The Health Benefits and Costs of Controlling Air Pollution in China

(Report to the China Council)

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I. Introduction

Many recent studies have put the damages from air pollution in China to human health and the environment at very high levels. For example, the World Bank (1997) estimated that air pollution caused 178,000 premature deaths in urban China in 1995 and valued health and material damages at nearly 5% of GDP. Other studies include Wang and Smith (1996a) and Feng (1999). Much of this damage is attributed to emissions of particulates and sulfur dioxide. Furthermore, this problem is expected to grow in the near future as rapid growth outpaces efforts to reduce emissions.

In light of this there have been many papers examining the various options to control or reduce these pollutants. These range from electricity generation policies to economic deregulation to eliminate subsidies on dirty fuels. Few of these studies however, make an integrated estimate of the economic costs and health benefits of these pollution control policies. The aim of this study is to examine some pollution control policies and how they might affect economic performance. We shall focus on general economy-wide policies, such as fuel taxes, rather than specific rules such as mandatory scrubbers or other detailed sector-specific policies. We examine how these taxes affect fuel use and hence emissions and health damages. At the same time we estimate how these taxes affect output, allocation of resouces, other existing taxes, and over time, how they affect economic growth.

The estimation of health damages and its valuation is the subject of much research and debate. We shall discuss these to explain how we use the various estimates that exist for China. The range of uncertainty is considerable given the complexity of the economy-environment-health linkages, but we believe our estimates are instructive.

We find that a policy that imposes even moderate taxes on fuels could reduce health damages by 20%, lower GDP by 0.1%, and lower aggregate consumption by 0.5% in the short run. Depending on how the pollution tax revenues are used, the long run effects could be positive on GDP. For example, if these revenues are recycled towards investment then consumption and GDP over the longer term are both higher. The value of the health damage reduced by this moderate fuel tax policy is about 1.2% of GDP in the short run. Depending on how one wishes to weigh present versus future consumption, the sacrifice of consumption over time is about an order of magnitude smaller than the

benefit in damage reduction. This cost benefit ratio is in line with the discussions in World Bank (1997).

A more broad based but less efficient policy which taxes output based on the amount of pollution damage produced could reduce health damages by 3.5% a year, and in the short run lower GDP by 0.1%, and lower consumption by 0.3%. The fuel tax policy is more effective but require large adjustments in the Coal sector. The choice of policies would depend on the ability of the government to help the heavily taxed sector to adjust. The cost of adjusting to a lower coal economy should be an important topic of future research.

II. Methodology for policy design and analysis.

The use of taxes to correct for externalities has been examined by many recent studies. Some of these ask whether the traditional Pigovian tax (i.e. a tax equal to the marginal damage caused by the externality) is appropriate if we consider an economy that have many other tax distortions already in place. This is related to the question whether it is possible to have a double dividend, i.e. lower negative externalities and higher economic efficiency. See, e.g., Bovenberg and de Mooij (1994), Bovenberg and Goulder (1996), Goulder, Parry and Burtraw (1997), and Metcalf (2000).

These practical questions of optimal taxation must be answered with an explicit framework, that is, explicit assumptions of market structure, production functions, utility functions, etc. If one wishes to use a numerical model of the economy then one is implicitly saying that the elasticities of substitution used are appropriate for the range of price changes that will result from the taxes being considered. Furthermore, one should be careful to distinguish between the short and long run effects.

A systematic examination of the rapidly evolving tax system in China must await future analysis. In this paper we do not directly ask what the optimal system of taxes to correct air pollution externalities is. We ask a simpler question, what are the effects of employing taxes that are related to the level of pollution emitted, i.e. the effects on sectoral prices, output, consumption and economic growth. The reasons for this approach are simple. Firstly, the estimated externalities are large for many sectors as discussed

below. A full Pigovian tax would lead to large changes in prices, more than 100%. Changes of this magnitude are not reliably estimated using marginal analysis. Secondly, the damage to human health is estimated using linear functions, that is, pollutant concentration is a linear function of emissions, and health effects are linear functions of concentration. These linear approximations are not going to be very reliable for large changes in pollution emission. Thirdly, a proper optimal tax analysis should take intertemporal effects into account. This has to be done in a model that specifies a capital market for savings and investment. It is difficult to give an accurate characterization of the Chinese capital markets today with its mix of controlled credit markets and open stock markets, and we therefore, use a simpler approach that considers consumption one period at a time.

We employ a multi-sector model of the Chinese economy that we used previously to study the local health benefits of carbon control policies (Garbaccio, Ho, and Jorgenson 2000). Our approach is to first estimate the damages to human health from air pollution due to the current patterns of output and fuel use. These damages are attributed to the emissions from specific industries and we can thus calculate the average damage per unit output of each sector. Our input-output framework also allows us to calculate the damage per unit of coal or oil used. The health effects (e.g. the number of cases of premature deaths) are translated to *yuan* values. The model is dynamic and the value of damages are estimated each year as the projected economy expands and changes in structure.

Given these negative externalities from production of goods and use of fuels it is natural to impose taxes to ensure economic agents internalize these in their decisions. In the second step we impose taxes in proportion to the damages and examine the new trajectory of the economy. We shall examine two sets of policies. The first is a tax on sectoral output, where the tax rate is proportional to the health damage caused by the production of the commodity. This tax will cause the buyers of goods to face a price that reflects the pollution externalities, for example, users of cement will pay higher prices relative to users of apparel. This tax is not the most efficient[1] but is relatively easy to

[1] Fullerton, Hong and Metcalf (1999) finds that an "imprecise" output tax produces a welfare gain which is less than half that obtained from a direct pollution tax.

implement. Compared to the next policy, it produces smaller changes in prices and incomes, and may thus find broader political support.

The second policy is a tax on primary fuels, where the tax rate is proportional to the average damage per unit of fuel. Our data, described below, indicates that a ton of coal produces different levels of emissions and damages depending on which industry burns it. An efficient externality tax would tax the sectors differently. However, an industry specific fuel tax does not seem to us to be a feasible option and so we consider a tax that is applied equally to all users. This will cause producers to internalize the damages caused by their choice of fuels in their production decisions.

The most efficient policy is of course a direct tax on emissions. However, emissions of TSP are not currently measured (merely derived from fuel inputs), and could be measured only at high cost. SO2 from large sources may be amenable to a control policy like the U.S. trading program, but this is not believed to be a large source of health damage in China. Hence we consider only the feasible taxes on output and fuels.

Given the size of the estimated health damages these pollution taxes are large, to maintain revenue neutrality we cut other pre-existing taxes. The choice of the which taxes to cut, or which sectors to compensate affects both the mix of winners and losers in a given period, as well as the mix over time.

The Economic Model

Sectoral output is expressed as a function of capital, labor, intermediate inputs and level of technology. Let QI_{jt} denote the quantity of output from sector *j* in period t:

(1) $$QI_j = f(KD_j, LD_j, TD_j, A_{1j}, \ldots, A_{nj}, t)$$

where KD_j, LD_j, TD_j, and A_{ij} are capital, labor, land, and intermediate inputs, respectively. The intermediate inputs are partitioned into energy and non-energy aggregates, and the level of technology is represented by a smoothly rising function, $g(t)$. The top level production function is assumed to be constant returns to scale and written as :

(2) $$QI_{jt} = g(t) KD_{jt}^{\alpha_{Kj}} LD_{jt}^{\alpha_{Lj}} TD_{jt}^{\alpha_{Tj}} E_{jt}^{\alpha_{Ej}} M_{jt}^{\alpha_{Mj}}, \quad \text{where}$$

$$\log E_{jt} = \sum_k \alpha_{kj}^{E} \log A_{kjt} \qquad \text{k = coal, oil, gas, electricity, refined oil, gas prod}$$

.

$$\log M_{jt} = \sum_k \alpha_{kj}^{M} \log A_{kjt} \qquad k = \text{non-energy intermediate goods.}$$

Given output price PO_{jt}, and input prices, $P_{jt}^{KD}, PL_{jt}, PT_{jt,} PS_{it}$, the first order conditions from profit maximization gives the demands for inputs. (*PS* denotes the supply price of input i). For example, the demand for coal input is[2]:

(3) $$A_{coal,j,t} = \alpha_{Ei}\alpha_{coal,j}^{E} \frac{PO_{jt}QI_{jt}}{PS_{coal,t}}$$

The government imposes various taxes that are captured in our model, in 1997 these included sales tax, value-added tax, capital income tax and import tariffs. The gap between producer and buyer prices for output *j* caused by the sales tax t_{jt}^{t} and counterfactual externality tax t_{jt}^{x} is:

(4) $$PI_{jt} = (1 + t_{jt}^{t} + t_{jt}^{xv})PO_{jt} + t_{jt}^{xu}$$

We allow two different types of externality taxes, a unit tax (t_{jt}^{xu}), or an ad valorem tax (t_{jt}^{xv}).

The total supply of commodities comes from the domestic output and imports, and the price paid for inputs, as given in (3), is an aggregate of this buyer's price and import prices (PM_{it})[3]:

(5) $$PS_{it} = p^{s}(PI_{it}, PM_{it})$$

For the final demand sectors -- consumption, investment, government and exports -- we have a similar procedure of deriving demands from utility maximization. Households allocate income to savings and consumption. Given an allocation of VCC_t for total current consumption, the demand by households for coal consumption, like eq. (3) above, is:

[2] The parameters of the production function in (2) are allowed to change over time to reflect energy saving technical change. This is described in greater detail in the Appendix.

[3] The model distinguishes between industries (j) and commodities (i). Each commodity may be made by a few industries, and some industries make more than one commodity. For ease of exposition here we shall ignore this distinction. This is described in the Garbaccio, Ho and Jorgenson (2001).

(6) $$C_{coal,t} = \alpha^{C}_{coal,t} \frac{VCC_t}{PS_{coal,t}}$$

The details of this and other final demand components are given in the Appendix. The α^{C}_{it} coefficients are indexed by time and allowed to change giving consumption an exogenous income effect.

The Environment-Health Model

Emissions of local pollutants comes from two distinct sources, the first is due to the burning of fossil fuels (combustion emissions), the other from noncombustion processes (process emissions). A great deal of dust is produced in industries like cement production and building construction that is not related to the amount of fuel used. In this paper we concentrate on two pollutants, particulate matter less than 10 microns (PM-10) and sulfur dioxide (SO_2). PM-10 and SO_2 both have their origins in combustion and noncombustion sources. Our specification of emissions, concentrations, and dose-response follows Lvovsky and Hughes (1997).[4]

Total emissions from industry *j* is the sum of process emissions and combustion emissions from burning coal, oil, and gas. The household sector also produces pollution from combustion of fuels. Let EM_{jxt} denote the emissions of pollutant *x* from sector *j* at time *t* (in kilo tons):

(7) $$EM_{jxt} = \sigma_{jx} QI_{jt} + \sum_{f} \left(\psi_{jxf} AF_{jft} \right)$$

(8) $$AF_{jft} = \lambda_j \theta_f FT_{fjt}$$

$$FT_{jft} = \xi_f A_{fjt}$$

where x = PM-10, SO_2 , f = coal, oil, gas , j=1,....n,H .

σ_{jx} is process emissions of pollutant *x* from a unit of sector *j* output and ψ_{jxf} is the emissions from burning one unit of fuel *f* in sector *j*. AF_{jft} is the quantity of fuel *f* (in

[4] Lvovsky and Hughes (1997) discuss the choice of PM-10 rather than total suspended particulates (TSP). The data currently collected by the Chinese authorities are mostly in TSP. Health damage, however, is believed to be mainly due to finer particles. Lvovsky and Hughes make an estimate of the share of PM-10 in TSP and kept that constant. Improved data would obviously refine this and other analyses.

tons of oil equivalent (toe)) consumed by sector *j* in period *t*.[5] The constant *yuan* measure A_{ijt} is converted to physical units (e.g. $FT_{j,coal,t}$ tons of coal) by the ξ_f coefficient, and that is converted to toe's by the θ_f coefficient. For the Refining and Coal Products sector, only part of the fuel inputs is combusted, this loss ratio is given by λ_j. The *j* index runs over the *n* production sectors and the household sector.

The amount of emissions per *yuan* of output, or emissions per toe of fuel used, depends on the technology employed and will change as new investments are made. A proper study should take into account the costs of these new technologies and how much they reduce emissions and energy use.[6] Estimates of these factors have not yet been assembled for many industries in China and we use a simple mechanism to represent such changes. Lvovsky and Hughes (1997) make an estimate of the emission levels of "new" technology and write the actual emission coefficients as a weighted sum of the coefficients from the existing and new technologies. Using superscripts "*O*" and "*N*" to denote the old and new coefficients we have:

$$\psi_{jxft} = k_t \psi^O_{jxf} + (1-k_t)\psi^N_{jxf} \quad , \tag{9}$$

where the weight, k_t, is the share of old capital in the total stock of capital.[7]

Within each of the sectors there is considerable heterogeneity in plant size, vintage, etc. While we do not incorporate such detail into this research, we do note that, on average, different industries emissions enter the atmosphere at different levels. Following Lvovsky and Hughes we classify emission sources as low, medium, and high height. As a first approximation, emissions from the electric power sector are classified as high height, most of the manufacturing industries are classified as medium, and the

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[5] For the Petroleum Refining sector the input of oil is of course not the total purchases of crude but only that part which is burnt.

[6] For example, Jorgenson and Wilcoxen (1990) studied the economic effects of regulations in the U.S. using data on capital and operating costs of equipment that were installed in response to EPA regulations.

[7] This simple approach ignores the fact that cleaner equipment will likely cost more than dirty equipment. Furthermore, the exogenous energy efficiency improvements described above are set independently of these emission factors. An integrated approach would of course be preferred when such data becomes available.

nonmanufacturing and household sectors as low. The exact designations by sector are given in Table 7. Denoting the emissions of pollutant *x* at height *c* by E_{cxt} we have:

$$(10) \qquad E_{cxt} = \underset{j \in c}{EM_{jxt}} \quad , \qquad \text{where } c = \text{low, medium, high} \quad .$$

The next step is to estimate concentrations of pollutants in population centers due to these emissions. A good approach would be to disaggregate the emissions by geographic location and feed the data into an air dispersion model at each location. This would generate the concentrations at each population center from all sources of emissions. Such an elaborate exercise will have to be deferred to future work. Again we follow Lvovsky and Hughes and use reduced form coefficients to estimate the concentrations. However, unlike their distinguishing between large and other cities, we make a further simplification here and express the national average urban ambient concentration (in $\mu g / m^3$) as:

$$(11) \qquad C_{xt}^{N} = \gamma_{low,x} E_{low,xt} + \gamma_{medium,x} E_{medium,xt} + \gamma_{high,x} E_{high,xt} \quad ,$$

where the γ_{cx} coefficients translate emissions at height *c* to concentration of *x*.[8] These coefficients are obtained as a population weighted average over the estimates of 11 cities in the Lvovsky and Hughes study.

The formulation described above is rather crude and so we now briefly discuss the effects of misspecification of different parts of the procedure. An error in the γ_{cx} reduced form coefficients has a first-order effect on the level of concentration, which as we describe next, will have a first-order effect on the estimate of health damage. This has an important direct impact on the estimates of the absolute level of the value of damages. However, when we discuss the effects of policy changes (e.g. the percentage reduction in mortality due to a particular tax), then an error in γ_{cx} would have only a second-order

[8] Indexing this equation by cities would be more appropriate if we had a model that calculated economic activity regionally. At a minimum we would need to have projections of population by city to make use of such a disaggregation.

effect. (In this model this parameter only enters linearly, and with no feedback, so there are no second-order effects. However, in a more general specification, there will be.)

The next step is to estimate the damage to human health due to these levels of concentration of pollutants. In our base case we follow Lvovsky and Hughes (1997) who identify eight separate health effects for PM-10 and two for SO_2. The most important of these effects are mortality and chronic bronchitis. These effects, indexed by *h*, are given in Table 6. Again following Lvovsky and Hughes we assume a linear relation between concentration and health effects. The number of cases of health effect *h* in period *t* is written as :

(12) $$HE_{ht} = \sum_x \left(DR_{hx}(C_{xt}^N - \alpha_x) POP_t^u er \right) \qquad \text{h = Mortality, RHA,...} \quad ,$$

where DR_{hx} is the dose-response relationship (number of cases per million people per $\mu g / m^3$). α_x is the World Health Organization reference concentration, POP_t^u is the urban population (in millions), and er is the exposure rate (the share of the urban population exposed to pollution of concentration C_{xt}^N). The DR_{hx} coefficients are discussed in the Data section below.

Next we need to value these health damages in order to compare with the costs of reducing them. Let V_{ht} denote the value of one case of health effect h. The national value of damage due to all cases of *h* is given by:

(13) $$Damage_{ht} = V_{ht} HE_{ht}$$

Most studies of health damage valuation would use a fixed number for all years of their analysis. China, however, is experiencing rapid increases in real incomes. For example, if income rises at an annual rate of 5%, it would have risen 3.4 times in 25 years. We therefore index *V* by time too. In the base case, our model projects an average growth rate of 4-5% in per capita incomes over the next 40 years. Given this rate of increase, V_{ht} is rescaled each period assuming a linear income effect. The choice of values are discussed in the Data section below. The effects of revaluation may be seen in the last two columns of Table 6.

The value of total damages is simply the sum over all the health effects:

(14) $TD_t = \sum_h Damage_{ht}$.

We use valuations derived from contingent valuation (willingness to pay) studies. It should be pointed out that these are the valuations of people who suffer the health effect. This is not the same as calculating the medical costs, the cost of lost output of sick workers, the cost of parents time to take care of sick babies, etc. The personal willingness-to-pay may, or may not, include these costs, especially in a system of publicly provided medical care.

Rest of the Model

We summarize only key features of the model here, details are in the Appendix and Garbaccio, Ho and Jorgenson (2001). The model is a standard multi-sector Solow growth (dynamic recursive) model that is modified to recognize the two-tier plan-market nature of the Chinese economy. The equations of the model are summarized in Appendix A. As listed in Table 7, there are 30 sectors, including five energy sectors. Enterprises are given plan output quotas and the government fixes prices for part of their output. They also receive some plan inputs at subsidized prices. Marginal decisions, however, are made using the usual "price equals marginal cost" condition. Domestic output competes with imports, which are regarded as imperfect substitutes.

The household sector maximizes a utility function that has all 30 commodities as arguments. Income is derived from labor and capital and supplemented by transfers. As in the original Solow model, the private savings rate is set exogenously. Total national savings is made up of household savings and enterprise retained earnings. These savings, plus allocations from the central plan, finance national investment, the government deficit and current account surplus. This investment increases the stocks of both market and plan capital.

Labor is supplied inelastically by households and is mobile across sectors. The capital stock is partly owned by households and partly by the government. The plan part of the stock is immobile in any given period, while the market part responds to relative returns. Over time, plan capital is depreciated and the total stock becomes mobile across sectors.

The government imposes taxes on value added, sales, and imports, and also derives revenue from a number of miscellaneous fees. On the expenditure side, it buys commodities, makes transfers to households, pays for plan investment, makes interest payments on the public debt, and provides various subsidies. The government deficit is set exogenously and projected for the duration of the simulation period. This exogenous target is met by making government spending on goods endogenous.

Finally, the rest-of-the-world supplies imports and demands exports. World relative prices are set to the data in the last year of the sample period. The current account balance is set exogenously in this one-country model, and endogenous terms of trade exchange rate clears this equation.

The level of technology, *g(t)* in eq. (2), is projected exogenously, i.e. we make a guess of how input requirements per unit output fall over time, including energy requirements. For the latter, this is sometimes called the AEEI (autonomous energy efficiency improvement). In the model, there are separate sectors for coal mining, crude petroleum, natural gas, petroleum refining, electric power and gas (coal gas) production. Non-fossil fuels, including hydropower and nuclear power, are included as part of the electric power sector.

Policy Analysis

Our approach to analyzing the effects of externality taxes as given in eq. (4) is to first simulate a base case under the current tax system. We then apply the externality taxes and simulate a counterfactual case. The revenue from a unit externality tax is:

(15) $$R_EXT = \quad {}_j \; t_j^{xu} QI_j$$

To maintain revenue neutrality (hence keeping real government spending constant) we cut the VAT, the capital income tax and the sales tax. Using superscript C to denote the counterfactual simulation, the new tax rates are:

(16) $$t_t^{v,C} = \alpha t_t^v, \quad t_t^{k,C} = \alpha t_t^k, \quad t_t^{t,C} = \alpha t_t^t$$

In the counterfactual simulation α is endogenously chosen such that total government revenue is equal to that found in the base case. The economic and health outcomes in the two cases are then compared. We shall describe the calculation of the externality tax rates

in detail in the section V below after giving a description of the data and parameters involved in eqs (1)-(14).

III. Data and Health Damage Parameters

A great deal of economic, environment and health related data is required to implement the above model. We need economic data for the base year, the parameters of the various behavioral functions (e.g. energy share in the production functions), and projections of the exogenous variables. This includes projections of the population, the savings rate, productivity growth, import prices, the government deficit, etc. These data and forecasts for the economic component of the model are described in Garbaccio, Ho, and Jorgenson (2001). A particularly important data source is the 1997 input-output table (NBS 1999b) from which we derive a Social Accounting Matrix using additional information from the *China Statistical Yearbook* (NBS 1999a).[9] This matrix provides the flow of payments among the various sectors of the economy -- enterprises, capitalists, workers, government and rest-of-the-world.

Table 1 gives the sectoral characteristics of the economy, this is an update of the 1995 data in Garbaccio, Ho and Jorgenson. Agriculture is the biggest sector in terms of value added or employment but is not a major source of air pollution. The biggest energy users are Metals smelting, Chemicals and Households. These are, however, not the biggest polluters as we describe next (Table 2).

For the environment-health component described in section II above we obtained the *yuan* value of output and energy use for each sector from the 1997 input-output table and the quantities from the NBS (1999a). To calculate the fuel inputs we use the conversion coefficients (eq. 8) given in Fridley (2001). The sectoral emissions of total suspended particulates (TSP) and SO_2 are given in the *China Environmental Yearbook* (Env 1998) and also conveniently summarized in *China Energy Databook* (Fridley 2001, Tables 8.2, 8.4). (These data are not observations but calculated from fuel use and conversion parameters). The emissions data are given separately for process emissions

[9] This 1997 SAM is produced with assistance from the Development Research Center, Department of Development Strategy. See Zhai and Li (2000). The details are given in Garbaccio, Ho and Jorgenson (2001).

and combustion emissions. We follow Lvovsky and Hughes in converting Chinese TSP data to PM-10 by assuming a factor of 0.6.

The emissions data are given for 20 "industrial" sectors, and one total for the nonindustrial sector. We allocate the first set to our 23 mining, manufacturing and utility sectors, and the nonindustrial total to all our remaining 10 production sectors and household, assuming that they have the same emission coefficients. This undoubtedly underestimate the emissions from the service sectors, especially transportation, and will have to await improved estimates. The emissions of TSP and SO2 for our sectors are reported in Table 2.[10] Total national emissions of TSP from combustion was estimated at 11,000 ktons (ignoring TVE emissions), while TSP from noncombustion sources was 8,900 ktons. The sector with the highest process emissions of TSP is Nonmetal mineral products (mostly cement), while the one with the highest combustion emissions is Electricity.

From the process emissions and output data in 1997 we estimate the σ_{jx} coefficients in eq. (7), in ktons per billion *yuan*. These are given in Table 3 under "current emissions". The dirtiest sectors are Nonmetal mineral products, and Metals smelting (mostly iron and steel). Lvovsky and Hughes (1997) also provided separate estimates of the current (old) and new technology coefficients, σ_{jx}^{O} and σ_{jx}^{N}. We scale the new, low-emission, coefficients in the same ratio as that suggested by them, these are reported in Table 3 under "low emissions".

The fuel related emission coefficients (ψ_{jxf}) are derived starting from those in Lvovsky and Hughes. Their coefficients are scaled such that the sum over all fuel types, $\sum_f \psi_{jxf} AF_{jfg}$, is equal to the combustion emissions data for *x* in sector *j* in 1997, shown in the last two columns of Table 2. These updated coefficients are given in Table 4 for the three fuels, coal, oil and gas. Both old and new technology coefficients are reported there. Of the industrial sectors for which there are more reliable estimates, the dirtiest sectors

[10] There was a major extension of the emissions data beginning in 1995, when estimates were made for the previously ignored Township and Village Enterprises. However, no sectoral breakdown is given for them. We therefore ignore these estimates and calibrate the coefficients based on the limited emissions but actual observed concentrations. This understates the actual emission coefficients and overstates the concentration

for coal use are Sawmills and Paper. The non-industrial sectors have large coefficients but these are mulitplied by relatively low use of coal. Errors in these non-industrial coefficients are thus less serious even if the data here is sparse.

Lvovsky and Hughes (1997) give coefficients that transform emissions to concentrations separately for each of 11 major cities (eq. 11), based on 1993 data. We use this information, and the concentration data for the same 11 cities in 1997, to calculate an updated set of national average γ_{cx}'s. These are given in Table 5. Our estimate of the national urban concentration of TSP in 1997, averaging over these 11 cities using population data, is 298 $\mu g / m^3$, or 178 $\mu g / m^3$ for PM10. This is an improvement over our previous estimate of 192 $\mu g / m^3$ of PM10 for 1992 (Garbaccio, Ho and Jorgenson 2000). The estimated concentration for SO2 is 93 $\mu g / m^3$. The γ_{cx}'s reported in the bottom of Table 5 are our estimated national coefficients, these are about two orders of magnitude smaller than the Lvovsky and Hughes city-based coefficients.

Turning to the dose response coefficients DR_{hx}, our base case values are taken from World Bank (1997) and reported in Table 6. The 7.14 number for acute mortality is the estimated number of excess deaths per million people per year due to an increase in the concentration of PM-10 of one $\mu g / m^3$. This is equivalent to a 0.1% mortality effect, which is also the central estimate in Wang and Smith (1999b, Table 5).

Much debate and research is ongoing about the magnitude of these dose-response coefficients, and about how the effects of various pollutants interact. In addition, there is the issue of differential age impacts of these pollutants and the associated difficulty of measuring the "quality of life-years." Since much of the existing research has been done in developed countries, questions have been raised as to how these dose-response relationships should be translated to countries like China with very different pollution mixes, particle size distribution, and populations with different demographic and health characteristics. This is discussed in Wang and Smith (1999b, Appendix E) who also cite a range of estimates for mortality effects ranging from 0.04% to 0.30% for a $\mu g / m^3$ increase in PM-10 (see their Table 5).

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coefficients. The overall total is roughly correct although the sectoral effects are mistaken to the extent the

The World Bank sponsored a recent study to update earlier estimates used in World Bank (1997). This ECON (2000) report included new survey results from their recent study in Guangzhou. It discusses the inclusion of chronic effects of PM-10 in estimating DR_{hx}'s and suggested a coefficient of 0.4% for combined acute and chronic mortality (their Tables 3.2, 8.1). This is four times higher than the rate used in World Bank (1997). It stresses, however, that this is very uncertain, and gives a range of (0.00-0.6) for this coefficient. Their estimates are reproduced in the bottom half of Table 6. We shall also use these parameter values in our simulations below to illustrate the range of uncertainty.

The next difficult parameter are the valuations, V_{ht}. Various approaches have been used for valuations in the literature and we concur with ECON (2000) in the appropriateness of using the "willingness to pay" method. The valuation of these damages is a controversial and difficult exercise, with arguments over discounting (Heinzerling (1999)), whether the "contingent valuation" method works (Hammit and Graham (1999)), and how to aggregate the willingness to pay (Pratt and Zeckhauser (1996)). We believe the willingness to pay approach is valid although one may argue about how that could be implemented. We ignore age effects and shall use various estimates, as a base case we follow the route taken by most studies which use an estimated willingness to pay in the U.S. and scale them by the ratio of per capita incomes in China and the U.S.

The value of a statistical life chosen by World Bank (1997) and ADB(2000) is $3.6 million in the U.S.[11] The U.S. values associated with each of the 10 health effects identified are given in Table 6 under the column marked "Valuation in US". Multiplying them by the ratio of per capita incomes in 1997 (in nominal terms) gives the *yuan* values for China (next column in Table 6). Using this simple scaling means that we are assuming a linear income effect. Our estimate translated to US$ using the nominal exchange rate in 1997, is about $85,000. This is equivalent to the $77,000 figure for 1995 used in ECON (2000). This is a little above the World Bank (1997) figure of $60,000. At the other end, Fankhauser (1994) study of a low-income country gives a low estimate of

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missing TVE data is different from the other data.

US$112,480 per statistical life, and a high estimate of $168,720. Given the linear assumptions in our model, these alternative valuations may be applied by simply scaling our estimates.

Estimating the number of people affected by air pollution involves estimating and projecting the size of the urban population. Both the future total population and the urbanized portion have to be projected. We take total population projections the from World Bank (2001). These projections are also used to calculate the future labor supply. The rate of urbanization in China is rising and we project it to continue in a way similar to U.S. urbanization history. This is plotted in Appendix Fig A1. Details of this are given in Garbaccio, Ho and Jorgenson (2000) .

IV. The Base Case Simulation

The central aim of our methodology is to provide estimates of the change in damages and economic performance due to some externality control policy. It is not to give a projection of the future Chinese economy. We describe here the base projection to give the reader a clear idea of how our approach works, not to a forecast of the economy. Such forecasts involve many assumptions such as population growth and technical progress. We shall not describe these in detail, they only have second order effects on the percentage change in costs and benefits that we are trying to estimate[12].

We start the simulation in 1995 and so we initialize the economy to have the capital stocks that were available at the start of 1995 and the working age population of 1995 supplying labor. The economic model described in the appendix calculates the output of all commodities, consumption by households and the government, exports, and the savings available for investment. This investment augments the capital stock for the next period and we repeat the exercise. The level of output (specific commodities and total GDP) thus calculated depends on our projections of the population, savings behavior, changes in spending patterns as incomes rise, the ability to borrow from abroad, improvements in technology, etc. Our results are reported in Table 9. The 5.8% growth

[11] This is from Chapter 2 of World Bank (1997), which also discusses the use of "willingness to pay" valuation versus "human capital" valuation, the method used by many in China.

rate of GDP over the next 25 years that results from our assumptions is slightly less optimistic than the 6.7% growth rate projected a few years ago for China by the World Bank (1997), but still implies a very rapid growth in per capita income. The population is projected to rise at a 0.7% annual rate during these 25 years.

The dashed line in Figure A2 shows the fossil fuel based energy use in standard coal equivalents (sce) on the right-hand axis. Our assumptions on energy use improvements are fairly optimistic and together with changes in the structure of the economy, result in an energy-GDP ratio in 2020 that is half that in 1995.[13] The carbon emissions from fossil fuels are also plotted using the right-hand axis. The rate of growth of carbon emissions is even slower than the growth in energy use. This is mainly due to our assumptions on the shift from coal to oil.

With the industry outputs and input requirements calculated for each period we use equations (1)-(14) to calculate total emission of pollutants, the urban concentration of pollutants, and the health effects of these pollutants. The growth of PM-10 emissions is much slower than the growth in energy use and carbon emissions. This is due to the sharp difference in the assumed coefficients for new and old capital (see Tables 3 and 4). All sources of PM-10 increase emissions, with the largest rise coming from low-height sources. Projected SO_2 emissions rise much faster than particulates due to a less optimistic estimate of the improvement in the σ_{jx} and ψ_{jxf} coefficients.

In this base case we assume no increase in emission reduction efforts over time. This differs from Lvovsky and Hughes' (1997) BAU case which assumes that the largest 11 cities will choose what they call the "high investment" option. The result is that our estimate of current premature mortality is higher, 304,000 versus 230,000. The growth rate of health effects from our more optimistic assumptions of energy trends are a little lower. By 2020 our estimated excess deaths are 2.4 times the 1995 level, compared to the 3.7 times calculated in Lvovsky and Hughes' BAU case.

The fact that our estimates are not very different does not mean that either estimate is "good." We report the level estimates to explain our simulation procedure

[12] The datails of the projections of exogenous variables are discussed in more details in Garbaccio, Ho and Jorgenson (2000).

and to illustrate the magnitudes involved. To reiterate, this is not a forecast of emissions, but rather a projection if no changes in policy are made. We expect both the government and private sectors to have policies and investments that are different from today's.

V. Controlling Local Pollution with Corrective Taxes

a) Policy of using Output taxes

To implement corrective output taxes we need to know the marginal damage per unit output of each sector. The emissions from producing output in sector j is given by eq. (6). Given the form of (6) the marginal emission rate is equal to the average emission rate. This emission rate for pollutant *x*, in the base year *tb*, is given simply by $\frac{EM_{jx,tb}}{QI_{j,tb}}$. An additional unit of emission increases concentration by γ_j as in eq. (11), where γ_j could be one of three values depending on the emission height classification of *j*. An increase in the concentration by γ_j will produce an additional health effect of $\sum_x DR_{hx}\gamma_j POP_t^u er$ (using eq. 12). Finally, the value of the marginal damage from the last unit of output, summing over all health effects, is :

(17) $$MD_{jt} = \sum_h V_{ht} \sum_x \left(DR_{hx}\gamma_j POP_t^u er \frac{EM_{jx,tb}}{QI_{j,tb}} \right)$$

The results of this calculation is given in Table 7. As we can see from the dose response coefficients most of the damage is due to particulate emissions and a little from SO2 emissions. The highest health damage producing sector per yuan of output is Transportation with a rate of 5.1% (large low-height emissions), followed by the Building Material (Nonmetal mineral products) sector with 3.9%. Our first policy simulation is to set the externality tax equal to this marginal damage:

(18) $$t_{jt}^x = \lambda MD_{jt}$$

[13] The official data since 1995 shows a dramatic decline in energy use in China, not just the energy-output ratio but the absolute level of energy use. Sinton and Fridley (2000) gives a good discussion of this phenomenon. It might thus be argued that our "fairly optimistic" projections are not sufficiently so.

We experiment with two levels of taxes, $\lambda = 50\%$ and $\lambda = 100\%$. If one thinks that the response to a $\lambda = 100\%$ externality tax may lower the emissions so much that the marginal damage falls below that given in eq. (17) above due to nonlinearities in the effects, then one may proceed with a smaller tax first. Hence our approach of reporting two sets of results.

The economy wide effects of using these output taxes are given in Table 10, and the sectoral effects are given in Table 11. For the 50% case, in the first year the effect of the taxes is to raise prices and lower real wages. This leads to a fall in consumption of 0.26%. The prices of the dirty sectors rise relative to the cleaner sectors, and output of the dirty sectors – Building Materials, Primary Metals, Transportation – is correspondingly lowered. This leads to a modest reduction in emissions and health damages of 1.78%. The revenue raised from this tax is large, some 14% of total revenues in year one. This allows a large reduction, some 19.5%, in value-added and capital income taxes. This tax cut leads to higher retained earnings and hence investment.

The pattern of sectoral emission reductions is notable. While the highest damage is caused by low height emissions and taxed more heavily, the Electricity sector with high height emissions and lower taxes suffer a big reduction of output and emissions. This is due in part to the inter industry effects, the dirty sectors, like cement, shrinks a lot and with them comes a reduction in the demand for electricity. This illustrates the importance of using an input-output framework.

Over time the higher investment leads to higher GDP and by the 20th year GDP is 1.27% higher than the base case. With the higher level of counterfactual economic activity more emissions are generated and the reduction in damages due to the externality tax falls from 1.78% to 1.27%. However, the value of this damage reduction as a share of GDP is high since we revise the valuation every period in line with the rising per capita incomes.

When we apply a tax equal to 100% of the damage per unit output, the effects are amplified, although not proportionally. The reduction in real consumption in the first year is now a larger 0.56% while health damages fall 3.55%. The higher tax revenue leads to even higher investment and growth, i.e. a compulsory shift from consumption to savings. The sectoral effects are of the same pattern and bigger.

b) Policy of using Fuel taxes

Emissions are not linked one for one with output. Pollution is a function of fuel use and choice of control strategies. Fuel use per unit output is a function of the choice of capital and production techniques. We shall consider a simple policy of taxing fuels in proportion to the emissions produced using the current technology. Since coal is the highest contributor to particulate pollution it will bear the highest taxes and firms will be encouraged to switch to lower emitting fuels. As we can see in Table 4 the values for the emission coefficient ψ_{jxf} varies by sector, i.e. a ton of coal produces different levels of emissions in different sectors. To implement a simple national tax on each primary fuel we calculate the damage done by an average ton of coal. Using the method of deriving eq. (17), the average marginal damage, i.e. averaged over all the sectors in the base year, *tb*, is given by:

$$(19) \qquad AMD_{ft} = \sum_{h} V_{ht} \sum_{x} \left(DR_{hx} \gamma_j POP_t^u er \sum_{f} \sum_{J} \frac{\psi_{jxf} FT_{jf,tb}}{FT_{Jf,tb}} \right)$$

The above is in *yuan* per physical unit (tons of coal or tons of oil). The ad valorem externality tax on a *yuan* of fuel that fully incorporates this damage is:

$$(20) \qquad t_{ft}^{xv} = \xi_f AMD_{ft}$$

The values of the marginal damage by the two major fuel types are given in Table 8. As we can see, these are very high damages. If the tax rate in eq. (20) is applied to the economy, the price of coal will more than double. As we have discussed above, large changes are not well analyzed with marginal methods and linearity assumptions that we employ here. As in the first policy above, we set the externality tax to some fraction, λ, of this damage:

$$(21) \qquad t_{ft}^{xv} = \lambda \xi_f AMD_{ft}$$

We examine two cases, $\lambda = 20\%$ and $\lambda = 50\%$. Given the values of the marginal damage in Table 8, even a low $\lambda = 20\%$ would produce a 40% tax rate on the price of coal. The results are shown in Tables 12 and 13. This is dramatically different from the first policy experiment above. A tax of 20% of the marginal damages (i.e., 20% of 0.4678

yuan damage per yuan of coal) reduce the use of coal by 38% and PM emissions by 15.6%. The reduction in health damages from this is 20%. That is, a modest tax amounting to only 5.8% of total revenues in the first period will lead to a large reduction of pollution and related health damages. This large estimated effect is due in part to our 'optimistic' characterization of technology. We assumed a flexible production function, where firms may substitute relatively easily between inputs. However, it is reasonable to think that this level of fuel substitution could be achieved over time, even if one believes that the short run adjustment costs are much higher than we allowed for. The results for the 20th year is given in the last two columns of Table 12.

This reduction comes about from the reduced use of coal by all sectors, coal output falls by 28%, electricity output by 4.6%. The buyer's price of coal from this 20%AMD tax is 38% higher than the base case. The price to the producer falls somewhat. The tax on oil is much smaller and the output of the Refining sector falls only 2.58%. The small tax revenue from this fuel-only tax reduces the other taxes by 8.6%, much less than the product tax policy. This means a smaller switch from consumption to investment and a smaller change in GDP growth. The effects in the 20th year are thus quite similar to the first year, unlike the previous policy.

The pattern of emission reduction here is quite different also from that of the output tax policy. Here low height-high damage emissions are cut more than the medium height emissions, reflecting this more efficient control policy. High height emissions from Electricity is, however, also cut by a large amount due to the direct effect of higher coal prices and the indirect effect of reduced demand for expensive electricity.

If we apply a much higher tax, $\lambda = 50\%$ of the average marginal damage reported in Table 8, the effects are larger, and non-proportional. The reduction in consumption is 1.09% while damages fall 35.0% in the first year. Coal output is sharply reduced by 49%. While this adjustment may appear overly optimistic, one should keep in mind the possible long run adaptation to such a large tax.

VI. Sensitivity Analysis

(a) Alternative Dose Response

As we noted in the Data Section III above, there is a range of estimates for the dose-response coefficient. For acute mortality the value we take from World Bank (1997) is 7.14 deaths per million per $\mu g / m^3$. ECON (2000) suggests a range from 0-36 for acute and chronic mortality, with their central estimate at 24. We repeated the fuel tax simulations with this DR(deaths)=24. The $\lambda = 50\%$ tax case is used and the results are reported in Tables 14 and 15.

If we refer to eq. (5) for health effects, we see that it is linear but not proportional. The damages from coal and oil combustion are not proportionally higher than those given in Table 8. Hence in Table 14 we see that the reduction in premature mortality rises from 35.0%, using our base DR coefficient, to 51.0%, using the higher coefficient. The pollution tax as a share of total revenue rises from 9.97% to 14.3%. This higher tax caused by the higher DR will lead to an even bigger reduction in real wages and consumption. However, the value of damage reduced, as a share of GDP, is also much higher. That is, the benefit-cost ratio is still very high regardless of what the exact value of the dose-response coefficient is. One should bear in mind the methodology here generates a lower tax for lower estimated damages, i.e. lower distortions to the economy. The desirability of corrective taxes is not changed much by uncertainty of the DR value.

(b) Alternative tax offsets.

To show the magnitude of the gain in cutting other taxes that are reported in the simulations above, we run another counterfactual fuel tax simulation but with a lump sum rebate of the extra revenue instead of tax cuts. The results of the original experiment and this case are compared in Tables 16 and 17. The health benefits of the two cases are similar. The costs are, of course, different. The rebate to households causes consumption to fall by far less in this case, 1.1% versus 0.1%. This means that investment rises by far less than the simulations described in Section V above. The effect on GDP growth and future consumption is clear, far lower future consumption in the inefficient lump sum rebate case.

VII. Conclusions

We have begun the analysis of corrective taxes for controlling pollution externalities in China by using the relatively simple instruments and model. A more complete analysis would try to estimate the cost functions for reducing particulate and sulphur dioxide emissions in each sector. That is, the cost of using scrubbers or higher stacks or altering production processes. In the current analysis most of the emissions are attributed to fuel use, and the fuel taxes reduce fuel use. However, it is not fuel use per se that is the problem, but emissions from them, emissions that are not really in a fixed relation to the quantity of fuel but also in relation to the effort to reduce them. A specification of the costs of these efforts would be the next step in refining policy choices.

Nevertheless, we believe our simple analysis have some useful lessons. First, the long run benefits of applying externality taxes on pollution are much larger than the costs, even if one thinks that we have underestimated short run costs. Secondly, this result is robust to the many uncertainties underlying the effort to estimate health damage due to air pollution. This of course is predicated on applying the right level of tax. Third, the revenue from such externality taxes could be substantial, this may be an opportunity to move towards a more efficient tax system.

Appendix A: Description of the Economic Model

The main features of the model for China are discussed in this appendix, further details are given in Garbaccio, Ho, and Jorgenson (2000b). We describe the modeling of each of the main agents in the model in turn. Table A1 lists a number of parameters and variables which are referred to with some frequency. In general, a bar above a symbol indicates that it is a plan parameter or variable while a tilde indicates a market variable. Symbols without markings are total quantities or average prices. To reduce unnecessary notation, whenever possible, we drop the time subscript, *t*, from our equations.

A.1. Production

Each of the 30 industries is assumed to produce its output using a constant returns to scale technology. For each sector *j* this can be expressed as:

$$\text{(A1)} \quad QI_j = f(KD_j, LD_j, TD_j, A_{1j}, \ldots, A_{nj}, t) \quad ,$$

where KD_j, LD_j, TD_j, and A_{ij} are capital, labor, land, and intermediate inputs, respectively.[14] In sectors for which both plan and market allocation exists, output is made up of two components, the plan quota output ($\overline{QI}_j$) and the output sold on the market ($\tilde{QI}_j$). The plan quota output is sold at the state-set price ($\overline{PI}_j$) while the output in excess of the quota is sold at the market price ($\tilde{PI}_j$).

A more detailed discussion of how this plan-market formulation is different from standard market economy models is given in Garbaccio, Ho, and Jorgenson (1999). In summary, if the constraints are not binding, then the "two-tier plan/market" economy operates at the margin as a market economy with lump sum transfers between agents. The before-tax return to the owners of fixed capital in sector *j* is:

$$\text{(A2)} \quad profit_j = \overline{PI}_j \overline{QI}_j + \tilde{PI}_j \tilde{QI}_j - \tilde{P}_j^{KD} \tilde{KD}_j - PL_j LD_j - PT_j TD_j$$

[14] QI_j denotes the quantity of industry *j*'s output. This is to distinguish it from, QC_j, the quantity of commodity *j*. In the actual model each industry may produce more than one commodity and each commodity may be produced by more than one industry. In the language of the input output tables, we make use of both the USE and MAKE matrices. For ease of exposition we ignore this distinction here.

$$- \quad {}_{i} \; \overline{PS}_i \; \overline{A}_{ij} - \quad {}_{i} \; \tilde{PS}_i \; \tilde{A}_{ij} \quad .$$

For each industry, given the capital stock $\overline{K}_j$ and prices, the first order conditions from maximizing equation A2, subject to equation A1, determine the market and total input demands.

Given the lack of a consistent time-series data set, in this version of the model, we use Cobb-Douglas production functions. Equation A1 for the output of industry *j* at time *t* then becomes:

(A3) $QI_{jt} = g(t) KD_{jt}^{\alpha_{Kj}} LD_{jt}^{\alpha_{Lj}} TD_{jt}^{\alpha_{Tj}} E_{jt}^{\alpha_{Ej}} M_{jt}^{\alpha_{Mj}}$, where

$\log E_{jt} = \quad {}_{k} \; \alpha_{kj}^{E} \log A_{kjt}$ and k = coal, oil, gas, electricity, and refined petroleum

$\log M_{jt} = \quad {}_{k} \; \alpha_{kj}^{M} \log A_{kjt}$ and k = non-energy intermediate goods .

Here α_{Ej} is the cost share of aggregate energy inputs in the production process and α_{kj}^{E} is the share of energy of type *k* within the aggregate energy input. Similarly, α_{Mj} is the cost share of aggregate non-energy intermediate inputs and α_{kj}^{M} is the share of intermediate non-energy input of type *k* within the aggregate non-energy intermediate input.

To allow for biased technical change, the α_{Ej} coefficients are indexed by time and are updated exogenously. We set α_{Ej} to fall gradually over the next 40 years while the labor coefficient, α_{Lj}, rises correspondingly. The composition of the aggregate energy input (i.e. the coefficients α_{kj}^{E}) are also allowed to change over time. These coefficients are adjusted gradually so that they come close to resembling the U.S. use patterns of 1982. The exception is that the Chinese coefficients for coal for most industries will not vanish as they have in the U.S.[15] The coefficient *g(t)* in equation A3 represents technical

[15] We have chosen to use U.S. patterns in our projections of these exogenous parameters because they seem to be a reasonable anchor. While it is unlikely that China's economy in 2035 will mirror the U.S. economy of 1982, it is also unlikely to closely resemble any other economy. Other projections, such as those by the World Bank (1994), use the input-output tables of developed countries including the U.S. We have considered making extrapolations based on recent Chinese input-output tables, but given the short sample period and magnitude of the changes in recent years, this did not seem sensible.

progress and the change in *g(t)* is determined through an exponential function ($\dot{g}_j(t) = A_j \exp(-\mu_j t)$). This implies technical change that is rapid initially, but gradually declines toward zero. The price to buyers of this output includes the indirect tax on output and the carbon tax:

(A4) $$PI_i^t = (1+t_i^t)PI_i + t_i^c \quad .$$

A.2. Households

The household sector derives utility from the consumption of commodities, is assumed to supply labor inelastically, and owns a share of the capital stock. It also receives income transfers and interest on its holdings of public debt. Private income after taxes and the payment of various non-tax fees (*FEE*), Y^p, can then be written as:

(A5) $$Y^p = YL + DIV + G_I + G_transfer + R_transfer - FEE \quad ,$$

where YL denotes labor income from supplying LS units of effective labor, less income taxes. *YL* is equal to:

(A6) $$YL = (1 - t^L)PL\,LS \quad .$$

The relationship between labor demand and supply is given in equation A31 below. *LS* is a function of the working age population, average annual hours, and an index of labor quality:

(A7) $$LS_t = POP_t^w\, hr_t\, q_t^L \quad .$$

Household income is allocated between consumption (VCC_t) and savings. In this version of the model we use a simple Solow growth model formulation with an exogenous savings rate (s_t) to determine private savings (S_t^p):

(A8) $$S_t^p = s_t Y_t^p = Y_t^p - VCC_t \quad .$$

Household utility is a function of the consumption of goods such that:

$$\text{(A9)} \quad U_t = U(C_{1t},...,C_{nt}) = \sum_i \alpha_{it}^C \log C_{it} \quad .$$

Assuming that the plan constraints are not binding, then as in the producer problem above, given market prices and total expenditures, the first order conditions derived from equation A9 determine household demand for commodities, C_i, where $C_i = \overline{C}_i + \tilde{C}_i$. Here $\overline{C}_i$ and $\tilde{C}_i$ are household purchases of commodities at state-set and market prices. The household budget can be written as:

$$\text{(A10)} \quad VCC = \sum_i (\tilde{PS}_i \tilde{C}_i + \overline{PS}_i \overline{C}_i) \quad .$$

We use a Cobb-Douglas utility function because we currently lack the disaggregated data to estimate an income elastic functional form. However, one would expect demand patterns to change with rising incomes and this is implemented by allowing the α_{it}^C coefficients to change over time. These future demand patterns are projected using the U.S. use patterns of 1982.

A.3. Government and Taxes

In the model, the government has two major roles. First, it sets plan prices and output quotas and allocates investment funds. Second, it imposes taxes, purchases commodities, and redistributes resources. Public revenue comes from direct taxes on capital, value-added taxes, indirect taxes on output, tariffs on imports, the carbon tax, and other non-tax receipts:

(A11)

$$Rev = \sum_j t^k (P_j^{KD} KD_j - D_j) + t^V \sum_j (P_j^{KD} KD_j + PL_j LD_j + PT_j TD_j) + \sum_j t_j^t PI_j QI_j$$

$$+ \sum_i t_i^r PM_i^* M_i + \sum_i t_i^c (QI_i - X_i + M_i) + FEE \quad ,$$

where D_j is the depreciation allowance and X_i and M_i are the exports and imports of good *i*. The carbon tax per unit of fuel *i* is:

(A12) $t_i^c = t^x \theta_i$,

where t^x is the unit carbon tax calculated per ton of carbon and θ_i is the emissions coefficient for each fuel type *i*.

Total government expenditure is the sum of commodity purchases and other payments:

(A13) $Expend = VGG + G_INV + s_i^e PI_i X_i + G_I + G_IR + G_transfer$

Government purchases of specific commodities are allocated as shares of the total value of government expenditures, *VGG*. For good *i*:

(A14) $PS_i G_i = \alpha_i^G VGG$.

We construct a price index for government purchases as $\log PGG = {}_i \alpha_i^G \log PS_i$. The real quantity of government purchases is then:

(A15) $GG = \dfrac{VGG}{PGG}$.

The difference between revenue and expenditure is the deficit, ΔG, which is covered by increases in the public debt, both domestic (B) and foreign (B^{G*}):

(A16) $\Delta G_t = Expend_t - Rev_t$,

(A17) $B_t + B_t^{G*} = B_{t-1} + B_{t-1}^{G*} + \Delta G_t$.

The deficit and interest payments are set exogenously and equation A16 is satisfied by making the level of total government expenditure on goods, VGG, endogenous.

A.4. Capital, Investment, and the Financial System

We model the structure of investment in a fairly simple manner. In the Chinese economy, some state-owned enterprises receive investment funds directly from the state budget and are allocated credit on favorable terms through the state-owned banking system. Non-state enterprises get a negligible share of state investment funds and must borrow at what are close to competitive interest rates. There is also a small but growing stock market that provides an alternative channel for private savings. We abstract from these features and define the capital stock in each sector *j* as the sum of two parts, which we call plan and market capital:

(A18) $K_{jt} = \overline{K}_{jt} + \tilde{K}_{jt}$.

The plan portion evolves with plan investment and depreciation:

(A19) $\overline{K}_{jt} = (1-\delta)\overline{K}_{jt-1} + \overline{I}_{jt}$, t = 1, 2, …, T .

In this formulation, $\overline{K}_{j0}$ is the capital stock in sector *j* at the beginning of the simulation. This portion is assumed to be immobile across sectors. Over time, with depreciation and limited government investment, it will decline in importance. Each sector may also "rent" capital from the total stock of market capital, $\tilde{K}_t$:

(A20) $\tilde{K}_t = {}_j\tilde{K}_{jt}$, where $\tilde{K}_{ji} > 0$.

The allocation of market capital to individual sectors, $\tilde{K}_{jt}$, is based on sectoral rates of return. As in equation A2, the rental price of market capital by sector is $\tilde{P}_j^{KD}$. The supply of $\tilde{K}_{jt}$, subject to equation A20, is written as a translog function of all of the market capital rental prices, $\tilde{K}_{jt} = K_j(\tilde{P}_1^{KD}, \ldots, \tilde{P}_n^{KD})$.

In three sectors, agriculture, crude petroleum and gas mining, "land" is a factor of production. We have assumed that agricultural land and oil fields are supplied inelastically, abstracting from the complex property rights issues regarding land in China. After taxes, income derived from plan capital, market capital, and land is either kept as retained earnings by the enterprises, distributed as dividends, or paid to foreign owners:

(A21) $\sum_j profits_j + \sum_j \tilde{P}_j^{KD} \tilde{K}_j + \sum_j PT_j T_j = tax(k) + RE + DIV + r(B^*)$,

where $tax(k)$ is total taxes on capital (the first two terms on the right hand side of equation A11).[16]

As discussed below, total investment in the model is determined by savings. This total, *VII*, is then distributed to the individual investment goods sectors through fixed shares, α_{it}^I:

(A22) $PS_{it} I_{it} = \alpha_{it}^I VII_t$.

Like the α_{it}^C coefficients in the consumption function, the investment coefficients are indexed by time and projected using U.S. patterns for 1982. A portion of sectoral investment, $\bar{I}_t$, is allocated directly by the government, while the remainder, $\tilde{I}_t$, is allocated through other channels.[17] The total, I_t, can be written as:

(A23) $I_t = \tilde{I}_t + \bar{I}_t = I_{1t}^{\alpha_1^I} I_{2t}^{\alpha_1^I} \ldots I_{nt}^{\alpha_n^I}$.

As in equation A19 for the plan capital stock, the market capital stock, $\tilde{K}_{jt}$, evolves with new market investment:

(A24) $\tilde{K}_{jt} = (1-\delta)\tilde{K}_{jt-1} + \tilde{I}_{jt}$.

A.5. The Foreign Sector

Trade flows are modeled using the method followed in most single-country models. Imports are considered to be imperfect substitutes for domestic commodities and exports face a downward sloping demand curve. We write the total supply of commodity *i* as a CES function of the domestic (QI_i) and imported good (M_i):

[16] In China, most of the "dividends" are actually income due to agricultural land.

[17] It should be noted that the industries in the Chinese accounts include many sectors that would be considered public goods in other countries. Examples include local transit, education, and health.

(A25) $QS_i \;=\; A_0\left[\alpha^d QI_i^{\rho} \;+\; \alpha^m M_i^{\rho}\right]^{\frac{1}{\rho}}$,

where $PS_i QS_i \;=\; PI_i^t QI_i + PM_i M_i$ is the value of total supply. The purchaser's price for domestic goods, PI_i^t, is discussed in the producer section above. The price of imports to buyers is the foreign price plus tariffs (less export subsidies), multiplied by a world relative price, *e*:

(A26) $PM_i \;=\; e(1+t_i^r)PM_i^*$.

Exports are written as a simple function of the domestic price relative to world prices adjusted for export subsidies (s_{it}^e):

(A27) $X_{it} \;=\; EX_{it}\left|\dfrac{\tilde{PI}_{it}}{e_t(1+s_{it}^e)PE_{it}^*}\right|^{\eta_i}$,

where EX_{it} is base case exports that are projected exogenously.

The current account balance is equal to exports minus imports, less net factor payments, plus transfers:

(A28) $CA \;=\; {}_i\dfrac{PI_i X_i}{(1+s_i^e)} \;-\; {}_i\; PM_i M_i \;-\; r(B^*) \;-\; G_IR \;+\; R_transfer$,

Like the government deficits, the current account balances are set exogenously and accumulate into stocks of net foreign debt, both private (B_t^*) and public (B_t^{G*}):

(A29) $B_t^* \;+\; B_t^{G*} \;=\; B_{t-1}^* \;+\; B_{t-1}^{G*} \;-\; CA_t$.

A.6. Markets

The economy is in equilibrium in period *t* when the market prices clear the markets for the 30 commodities and the three factors. The supply of commodity *i* must satisfy the total of intermediate and final demands:

(A30) $QS_i = \sum_j A_{ij} + C_i + I_i + G_i + X_i \quad , \quad i = 1, 2, \ldots, 30.$

For the labor market, we assume that labor is perfectly mobile across sectors so there is one average market wage which balances supply and demand. As is standard in models of this type, we reconcile this wage with the observed spread of sectoral wages using wage distribution coefficients, ψ_{jt}^L. Each industry pays $PL_{jt} = \psi_{jt}^L PL_t /(1-t_j^V)$ for a unit of labor. The labor market equilibrium is then given as:

(A31) $\sum_j \psi_{jt}^L LD_{jt} = LS_t \quad .$

For the non-plan portion of the capital market, adjustments in the market price of capital, $\tilde{P}_j^{KD}$, clears the market in sector *j*:

(A32) $KD_{jt} = \psi_{jt}^K K_{jt} \quad ,$

where ψ_{jt}^K converts the units of capital stock into the units used in the production function. The rental price PT_j adjusts to clear the market for "land":

(A33) $TD_j = T_j \quad ,$ where j = "agriculture", "crude petroleum", "gas mining".

In this model without foresight, investment equals savings. There is no market where the supply of savings is equated to the demand for investment. The sum of savings by households, businesses (as retained earnings), and the government is equal to the total value of investment plus the budget deficit and net foreign investment:

(A34) $S^p + RE + G_INV = VII + \Delta G + CA \quad .$

The budget deficit and current account balance are fixed exogenously in each period. The world relative price (*e*) adjusts to hold the current account balance at its exogenously determined level.

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Table 1 Sectoral Characteristics for China, 1997

	Sector	Gross Output (bil. *yuan*)	Value Added (bil. *yuan*)	Gross energy (bil. *yuan*)	Energy Use (mil. tn. coal equivalent)
1	Agriculture	2467.7	1474.2	42.1	59.05
2	Coal mining and processing	238.0	118.2	23.2	57.91
3	Crude petroleum mining	188.1	123.0	27.2	33.25
4	Natural Gas Mining	10.9	5.9	1.4	2.40
5	Metal ore mining	115.2	39.9	12.2	8.18
6	Non-ferrous mineral mining	222.4	96.6	24.4	13.49
7	Food products and tobacco	1371.3	381.4	21.4	38.43
8	Textile goods	913.0	258.1	14.4	30.80
9	Apparel, leather	627.0	193.1	5.6	4.37
10	Sawmills and furniture	222.5	63.1	6.2	5.01
11	Paper products, printing	445.5	139.1	16.7	21.99
12	Petroleum processing & coking	308.5	71.9	156.4	73.89
13	Chemical	1488.8	402.4	136.0	192.80
14	Nonmetal mineral products	874.9	276.0	97.0	123.17
15	Metals smelting and pressing	750.2	159.2	87.3	214.48
16	Metal products	477.8	116.3	23.0	10.45
17	Machinery and equipment	882.1	282.4	30.5	24.48
18	Transport equipment	570.7	158.2	13.4	15.19
19	Electrical machinery	563.3	130.2	12.1	6.47
20	Electronic & telecom. equipment	488.1	124.4	5.4	4.93
21	Instruments	96.0	29.3	2.0	0.83
22	Other manufacturing	286.9	125.5	7.8	13.25
23	Electricity, steam & hot water	380.8	163.8	107.7	100.76
24	Gas production and supply	12.4	3.3	5.8	4.27
25	Construction	1738.6	499.7	63.0	11.79
26	Transport and warehousing	506.6	279.8	64.2	68.43
27	Post & telecommunication	195.9	112.6	6.2	7.00
28	Commerce & Restaurants	1412.6	726.3	31.0	23.94
29	Finance and insurance	359.5	219.5	3.4	1.82
30	Real estate	185.5	140.8	2.4	2.63
31	Social services	564.5	224.3	26.0	14.55
32	Health, Education, other services	658.5	314.8	21.5	19.41
33	Public administration	443.4	200.0	14.7	8.61
	Households			62.2	163.68
	Totals	**20067**	**7653.1**		**1381.73**

Notes: The sum of Value Added is GDP. Gross energy refers to the value of purchased primary and secondary energy inputs, including feedstocks. Energy Use is energy from primary and secondary sources, excluding those converted to secondary energy.
Sources: Input Output Table 1997; China Statistical Yearbook 1999; and authors' estimates.

Table 2 Sectoral Emissions 1997 (ktons, excl. TVEs)

	Sector	Process Emissions TSP	Process Emissions SO2	Combustion Emissions TSP	Combustion Emissions SO2
1	Agriculture	0.00	0.00	279.2	480.4
2	Coal mining and processing	64.73	29.08	180.7	163.1
3	Crude petroleum mining	51.14	22.98	56.9	78.4
4	Natural Gas Mining	2.96	1.33	0.3	0.7
5	Metal ore mining	31.34	14.08	22.0	21.2
6	Non-ferrous mineral mining	60.48	27.17	44.0	44.8
7	Food products and tobacco	15.94	10.99	310.4	467.3
8	Textile goods	2.77	1.67	166.1	332.3
9	Apparel, leather	0.90	0.15	16.4	23.8
10	Sawmills and furniture	45.73	3.83	90.2	113.8
11	Paper products, printing	91.56	7.66	200.5	253.6
12	Petroleum processing & coking	76.46	51.00	71.6	112.3
13	Chemical	199.73	213.91	671.8	1215.5
14	Nonmetal mineral products	6683.48	588.82	1133.2	707.3
15	Metals smelting and pressing	1244.21	925.02	632.0	738.5
16	Metal products	84.27	8.35	38.9	25.9
17	Machinery and equipment	24.13	4.44	125.4	184.7
18	Transport equipment	15.61	2.87	42.9	64.6
19	Electrical machinery	15.41	2.84	28.0	43.8
20	Electronic & telecom. equipment	13.35	2.46	8.3	13.2
21	Instruments	2.63	0.48	6.0	9.1
22	Other manufacturing	99.45	54.51	82.8	180.9
23	Electricity, steam & hot water	71.75	48.80	3953.0	7845.9
24	Gas production and supply	3.06	2.04	15.5	23.7
25	Construction	0.00	0.00	209.1	541.3
26	Transport and warehousing	0.00	0.00	508.9	797.2
27	Post & telecommunication	0.00	0.00	0.1	7.4
28	Commerce & Restaurants	0.00	0.00	206.7	356.6
29	Finance and insurance	0.00	0.00	23.6	36.5
30	Real estate	0.00	0.00	127.1	162.2
31	Social services	0.00	0.00	389.1	577.0
32	Health, Education, other services	0.00	0.00	731.4	933.8
33	Public administration	0.00	0.00	196.0	283.3
	Households			406.0	764.3
	Totals	**8901**	**2024**	**10974**	**17604**

Notes: Data from China Environmental Yearbook; Fridley (2001); authors' estimates. Beginning in 1995 data for emissions were expanded to include Township and Village Enterprises, however, sectoral estimates were not made for them. The estimates for nonmanufacturing sectors are made from the data for nonindustrial emissions.

Table 3. Process Emission Factors, σ_{jx}

	Sector	TSP Current Emissions	TSP Low Emissions	SO2 Current Emissions	SO2 Low Emissions
1	Agriculture	0.000	0.000	0.000	0.000
2	Coal mining and processing	0.272	0.054	0.122	0.122
3	Crude petroleum mining	0.272	0.054	0.122	0.122
4	Natural Gas Mining	0.272	0.054	0.122	0.122
5	Metal ore mining	0.272	0.054	0.122	0.122
6	Non-ferrous mineral mining	0.272	0.054	0.122	0.122
7	Food products and tobacco	0.012	0.012	0.008	0.008
8	Textile goods	0.003	0.003	0.002	0.001
9	Apparel, leather	0.001	0.001	0.000	0.000
10	Sawmills and furniture	0.206	0.041	0.017	0.017
11	Paper products, printing	0.206	0.041	0.017	0.008
12	Petroleum processing & coking	0.248	0.248	0.165	0.165
13	Chemical	0.134	0.134	0.144	0.126
14	Nonmetal mineral products	7.639	1.528	0.673	0.336
15	Metals smelting and pressing	1.658	0.332	1.233	0.616
16	Metal products	0.176	0.176	0.017	0.017
17	Machinery and equipment	0.027	0.027	0.005	0.005
18	Transport equipment	0.027	0.027	0.005	0.005
19	Electrical machinery	0.027	0.027	0.005	0.005
20	Electronic & telecom. equipment	0.027	0.027	0.005	0.005
21	Instruments	0.027	0.027	0.005	0.005
22	Other manufacturing	0.347	0.347	0.190	0.190
23	Electricity, steam & hot water	0.188	0.188	0.128	0.128
24	Gas production and supply	0.248	0.248	0.165	0.165
25	Construction	0.000	0.000	0.000	0.000
26	Transport and warehousing	0.000	0.000	0.000	0.000
27	Post & telecommunication	0.000	0.000	0.000	0.000
28	Commerce & Restaurants	0.000	0.000	0.000	0.000
29	Finance and insurance	0.000	0.000	0.000	0.000
30	Real estate	0.000	0.000	0.000	0.000
31	Social services	0.000	0.000	0.000	0.000
32	Health, Education, other services	0.000	0.000	0.000	0.000
33	Public administration	0.000	0.000	0.000	0.000

Notes: "Current emissions" are those denoted σ_{jx}^{O} in the text, and "low emissions" are the new technology σ_{jx}^{N}. All are in tons per million 1997 *yuan*.

Table 4a. Combustion Emission Factors (TSP), ψ_{jxf}

		Current Emissions			Low Emissions Technology		
		Coal	Oil	Gas	Coal	Oil	Gas
1	Agriculture	43708	164	27	21854	164	27
2	Coal mining and processing	8852	33	6	4426	33	6
3	Crude petroleum mining	8852	33	6	4426	33	6
4	Natural Gas Mining	8852	33	6	4426	33	6
5	Metal ore mining	8852	33	6	4426	33	6
6	Non-ferrous mineral mining	8852	33	6	4426	33	6
7	Food products and tobacco	18708	70	12	9354	70	12
8	Textile goods	15239	57	10	7619	57	10
9	Apparel, leather	4866	18	3	2433	18	3
10	Sawmills and furniture	22022	1062	24	11406	705	24
11	Paper products, printing	22022	1062	24	11406	705	24
12	Petroleum processing & coking	6588	659	11	2196	659	11
13	Chemical	8675	867	14	2892	867	14
14	Nonmetal mineral products	10865	1087	18	3622	1087	18
15	Metals smelting and pressing	6836	684	11	2279	684	11
16	Metal products	4244	16	3	2122	16	3
17	Machinery and equipment	6936	26	4	3468	26	4
18	Transport equipment	6936	26	4	3468	26	4
19	Electrical machinery	6936	26	4	3468	26	4
20	Electronic & telecom. equipment	6936	26	4	3468	26	4
21	Instruments	6936	26	4	3468	26	4
22	Other manufacturing	12097	45	8	6048	45	8
23	Electricity, steam & hot water	20527	342	0	6842	342	0
24	Gas production and supply	6588	659	11	2196	659	11
25	Construction	43708	164	27	21854	164	27
26	Transport and warehousing	43708	5463	27	21854	2732	27
27	Post & telecommunication	43708	164	27	21854	164	27
28	Commerce & Restaurants	43708	164	27	21854	164	27
29	Finance and insurance	43708	164	27	21854	164	27
30	Real estate	43708	164	27	21854	164	27
31	Social services	43708	164	27	21854	164	27
32	Health, Education, other services	43708	164	27	21854	164	27
33	Public administration	43708	164	27	21854	164	27
	Households	21854	437	27	10927	437	27

Note: Coefficients ψ^{O}_{jxf} and ψ^{N}_{jxf} (old and new technology) in tons of TSP per million tons of oil equivalent (toe).

Table 4b. Combustion Emission Factors (SO2), ψ_{jxf}

		Current Emissions			Low Emissions Technology		
		Coal	Oil	Gas	Coal	Oil	Gas
1	Agriculture	54876	13719	0	41157	13719	0
2	Coal mining and processing	7737	1934	0	5803	1934	0
3	Crude petroleum mining	7737	1934	0	5803	1934	0
4	Natural Gas Mining	7737	1934	0	5803	1934	0
5	Metal ore mining	7737	1934	0	5803	1934	0
6	Non-ferrous mineral mining	7737	1934	0	5803	1934	0
7	Food products and tobacco	27456	6864	0	20592	6864	0
8	Textile goods	29769	7442	0	22326	7442	0
9	Apparel, leather	6714	1679	0	5036	1679	0
10	Sawmills and furniture	27043	6761	0	20282	6761	0
11	Paper products, printing	27043	6761	0	20282	6761	0
12	Petroleum processing & coking	9215	2304	0	6911	2304	0
13	Chemical	14780	3695	0	11085	3695	0
14	Nonmetal mineral products	6682	1671	0	5012	1671	0
15	Metals smelting and pressing	7696	3848	0	5772	3848	0
16	Metal products	2700	675	0	2025	675	0
17	Machinery and equipment	9712	2428	0	7284	2428	0
18	Transport equipment	9712	2428	0	7284	2428	0
19	Electrical machinery	9712	2428	0	7284	2428	0
20	Electronic & telecom. equipment	9712	2428	0	7284	2428	0
21	Instruments	9712	2428	0	7284	2428	0
22	Other manufacturing	25451	6363	0	19088	6363	0
23	Electricity, steam & hot water	40109	8913	0	35652	8913	0
24	Gas production and supply	9215	2304	0	6911	2304	0
25	Construction	54876	13719	0	41157	13719	0
26	Transport and warehousing	54876	13719	0	41157	13719	0
27	Post & telecommunication	54876	13719	0	41157	13719	0
28	Commerce & Restaurants	54876	13719	0	41157	13719	0
29	Finance and insurance	54876	13719	0	41157	13719	0
30	Real estate	54876	13719	0	41157	13719	0
31	Social services	54876	13719	0	41157	13719	0
32	Health, Education, other services	54876	13719	0	41157	13719	0
33	Public administration	54876	13719	0	41157	13719	0
	Households	41157	686	0	20579	686	0

Note: Coefficients ψ^{O}_{jxf} and ψ^{N}_{jxf} (old and new technology) in tons of TSP per million tons of oil equivalent (toe).

Table 5. Concentration and Emissions

	Conc. of TSP $\mu g / m^3$	PM10 $\mu g / m^3$	Conc. of SO2 $\mu g / m^3$
Beijing	377	226	124
Tainjing	318	191	75
Shenyang	369	221	82
Harbin	310	186	26
Shanghai	229	137	68
Jinan	420	252	141
Wuhan	241	145	42
Guangzhou	217	130	70
Chongqing	200	120	208
Chendu	248	149	60
Xian	385	231	91
National urban average	298	178	93
Coefficients linking emissions to national concentration:			
γ_{low}		0.03269	0.01687
γ_{medium}		0.00590	0.00304
γ_{high}		0.00093	0.00048

Sources: Fridley (2001); authors' calculations from Lvovsky and Hughes (1997).

Table 6. Dose-Response and Valuation Estimates for PM-10 and SO_2

	Health Effect	Cases per 1 mil. people for a 1 μg/m^3 increase	Valuation in U.S. in US$	Valuation in China *yuan 97*	Valuation in 2020 *yuan97*
	Due to PM-10:	**World Bank (1997)**			
1	Mortality (deaths)	7.14	3,600,000	702,068	2464000
2	Respiratory hospital admissions (cases)	12	4,750	926.3	3251
3	Emergency room visits (cases)	235	140	27.3	96
4	Restricted activity days (days)	57,500	60	11.7	41
5	Lower respiratory infection/child asthma (cases)	23	50	9.8	34
6	Asthma attacks (cases)	2,608	50	9.8	34
7	Chronic bronchitis (cases)	61	72,000	14,041	49300
8	Respiratory symptoms (cases)	183,000	50	9.8	34
	Due to SO_2:				
9	Chest discomfort	10,000	50	9.8	34
10	Respiratory systems/child	5	50	9.8	34
	Due to PM-10:	**ECON (2000)**			
	Deaths	24			
	Respiratory hospital admissions	56			
	Emergency room visits	55			
	Chronic bronchitis (children)	403			

Sources: Dose-response data are from World Bank (1997) and ECON (2000, Table 8.1). Valuation in U.S. $ are from Lvovsky and Hughes (1997). Valuation in *yuan* are authors' estimates.

Table 7 Health Damage per Yuan of Output

	Sector	from PM	from SO2	Emission Height
1	Agriculture	0.004922	0.000036	low
2	Coal Mining	0.007366	0.000054	medium
3	Crude Petroleum	0.001296	0.000009	medium
4	Gas Mining	0.001296	0.000009	medium
5	Metal Ore Mining	0.003455	0.000025	medium
6	Other Non-metallic Ore Mining	0.003079	0.000022	medium
7	Food Manufacturing	0.002109	0.000015	medium
8	Textiles	0.001233	0.000009	medium
9	Apparel & Leather Products	0.000143	0.000001	medium
10	Lumber & Furniture Manufacturing	0.003185	0.000023	medium
11	Paper, Cultural, & Educational Articles	0.001387	0.000010	medium
12	Electric Power	0.012329	0.000090	high
13	Petroleum Refining	0.009994	0.000073	medium
14	Chemicals	0.004197	0.000031	medium
15	Building Material	0.039283	0.000286	medium
16	Primary Metals	0.010591	0.000077	medium
17	Metal Products	0.000428	0.000003	medium
18	Machinery	0.001243	0.000009	medium
19	Transport Equipment	0.000604	0.000004	medium
20	Electric Machinery & Instruments	0.000595	0.000004	medium
21	Electronic & Communication Equipment	0.000402	0.000003	medium
22	Instruments and Meters	0.000878	0.000006	medium
23	Other Industry	0.036626	0.000267	medium
24	Construction	0.003212	0.000023	low
25	Transportation & Communications	0.051175	0.000373	low
26	Commerce	0.009576	0.000070	low
27	Public Utilities	0.025159	0.000183	low
28	Culture, Education, Health, & Research	0.016146	0.000118	low
29	Finance & Insurance	0.008002	0.000058	low
30	Public Administration	0.016637	0.000121	low
	Households	---	---	low

Note: This is the damage to human health in urban areas in *yuan* due to the emission of pollutant x from producing one *yuan* of output from sector j.

Table 8. Health Damage from Fuels

	AMD	t_f^{xv}
	yuan per ton	yuan per yuan
Coal	292.49	2.339
Oil	84.69	0.078

Notes: AMD is the average marginal damage per ton of fuel (averaged over all sectors). t_f^{xv} is the damage per yuan of fuel.

Table 9 Selected Variables from Base Case Simulation

Variable	1995	2010	2030
Population (mil.)	1,211	1,364	1,519
GDP (bil. 1995 *yuan*)	5,990	17,020	31,960
Energy Use (fossil fuels, mil. tons sce)	1,200	2,090	2,460
Coal Use (mil. tons)	1,330	2,240	2,390
Oil Use (mil. tons)	160	320	505
Carbon Emissions (mil. tons)	820	1,410	1,630
Particulate Emissions (mil. tons)	20.45	18.48	20.94
From High Height Sources	4.49	3.44	3.75
From Medium Height Sources	9.88	6.63	6.86
From Low Height Sources	6.08	8.41	10.33
SO_2 Emissions (mil. tons)	18.94	29.81	37.18
Premature Deaths (1,000)	304	516	848
Health Damage (bil. 1995 *yuan*)	321	545	897
Health Damage/GDP	5.36%	3.20%	2.81%

Table 10 Effects of an Emissions-based Product Tax

Variable	Effect in 1st Year with: tax rate = 50% of damages	Effect in 1st Year with: tax rate = 100% of damages	Effect in 20th Year with: tax rate = 50% of damages	Effect in 20th Year with: tax rate = 100% of damages
GDP	-0.02%	-0.07%	+1.27%	+2.37%
Consumption	-0.26%	-0.56%	+0.55%	+0.93%
Investment	+0.72%	+1.36%	+3.14%	+6.03%
Particulate Emissions	-1.99%	-3.93%	-1.42%	-2.90%
High Height Sources	-2.36%	-4.69%	-1.72%	-3.53%
Medium Height Sources	-2.39%	-4.69%	-1.84%	-3.69%
Low Height Sources	-1.04%	-2.09%	-0.99%	-2.06%
Particulate Concentration	-1.37%	-2.72%	-1.10%	-2.26%
SO2 Emissions	-1.66%	-3.31%	-1.33%	-2.76%
SO_2 Concentration	-1.13%	-2.27%	-1.35%	-2.75%
Premature Deaths	-1.78%	-3.55%	-1.33%	-2.73%
Value of Health Damages	-1.78%	-3.55%	-1.27%	-2.68%
Change in other tax rates	-19.5%	-38.4%	-30.0%	-58.5%
Reduction in Damages/GDP (%)	0.10	0.21	0.13	0.28
Pollution tax/Total tax revenue %	14.1	27.2	19.9	38.1

Notes: The entries are % changes between the counterfactual tax case and the base case.
The last two rows are % shares.

Table 11 Sectoral Effects of an Emissions-based Product Tax, % change year 1.

		tax=50%damages		tax=100%damages	
	Sector	**Price**	**Quantity**	**Price**	**Quantity**
1	Agriculture	0.42	-0.29	0.74	-0.60
2	Coal Mining	0.00	-1.75	0.11	-3.48
3	Crude Petroleum	-1.01	-0.86	-1.93	-1.71
4	Gas Mining	-1.01	-0.86	-1.93	-1.71
5	Metal Ore Mining	0.11	-1.08	0.11	-2.17
6	Other Non-metallic Ore Mining	-0.21	-0.48	-0.42	-0.96
7	Food Manufacturing	-0.51	0.47	-0.92	0.91
8	Textiles	-0.11	-0.48	-0.22	-0.98
9	Apparel & Leather Products	-0.11	-0.12	-0.22	-0.27
10	Lumber & Furniture Manufacturing	0.22	-0.34	0.65	-0.71
11	Paper, Cultural, & Educational Articles	-0.11	-0.63	-0.22	-1.26
12	Electric Power	0.00	-1.32	0.00	-2.64
13	Petroleum Refining	-0.10	-2.06	-0.10	-4.07
14	Chemicals	0.11	-0.77	0.21	-1.57
15	Building Material	3.51	-3.53	7.03	-6.87
16	Primary Metals	0.96	-1.36	1.92	-2.73
17	Metal Products	0.22	-0.36	0.54	-0.75
18	Machinery	0.00	0.17	0.11	0.30
19	Transport Equipment	-0.32	0.02	-0.54	0.01
20	Electric Machinery & Instruments	0.11	-0.34	0.33	-0.71
21	Electronic & Communication Equipment	0.00	0.00	0.11	-0.02
22	Instruments and Meters	-0.11	-0.65	-0.21	-1.31
23	Other Industry	3.25	-4.20	6.60	-8.15
24	Construction	0.96	0.21	2.03	0.35
25	Transportation & Communications	3.19	-3.79	6.39	-7.41
26	Commerce	0.54	-1.03	1.09	-2.05
27	Public Utilities	1.52	-1.21	3.15	-2.41
28	Culture, Education, Health, & Research	1.92	-1.07	3.73	-2.10
29	Finance & Insurance	-0.29	-0.46	-0.49	-0.93
30	Public Administration	2.35	-0.37	4.69	-0.71

Note: This is the % change in sectoral prices (purchaser's price) and quantities in the first year due to an emissions tax on sectoral output.

Table 12 Effects of an Emissions-based Fuel Tax

Variable	Effect in 1st Year with: tax rate = 20% of damages	Effect in 1st Year with: tax rate = 50% of damages	Effect in 20th Year with: tax rate = 20% of damages	Effect in 20th Year with: tax rate = 50% of damages
GDP	-0.14%	-0.52%	+0.24%	-0.08%
Consumption	-0.45%	-1.09%	+0.03%	-0.46%
Investment	+0.40%	+0.41%	+0.77%	+0.89%
Particulate Emissions	-15.6%	-27.3%	-18.8%	-32.4%
High Height Sources	-27.4%	-47.6%	-35.3%	-59.8%
Medium Height Sources	-9.9%	-17.4%	-11.6%	-19.9%
Low Height Sources	-16.5%	-29.3%	-17.0%	-29.7%
Particulate Concentration	-15.2%	-26.8%	-16.5%	-28.9%
SO2 Emissions	-18.9%	-33.1%	-23.3%	-39.9%
SO_2 Concentration	-14.7%	-26.0%	-14.6%	-25.8%
Premature Deaths	-19.7%	-35.0%	-20.0%	-34.9%
Value of Health Damages	-19.7%	-35.0%	-20.0%	-34.9%
Change in other tax rates	-8.6%	-14.6%	-6.5%	-11.1%
Reduction in Damages/GDP (%)	1.16	2.05	2.11	3.69
Pollution tax/Total tax revenue %	5.80	9.97	4.09	7.16

Notes: The entries are % changes between the counterfactual tax case and the base case. The last two rows are % shares.

Table 13 Sectoral Effects of an Emissions-based Fuel Tax, % change year 1

		tax=20%damages		tax=50%damages	
	Sector	**Price**	**Quantity**	**Price**	**Quantity**
1	Agriculture	0.21	0.08	0.42	0.01
2	Coal Mining	37.61	-28.47	90.68	-49.08
3	Crude Petroleum	-0.10	-0.61	-0.30	-1.51
4	Gas Mining	-0.10	-0.61	-0.30	-1.51
5	Metal Ore Mining	0.74	-0.69	1.59	-1.57
6	Other Non-metallic Ore Mining	0.42	-0.92	1.04	-1.90
7	Food Manufacturing	0.00	0.21	0.10	0.18
8	Textiles	0.32	-0.27	0.76	-0.71
9	Apparel & Leather Products	0.33	-0.17	0.66	-0.49
10	Lumber & Furniture Manufacturing	0.54	-0.29	1.29	-0.82
11	Paper, Cultural, & Educational Articles	0.33	-0.23	0.76	-0.63
12	Electric Power	3.86	-4.60	8.24	-9.08
13	Petroleum Refining	2.60	-2.58	6.14	-5.84
14	Chemicals	0.64	-0.83	1.50	-1.85
15	Building Material	1.38	-1.10	2.98	-2.45
16	Primary Metals	1.28	-1.25	2.77	-2.70
17	Metal Products	0.65	-0.60	1.52	-1.36
18	Machinery	0.43	-0.28	1.08	-0.79
19	Transport Equipment	0.32	0.10	0.86	-0.09
20	Electric Machinery & Instruments	0.43	-0.54	1.09	-1.23
21	Electronic & Communication Equipment	0.44	0.01	0.88	-0.19
22	Instruments and Meters	0.32	-0.69	0.75	-1.46
23	Other Industry	0.32	-0.96	0.97	-1.92
24	Construction	0.64	0.24	1.50	0.08
25	Transportation & Communications	0.31	-0.36	0.82	-0.94
26	Commerce	0.00	-0.07	0.22	-0.25
27	Public Utilities	0.30	-0.11	0.81	-0.36
28	Culture, Education, Health, & Research	0.43	-0.18	0.85	-0.43
29	Finance & Insurance	-0.20	0.20	-0.10	0.18
30	Public Administration	0.43	-0.02	0.85	-0.05

Note: This is the % change in sectoral prices (purchaser's price) and quantities in the first year due to a tax on fuels.

Table 14 Dose Response and policy effects
(High DR versus Base DR)

Variable	Effect in 1st Year with: tax = 50% of damages		Effect in 20th Year with: tax = 50% of damages	
	Base DR	High DR	Base DR	High DR
GDP	-0.52%	-1.32%	-0.08%	-1.19%
Consumption	-1.09%	-2.22%	-0.46%	-1.75%
Investment	+0.41%	-0.01%	+0.89%	+0.27%
Particulate Emissions	-27.3%	-39.4%	-32.4%	-44.5%
High Height Sources	-47.6%	-67.1%	-59.8%	-79.1%
Medium Height Sources	-17.4%	-25.2%	-19.9%	-27.5%
Low Height Sources	-29.3%	-42.8%	-29.7%	-47.8%
Particulate Concentration	-26.8%	-39.2%	-28.9%	-40.6%
SO2 Emissions	-33.1%	-43.4%	-39.9%	-54.1%
SO_2 Concentration	-26.0%	-38.2%	-25.8%	-36.8%
Premature Deaths	-35.0%	-51.0%	-34.9%	-49.0%
Value of Health Damages	-35.0%	-51.0%	-34.9%	-49.0%
Change in other tax rates	-14.6%	-20.5%	-11.1%	-15.3%
Reduction in Damages/GDP (%)	2.05	7.21	3.69	12.4
Pollution tax/Total tax revenue %	9.97	14.3	7.16	10.4

Notes: The entries under "Base DR" are taken from Table 12, the "High DR" uses the mortality coefficient from ECON(2000). Both are done with a fuel tax equal to 50% of average marginal damage.

Table 15 Dose Response and policy effects on sectors
High DR versus Base DR (% change year 1)

		Base DR tax=50%damages		High DR tax=50%damages	
	Sector	**Price**	**Quantity**	**Price**	**Quantity**
1	Agriculture	0.42	0.01	0.84	-0.27
2	Coal Mining	90.68	-49.08	205.93	-68.78
3	Crude Petroleum	-0.30	-1.51	-0.71	-3.31
4	Gas Mining	-0.30	-1.51	-0.71	-3.31
5	Metal Ore Mining	1.59	-1.57	2.98	-3.05
6	Other Non-metallic Ore Mining	1.04	-1.90	2.19	-3.38
7	Food Manufacturing	0.10	0.18	0.51	-0.15
8	Textiles	0.76	-0.71	1.62	-1.52
9	Apparel & Leather Products	0.66	-0.49	1.32	-1.13
10	Lumber & Furniture Manufacturing	1.29	-0.82	2.59	-1.84
11	Paper, Cultural, & Educational Articles	0.76	-0.63	1.63	-1.37
12	Electric Power	8.24	-9.08	15.22	-15.20
13	Petroleum Refining	6.14	-5.84	13.22	-11.80
14	Chemicals	1.50	-1.85	3.00	-3.53
15	Building Material	2.98	-2.45	5.54	-4.65
16	Primary Metals	2.77	-2.70	5.12	-4.98
17	Metal Products	1.52	-1.36	2.82	-2.64
18	Machinery	1.08	-0.79	2.05	-1.76
19	Transport Equipment	0.86	-0.09	1.72	-0.68
20	Electric Machinery & Instruments	1.09	-1.23	2.17	-2.37
21	Electronic & Communication Equipment	0.88	-0.19	1.64	-0.69
22	Instruments and Meters	0.75	-1.46	1.50	-2.69
23	Other Industry	0.97	-1.92	1.95	-3.30
24	Construction	1.50	0.08	2.78	-0.60
25	Transportation & Communications	0.82	-0.94	1.85	-2.14
26	Commerce	0.22	-0.25	0.44	-0.68
27	Public Utilities	0.81	-0.36	1.63	-0.91
28	Culture, Education, Health, & Research	0.85	-0.43	1.60	-0.87
29	Finance & Insurance	-0.10	0.18	0.10	-0.10
30	Public Administration	0.85	-0.05	1.71	-0.09

Notes: The entries under "Base DR" are taken from Table 13, the "High DR" uses the mortality coefficient from ECON(2000). Both are done with a fuel tax equal to 50% of average marginal damage.

Table 16 Effects of different tax offset policies (fuel tax policy)

Variable	Effect in 1st Year with: tax = 50% of damages		Effect in 20th Year with: tax = 50% of damages	
	Cut other taxes	Lump sum Rebate	Cut other taxes	Lump sum Rebate
GDP	-0.52%	-0.56%	-0.08%	-0.84%
Consumption	-1.09%	-0.05%	-0.46%	-0.56%
Investment	+0.41%	-0.71%	+0.89%	-0.67%
Particulate Emissions	-27.3%	-27.7%	-32.4%	-33.0%
High Height Sources	-47.6%	-47.9%	-59.8%	-60.1%
Medium Height Sources	-17.4%	-18.1%	-19.9%	-20.9%
Low Height Sources	-29.3%	-29.1%	-29.7%	-30.1%
Particulate Concentration	-26.8%	-26.7%	-28.9%	-29.3%
SO2 Emissions	-33.1%	-33.4%	-39.9%	-40.5%
SO_2 Concentration	-26.0%	-26.1%	-25.8%	-26.4%
Premature Deaths	-35.0%	-35.0%	-34.9%	-35.4%
Value of Health Damages	-35.0%	-35.0%	-34.9%	-35.4%
Change in other tax rates	-14.6%	0%	-11.1%	0%
Reduction in Damages/GDP (%)	2.05	2.06	3.69	3.74
Pollution tax/Total tax revenue %	9.97	9.97	7.16	7.14

Notes: The entries under "Cut other taxes" are taken from Table 12, the "Lump sum tax" rebates the pollution tax revenue as a lump sum to households. Both are done with a fuel tax equal to 50% of average marginal damage.

Table 17 Effects of different tax offset policies (fuel tax policy)
(% change year 1)

		Cut other taxes tax=50%damages		Lump sum tax tax=50%damages	
	Sector	**Price**	**Quantity**	**Price**	**Quantity**
1	Agriculture	0.42	0.01	1.58	0.34
2	Coal Mining	90.68	-49.08	92.80	-49.32
3	Crude Petroleum	-0.30	-1.51	0.71	-2.14
4	Gas Mining	-0.30	-1.51	-0.71	-2.14
5	Metal Ore Mining	1.59	-1.57	2.66	-2.48
6	Other Non-metallic Ore Mining	1.04	-1.90	2.29	-2.78
7	Food Manufacturing	0.10	0.18	2.05	-0.05
8	Textiles	0.76	-0.71	2.06	-0.98
9	Apparel & Leather Products	0.66	-0.49	1.98	-0.26
10	Lumber & Furniture Manufacturing	1.29	-0.82	2.48	-1.22
11	Paper, Cultural, & Educational Articles	0.76	-0.63	2.06	-0.98
12	Electric Power	8.24	-9.08	9.59	-9.55
13	Petroleum Refining	6.14	-5.84	7.49	-6.70
14	Chemicals	1.50	-1.85	2.79	-2.30
15	Building Material	2.98	-2.45	4.26	-3.32
16	Primary Metals	2.77	-2.70	4.05	-3.71
17	Metal Products	1.52	-1.36	2.61	-2.03
18	Machinery	1.08	-0.79	2.26	-1.70
19	Transport Equipment	0.86	-0.09	2.15	-1.14
20	Electric Machinery & Instruments	1.09	-1.23	2.28	-1.74
21	Electronic & Communication Equipment	0.88	-0.19	1.97	-0.50
22	Instruments and Meters	0.75	-1.46	1.82	-2.24
23	Other Industry	0.97	-1.92	2.06	-2.48
24	Construction	1.50	0.08	2.68	-1.03
25	Transportation & Communications	0.82	-0.94	1.96	-1.44
26	Commerce	0.22	-0.25	1.31	-0.53
27	Public Utilities	0.81	-0.36	1.93	-0.74
28	Culture, Education, Health, & Research	0.85	-0.43	1.60	0.03
29	Finance & Insurance	-0.10	0.18	1.38	-0.44
30	Public Administration	0.85	-0.05	1.60	0.07

Notes: The entries under "Cut other taxes" are taken from Table 12, the "Lump sum tax" rebates the pollution tax revenue as a lump sum to households. Both are done with a fuel tax equal to 50% of average marginal damage.

Figure A1: Data and Projections of Urban Population as a Percentage of Total

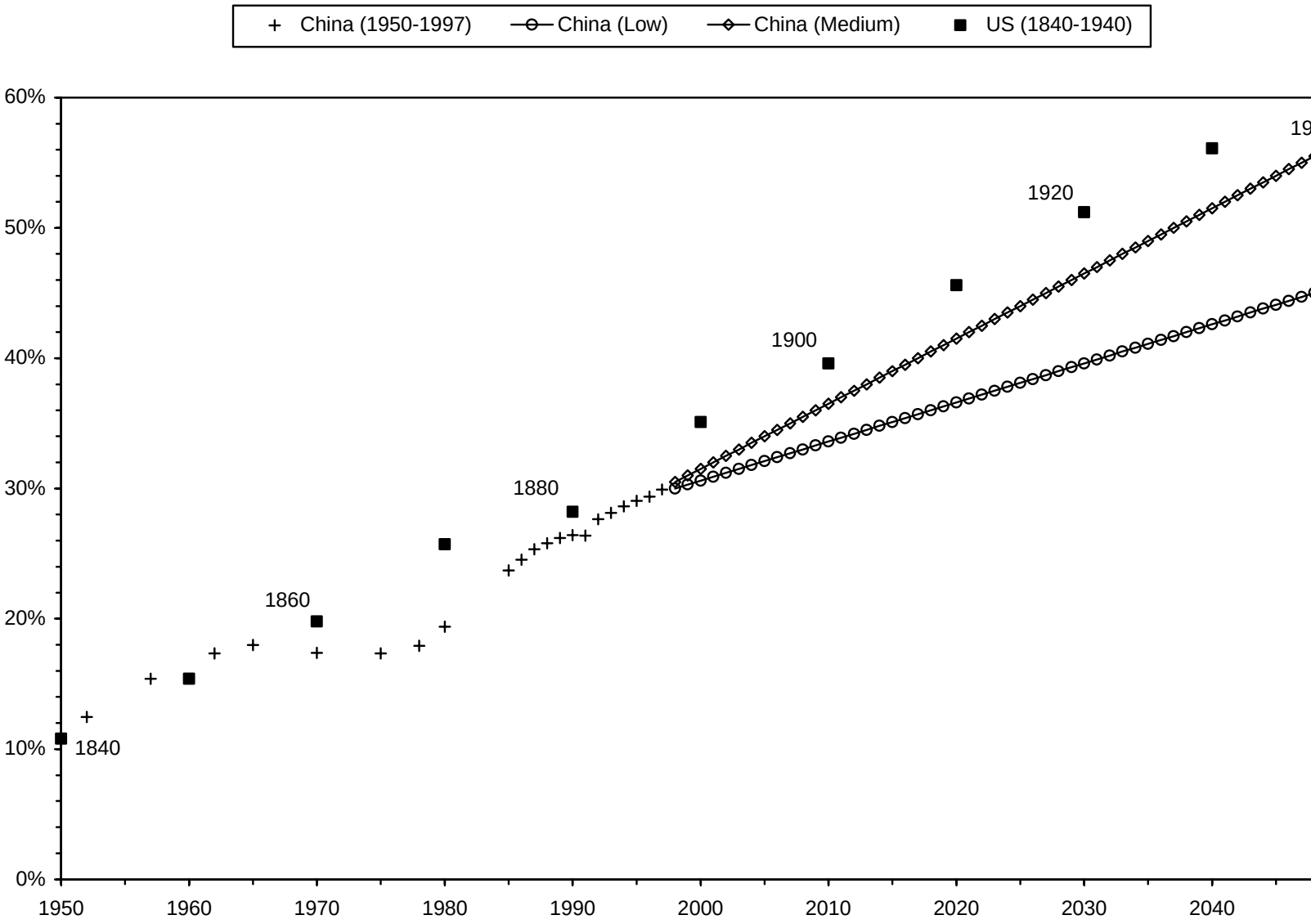
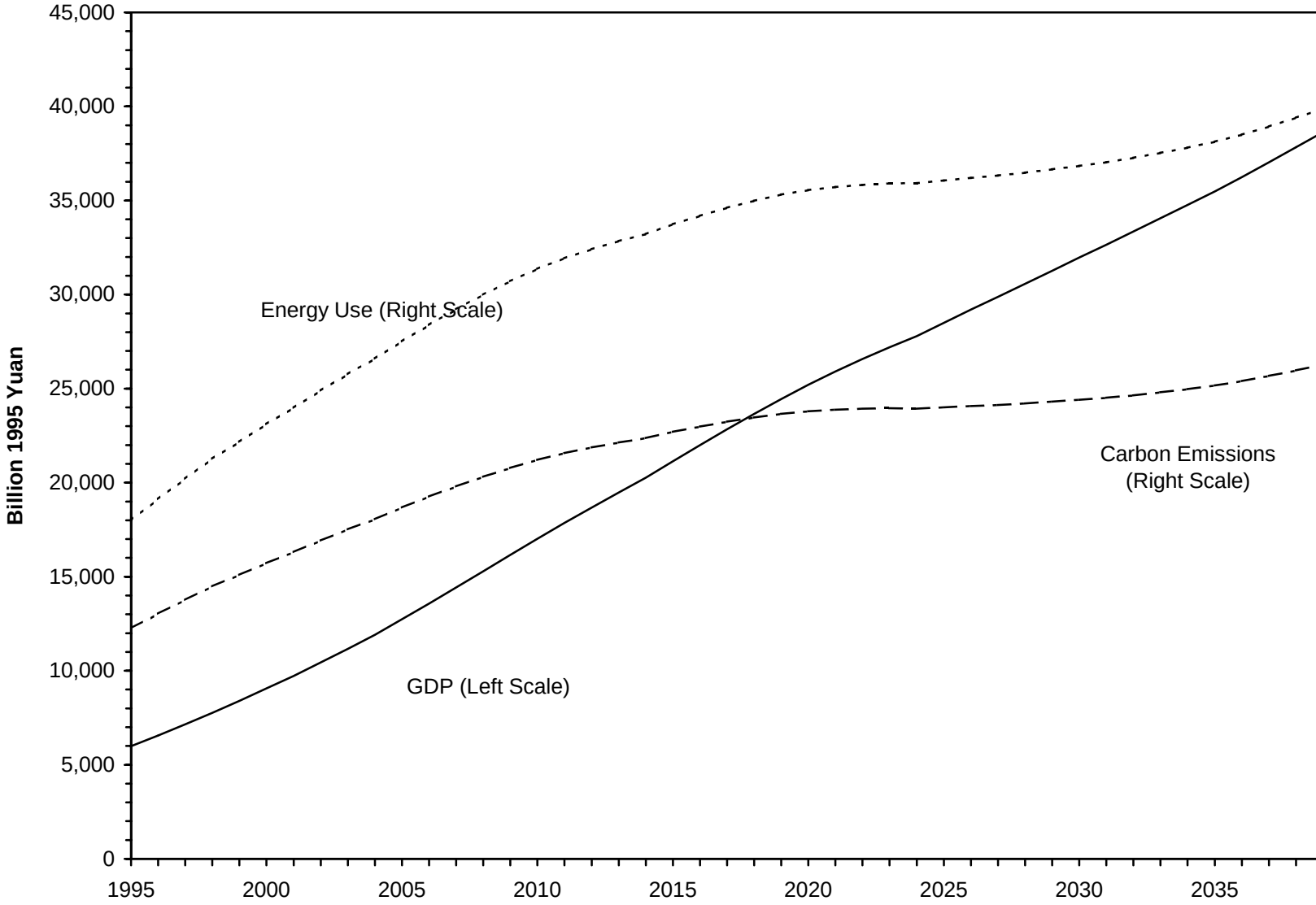


Figure A2: GDP, Energy, and Carbon Emissions 1995-2040



Note: Energy use is in standard coal equivalents (SCE).