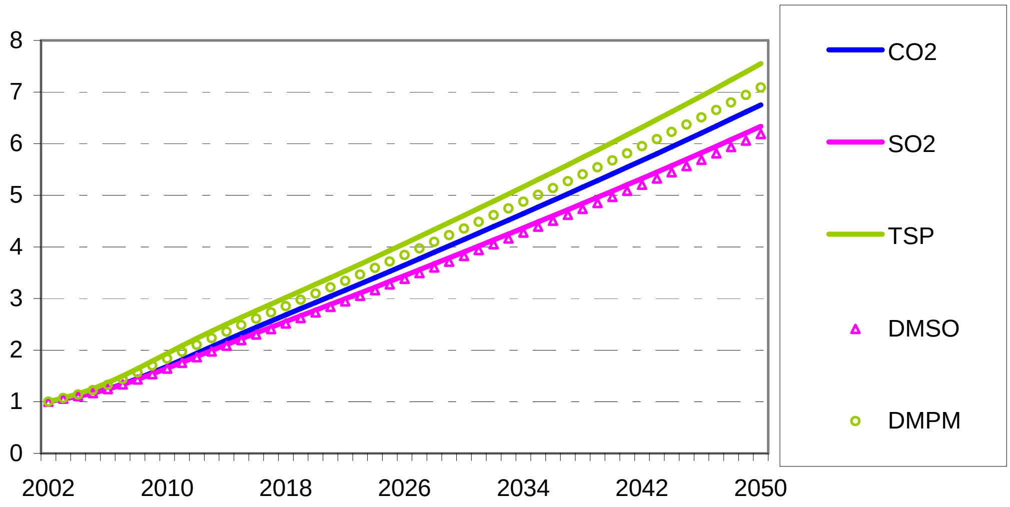
Figure 2 Linkage between the economic model and the environmental model in the G-cubed

Figure 3 Time paths of GDP, Consumpton, Investment and Energy consumption in the baseline, 2002 =1.00



Source: G-cubed simulation.

Figure 4 Time paths of Emissions and Damge projected in the baseline, 2002 =1.00



Source: G-cubed simulation.

Figure 5(a) Percentage change due to a carbon tax = US$10/ton

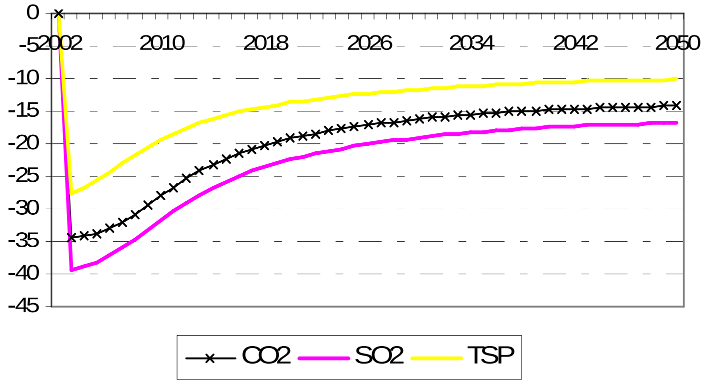


Figure 5(b) Percentage change due to a carbon tax = US$10/ton

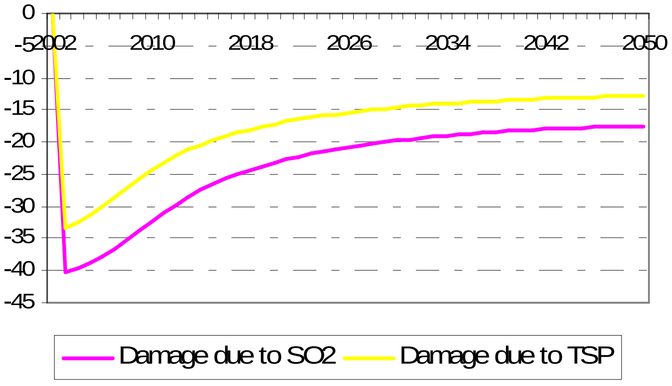


Figure 5(c)Percentage change due to a carbon tax = US$10/ton

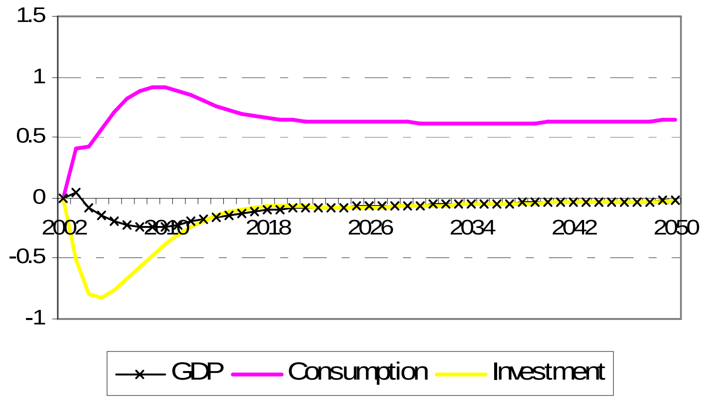


Figure 5(d)Percentage change due to a carbon tax = US$10/ton

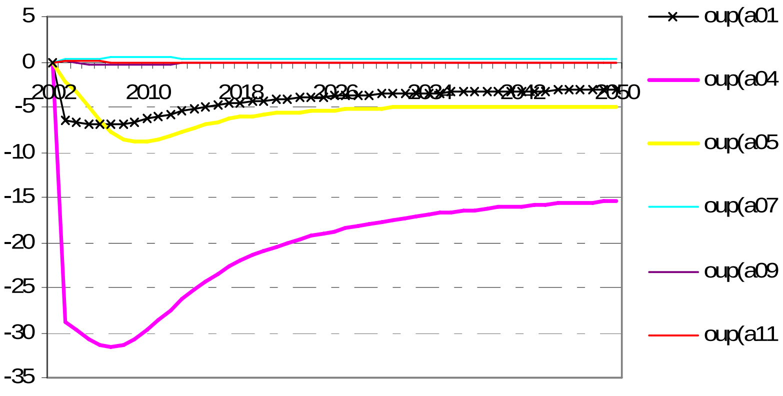
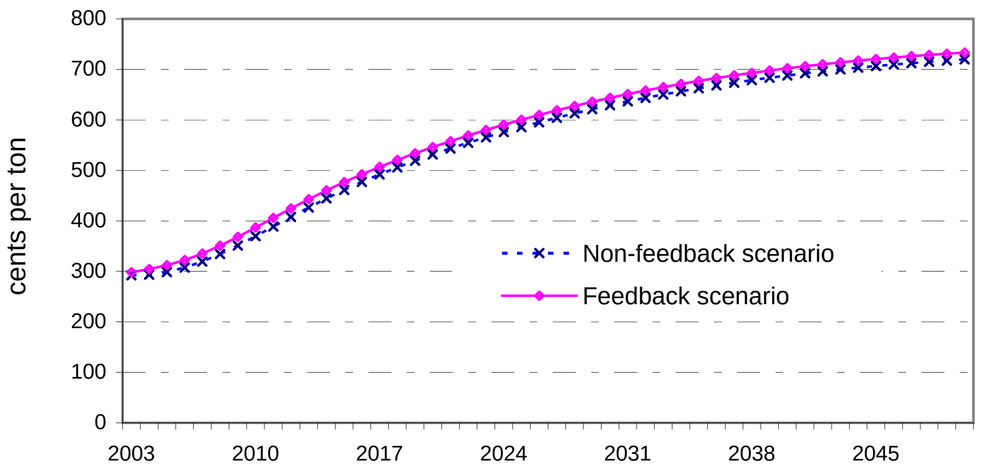
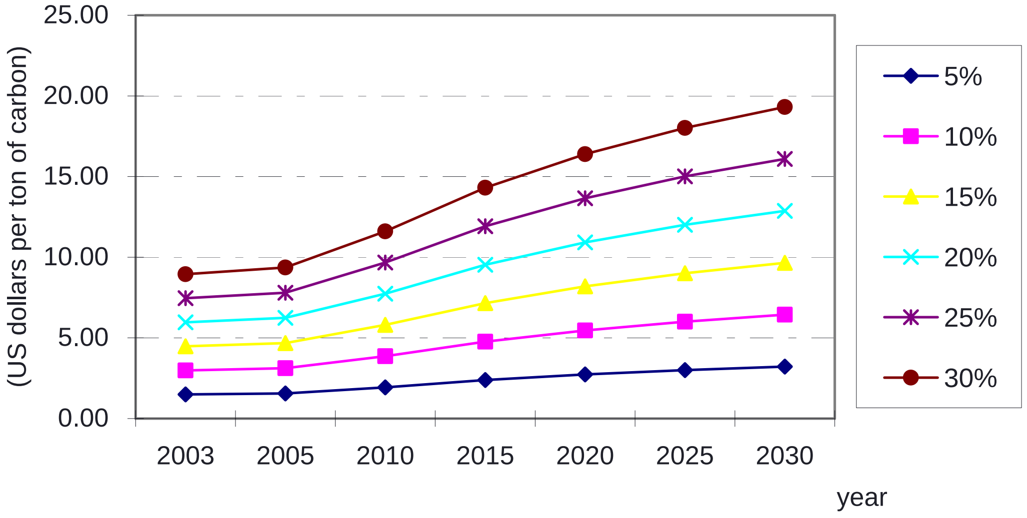


Figure 6 Carbon tax required to attain a given reduction in CO2 Emissons (10% reduction from baseline by 2050)



Source: G-cubed simulation.

Figure 7 Carbon tax rates required to attain different emissions targets



Source: G-cubed simulation.

Table 1 Environmental CGE models for China

Reference	Sectors	Dynamics	Data	Energy goods	Emissions	Ancillary benefits	Feedback	Specific features
Xie (1995)	7	Static	1990	Aggregate energy (1)	Waste water, smog dust, solid wast	No	No	Pollutant-specific abatement sectors, Environmental SAM
Zhang (1998)	10	Dynamic recursive	1987	Coal, oil, natural gas, electricity (4)	CO2	No	No	
Garbaccio, Ho, Jorgenson (1996) Version 1	29	Dynamic	1992	Coal, oil, electricity, refined petroleum (4)	CO2	No	No	Plan and market components
Fisher-Vanden (2003)	29	Dynamic intertemporal	1992	Coal mining, crude oil, natural gas, electric power, petroleum refining (4)	CO2	No	No	market reforms on structural change
Jiang (2003)	12	Dynamic intertemporal	1997	Electric utilities, gas utilities, petroleum refining, coal mining, crude oil and gas extraction (5)	CO2	No	Yes	Multi-country
He (2005)	55	Static	1997	Coal, oil and coke, natural gas, electricity generation (4)	SO2	No	No	Desulfur policy and trade liberazation

Garbaccio, Ho, Jorgenson (2000) Version 2	33	Dynamic	1995	Coal mining, crude oil, natural gas, electric power, refining coal production (5)	CO2, TSP, SO2	Yes	No	Plan and market components
O'Connor et al. (2003)	61	Dynamic recursive	1997	Coal, refined petroleum, electricity, gas (4)	CO2, TSP, SO2, NOx	Yes	No	Rural/urban and Two-region (Guangdong and the rest of China)
Aunan et al. (2007)	61	Dynamic recursive	1997	Coal, refined petroleum, electricity, gas (4)	CO2, TSP, SO2, NOx, VOC, CO	Yes	No	Rural/urban and Two-region (Guangdong and the rest of China)
This paper (2008)	12	Dynamic intertemporal	2002	Electric utilities, gas utilities, petroleum refining, coal mining, crude oil and gas extraction (5)	CO2, TSP, SO2	Yes	Yes	Multi-country

Sources: As indicated.

Table 2 Selected Variables from Base-Case Simulation (Feedback scenario)

Variable	Unit	2002	2030	Average Annual growth rate
GDP	(US 2002 billion dollars)	1,063.86	5,369.43	5.98%
Consumption	(US 2002 billion dollars)	536.31	1,856.65	4.54%
Investment	(US 2002 billion dollars)	381.58	2,495.38	7.12%
Energy Consumption	(btu)	39.36	151.45	4.94%
Energy/GDP	(%)	3.70%	2.82%	
CO2 emissions	(million tons)	4,150.56	17,061.93	5.19%
SO2 emissions	(million tons)	20.63	80.50	4.99%
TSP emissions	(million tons)	17.60	81.11	5.63%
Health effects	(million cases)	5,530.62	23,005.33	
Due to SO2	(million cases)	401.56	662.37	1.80%
Due to TSP	(million cases)	5,129.07	22,342.95	5.41%
Damage	(US 2002 billion dollars)	71.86	308.50	5.36%
Due to SO2	(US 2002 billion dollars)	8.52	32.60	4.92%
Due to TSP	(US 2002 billion dollars)	63.34	275.90	5.41%
Damage/GDP	(%)	6.75%	5.75%	

Source: Simulation from G-cubed.

Table 3 Feedback effects on Selected Variables

Variable	(Unit)	2030		
		Without Feedback	With Feedback	% change
GDP	(US 2002 billion dollars)	5398.31	5,369.43	-0.53%
Consumption	(US 2002 billion dollars)	1836.60	1,856.65	1.09%
Investment	(US 2002 billion dollars)	2533.96	2,495.38	-1.52%
Energy Consumption	(btu)	156.52	151.45	-3.24%
Energy/GDP	(%)	2.90%	2.82%	-0.08%
CO2 emissions	(million tons)	17489.23	17,061.93	-2.44%
SO2 emissions	(million tons)	83.11	80.50	-3.14%
TSP emissions	(million tons)	83.36	81.11	-2.69%
Health effects				
Due to SO2	(million cases)	662.40	662.37	0.00%
Due to TSP	(million cases)	22902.50	22,342.95	-2.44%
Damage	(US 2002 billion dollars)	316.30	308.50	-2.47%
Due to SO2	(US 2002 billion dollars)	33.49	32.60	-2.66%
Due to TSP	(US 2002 billion dollars)	282.81	275.90	-2.44%
Damage/GDP	(%)	5.86%	5.75%	-0.11%

Source: Simulation from G-cubed.

Table 4 Effects of a carbon tax of US$10/ton on selected variables

Variable	Effect in the 1st Year	Effect in the 20th Year
GDP	-0.09%	-0.08%
Consumption	0.43%	0.63%
Investment	-0.80%	-0.08%
Energy use	-27.56%	-15.61%
Product price index	0.60%	1.05%
Consumption price index	0.55%	0.67%
CO2 emissions	-32.66%	-17.22%
SO2 emissions	-38.82%	-21.13%
TSP emissions	-26.75%	-12.89%
Health Effects		
Due to SO2	-0.03%	-0.03%
Due to TSP	-32.46%	-16.20%
Values of Damage		
Due to SO2	-39.62%	-21.87%
Due to TSP	-32.46%	-16.20%
Carbon tax revenue	9.09%	12.75%

Note: The tax is imposed from 2003 onwards. The effects are expressed as the percentage change from the baseline.
Source: G-cubed simulation.

Table 5 Effects of a carbon tax of US$10/ton on sectoral prices

Variable	Effect in the 1st Year	Effect in the 5th Year	Effect in the 20th Year
01 Electric Utilities	5.55%	7.57%	7.67%
02 Gas Utilities	8.83%	11.07%	11.25%
03 Petroleum refining	4.55%	7.39%	7.55%
04 Coal mining	-4.82%	0.34%	1.48%
05 Crude oil and gas	-3.24%	1.38%	1.80%
06 Mining	-0.10%	0.31%	0.26%
07 Agriculture	0.27%	0.39%	0.22%
08 Forestry and Wood Products	0.08%	0.43%	0.33%
09 Other Durable Manufacturing	-0.36%	0.16%	0.06%
10 Other Non-Durable Manufacturing	0.41%	0.70%	0.59%
11 Transportation	-0.09%	0.32%	0.24%
12 Services	-0.69%	-0.51%	-0.60%

Note: The tax is imposed from 2003 onwards. The effects are expressed as the percentage change from the baseline.

Source: G-cubed simulation.

Table 6 Effects of a carbon tax of US$10/ton on sectoral output

Variable	Effect in the 1st Year	Effect in the 20th Year
01 Electric Utilities	-6.67%	-4.02%
02 Gas Utilities	-8.15%	-5.96%
03 Petroleum refining	-5.14%	-3.77%
04 Coal mining	-29.71%	-19.71%
05 Crude oil and gas	-3.33%	-5.53%
06 Mining	-0.32%	-0.18%
07 Agriculture	0.28%	0.34%
08 Forestry and Wood Products	-0.63%	-0.25%
09 Other Durable Manufacturing	-0.12%	-0.11%
10 Other Non-Durable Manufacturing	0.04%	0.01%
11 Transportation	0.09%	-0.02%
12 Services	0.84%	0.36%
Total output	-0.37%	-0.25%

Note: The tax is imposed from 2003 onwards. The effects are expressed as the percentage change from the baseline.

Source: G-cubed simulation.

Table 7 Sensitivity Analysis of effects of a carbon tax of US$10/ton on selected variables in the long run

Variable	baseline	halving sigma_o	halving sigma_e	halving sigma_e&m
	(A)	(B)	(C)	(D)
GDP	-0.06%	-0.14%	-0.19%	-0.19%
Consumption	0.62%	0.48%	0.53%	0.53%
Investment	-0.07%	-0.08%	-0.19%	-0.19%
Total domestic output	-0.23%	-0.18%	-0.35%	-0.35%
Energy use	-14.10%	-9.83%	-11.56%	-11.54%
Product price index	1.05%	0.98%	1.48%	1.47%
Consumption price index	0.67%	0.58%	1.04%	1.03%
CO2 emissions	-15.53%	-11.86%	-11.29%	-11.25%
SO2 emissions	-19.06%	-14.99%	-15.18%	-15.14%
TSP emissions	-11.62%	-9.46%	-8.96%	-8.92%
Health Effects				
Due to SO2	-0.03%	-0.03%	-0.03%	-0.03%
Due to TSP	-14.61%	-12.77%	-11.12%	-11.08%
Values of Damage				
Due to SO2	-19.78%	-16.79%	-15.36%	-15.31%
Due to TSP	-14.61%	-12.77%	-11.12%	-11.08%

Note: The effects are expressed as the percentage change from the baseline in each case.
Source: G-cubed simulation.

Appendix A: Tables of parameters

Table A-1 CO2 emission coefficients in the G-Cubed

sectors	Coefficients on coal use	Coefficients on oil and gas use	Coefficients on durable goods	Coefficients on sectoral output	Coefficients on household consumption
	α_{j04}	α_{j05}	α_{j09}	β_j	γ_h
01 Electric Utilities	265.7	72.2	0.0	0.0	0.0
02 Gas Utilities	174.9	47.5	0.0	0.0	0.0
03 Petroleum refining	4.6	1.2	0.0	0.0	0.0
04 Coal mining	318.8	86.6	0.0	0.0	388.7
05 Crude oil and gas extraction	218.5	59.4	0.0	0.0	105.6
06 Mining	498.6	135.5	0.0	0.0	0.0
07 Agriculture	577.2	156.9	0.0	0.0	3.7
08 Forestry and Wood Products	190.4	51.7	0.0	0.0	5.8
09 Other Durable Manufacturing	584.8	158.9	0.937	0.0	0.0
10 Other Non-Durable Manufacturing	418.7	113.8	0.0	0.0	0.0
11 Transportation	2164.8	588.3	0.0	0.0	0.0
12 Services	2004.6	544.8	0.0	0.0	0.0

Notes: The omitted coefficients in some sectors are zeros and thus not shown here.

Source: Author’s calculation.

Table A-2 TSP emission coefficients in the G-Cubed

sectors	Coefficients on coal use	Coefficients on oil and gas use	Coefficients on sectoral output	Coefficients on household consumption
	α_{j04}	α_{j05}	β_j	γ_h
01 Electric Utilities	0.5780	0.2015	0.0003	0.0
02 Gas Utilities	0.0832	0.0290	0.0222	0.0
03 Petroleum refining	0.0193	0.0067	0.0011	0.0
04 Coal mining	0.7656	0.2669	0.0075	3.5275
05 Crude oil and gas extraction	0.0640	0.0223	0.0001	1.2296
06 Mining	3.0936	1.0783	0.0036	0.0
07 Agriculture	1.2346	0.4303	0.0000	0.0
08 Forestry and Wood Products	1.5325	0.5342	0.0002	0.0
09 Other Durable Manufacturing	2.0086	0.7001	0.0077	0.0
10 Other Non-Durable Manufacturing	1.4537	0.5067	0.0003	0.0
11 Transportation	3.0181	1.0520	0.0000	0.0
12 Services	18.5097	6.4517	0.0000	0.0

Notes: The omitted coefficients in some sectors are zeros and thus not shown here.

Source: Author’s calculation.

Table A-3 SO2 emission coefficients in the G-Cubed

sectors	Coefficients on coal use	Coefficients on oil and gas use	Coefficients on sectoral output	Coefficients on household consumption
	α_{j04}	α_{j05}	β_j	γ_h
01 Electric Utilities	1.3176	0.4592	0.0002	0.0
02 Gas Utilities	0.1571	0.0548	0.0000	0.0
03 Petroleum refining	0.0167	0.0058	0.0028	0.0
04 Coal mining	0.8040	0.2802	0.0043	6.1901
05 Crude oil and gas extraction	0.0754	0.0263	0.0004	2.1576
06 Mining	3.9296	1.3697	0.0011	0.0
07 Agriculture	3.2187	1.1219	0.0000	0.0
08 Forestry and Wood Products	0.8974	0.3128	0.0003	0.0
09 Other Durable Manufacturing	1.8136	0.6321	0.0017	0.0
10 Other Non-Durable Manufacturing	2.0368	0.7100	0.0002	0.0
11 Transportation	5.7872	2.0172	0.0000	0.0
12 Services	43.4097	15.1308	0.0000	0.0

Notes: The omitted coefficients in some sectors are zeros and thus not shown here.

Source: Author's calculation.

Table A-4 Dose response coefficients and valuation per case

Health effects	Dose-Reponses coefficients (DR) (cases per million per $\mu g / m^3$)	Valuation per case (v) (2002 us dollar)
Due to PM:		
01 mortality	1.95	103447.70
02 respiratory hospital admissions	12	524.58
03 emergency room visits	235	24.59
04 restricted activity days	57500	2.42
05 lower respiratory infection/children (asthma)	23	13.85
06 asthma attacks	2608	4.33
07 chronic bronchitis	61	41379.08
08 respiratory symptoms	183000	0.64
Due to SO2:		
01 mortality	1.95	103447.70
09 chest discomfort	10000	1.07
10 respiratory symptoms in children	5	1.07

Sources: Adjusted based on World Bank (2007) and Ho and Jorgenson (2007b).

Table A-5 Intake fractions used to estimate the health effects

Sectors	Intake Fractions	
	iF_{PM}	iF_{SO2}
01 Electric Utilities	5.12E-06	5.64E-06
02 Gas Utilities	1.24E-05	1.97E-05
03 Petroleum refining	1.24E-05	1.97E-05
04 Coal mining	1.24E-05	1.97E-05
05 Crude oil and gas extraction	1.24E-05	1.97E-05
06 Mining	1.24E-05	1.97E-05
07 Agriculture	1.83E-06	3.93E-07
08 Forestry and Wood Products	1.24E-05	1.97E-05
09 Other Durable Manufacturing	1.24E-05	1.97E-05
10 Other Non-Durable Manufacturing	1.24E-05	1.97E-05
11 Transportation	9.15E-05	1.97E-05
12 Services	4.57E-05	1.97E-05
13 household	2.74E-05	1.97E-05

Source: Adjusted based on Ho and Jorgenson (2007b).

Table A-6 Damage elasticity (θ) in each sector

	Damage elasticity (θ)		
	θ_{CO2}	θ_{PM}	θ_{SO2}
01 Electric Utilities	0	0.0300	0.0071
02 Gas Utilities	0	0.0399	0.0031
03 Petroleum refining	0	0.0055	0.0011
04 Coal mining	0	0.0228	0.0029
05 Crude oil and gas extraction	0	0.0011	0.0003
06 Mining	0	0.0071	0.0007
07 Agriculture	0.1778	0.0000	0.0034
08 Forestry and Wood Products	0	0.0015	0.0002
09 Other Durable Manufacturing	0	0.0128	0.0008
10 Other Non-Durable Manufacturing	0	0.0027	0.0006
11 Transportation	0	0.0120	0.0005
12 Services	0	0.0255	0.0024

Source: Author’s calculation.