Market policies to control air pollution damages in China

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1 Introduction

In light of the severe estimated damages caused by air pollution there have been many studies examining various options to control or reduce emissions. These range from electricity generation policies to energy efficiency policies to economic deregulation to eliminate subsidies on dirty fuels.[1] Only a few of these studies, however, make an integrated estimate of the economic costs and health benefits of these pollution control policies.[2]

The aim of this report is to examine some market-based pollution control policies and how they might affect economic performance. We shall focus on general economy-wide policies, such as fuel charges, rather than specific rules such as mandatory scrubbers or other sector-specific policies. We examine how these pollution fees affect fuel use and hence emissions and health damages. At the same time we estimate how these taxes affect output, allocation of resources, other existing taxes, and over time, how they affect economic growth. The effects on greenhouse gas emissions is also considered. This report builds on a companion paper, Ho and Jorgenson (2003a), that calculated the health damages of air pollution by sector. (Hereafter referred to as HJ).

There is substantial uncertainty underlying health damage estimates, as many authors have emphasized (e.g. HUCE 2002). These include the emissions-concentration relation, the dose-response coefficients, and the valuation of premature mortality. In doing this cost and benefit assessment here we are adding another layer of uncertainty about how the economic agents interact, and about how enterprises respond to changes in prices. Nevertheless, we believe our results are instructive. They give us a sense of the relative magnitudes of the costs and benefits involved which would help prioritize mitigation efforts.

We find that a policy that imposes even moderate levies on fuels could reduce health damages by 9%, while only lowering GDP by 0.1%, and aggregate consumption by 0.1% in the short run. Depending on how the pollution fee revenues are used, the long run effects could be positive on GDP. 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

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[1] A partial list of English papers include Sunman, Monasinghe and Zhang, and Panayotou and Wu, in Warford and Li (2002); Chandler et.al. (1998); World Bank (1997); Dasgupta, Wang and Wheeler (1997) contains references to other World Bank analysis; Maddison et. al. (1999); Sinton et.al. (1999) is one in a series of energy policy status reports by Lawrence Berkeley Laboratory.

[2] An example is Aunan, et.al. (2002) which discusses the impact of a carbon tax, and Ho, Jorgenson and Di (2002).

fuel tax policy is about 0.34% 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 4.3% a year, and in the short run lower GDP and consumption by 0.1%. The fuel charge policy is more effective but require large adjustments in the coal sector.

We performed sensitivity analysis of the many uncertain parameters in our analysis, including the crucial dose-response and health endpoints valuations. We find that our conclusion of a high benefit-cost ratio is robust to these parameters.

2 Methodology for analyzing pollution fees.

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).

In this report 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 fees that are related to the level of pollution emitted, i.e. the effects on sector 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 as described in Ho and Jorgenson (2003a). 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 ignores optimization over time.

We employ a multi-sector model of the Chinese economy that has been used previously to study the local health benefits of carbon control policies (Garbaccio, Ho, and Jorgenson 2000). Our approach is to first use the estimates from Ho and Jorgenson (2003a) of damages to human health from air pollution due to the current patterns of output and fuel use as the base case. These damages are attributed to the emissions from specific industries and we calculated 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 economic 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 sector 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[3] but is relatively easy to 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. The estimates in HJ show 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

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[3] 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.

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.

2.1 The Environment-Health Model

Our economic model (described in the next section) generates output for each of 33 sectors and their demands for inputs, including energy. In Ho and Jorgenson (2003a) we described how emissions of TSP and SO2 are generated from the combustion of fossil fuels and from noncombustion processes (process emissions). These emissions were then related to the ambient concentrations in urban China, and the health damages were calculated.

In HJ we calculated the current health damages using two methods. In the first method, we follow the approach in Lvovsky and Hughes (1997) to make a rough estimate of damages due to emissions from every sector of the economy (hereafter referred to as LH). In the second, we apply the intake fraction method for the most polluting sectors to obtain a more precise estimate. These methods are briefly summarized here again for convenient reference.

Total emissions of *x* from industry *j* (EM_{jxt}) at time *t* (in kilo tons) is the sum of non-combustion and combustion sources which are given by the level of output (QI_{jt}) and fuel inputs respectively :

$$(1) \qquad EM_{jxt} = EM^{NC}_{jxt} + EM^{C}_{jxt}$$

$$EM^{NC}_{jxt} = \sigma_{jx} QI_{jt}$$

$$EM^{C}_{jxt} = \sum_{f} \left(\psi_{jxf} AF_{jft} \right)$$

$$(2) \qquad AF_{jft} = \lambda_j \theta_f FT_{fjt}$$

$$(3) \qquad FT_{jft} = \xi_f A_{fjt}$$

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

σ_{jx} is process emissions coefficient and ψ_{jxf} is the emission factor for fuel *f* in sector *j*. AF_{jft} is the quantity of fuel *f* (in tons of oil equivalent (toe)) consumed.[4] The constant *yuan* measure A_{ijt} derived from the input-output matrix is converted to physical units by the ξ_f coefficient (e.g. $FT_{j,coal,t}$ tons of coal). The physical units are 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 complete study should take into account the costs of these new technologies and how much they reduce emissions and energy use.[5] Estimates of these factors have not yet been assembled for many industries in China and we use a simple mechanism to represent such changes. LH makes 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:

$$(4) \qquad \psi_{jxft} = k_t \psi^{O}_{jxf} + (1 - k_t)\psi^{N}_{jxf} \quad ,$$

where the weight, k_t, is the share of old capital in the total stock of capital.[6] For our purposes, the use of these old and new coefficients generate a more realistic base case but they do not affect the costs of pollution control as they should in a more general model.

The next step is to estimate the concentrations of pollutants in population centers due to these emissions and then estimate the health effects. We use two methods to do this, the Lvovsky and Hughes (1997) approach, and the intake fraction method as described in HJ.

(i) The LH Method

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[4] 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.

[5] 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.

[6] 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.

We first divide the emissions into urban and rural sources since we assume that only the urban population is exposed to these pollutants. This urban portion is allocated simply using a fixed ratio:

$$(5) \qquad EM^{u}_{jxt} = \upsilon_j EM_{jxt}$$

The emission sources are then classified as low, medium, or high height. The electric power sector is classified as high, manufacturing as medium, and the nonmanufacturing and household sectors as low (Table 10 in HJ give the exact classifications). The urban emissions at height *c* are simply the sum of the emissions from sectors in class *c* :

$$(5) \qquad E^{u}_{cxt} = \underset{j \in c}{} EM^{u}_{jxt} \qquad , \qquad \text{where } c = \text{low, medium, high} \quad .$$

The national average urban ambient concentration (in $\mu g / m^3$) is then expressed as a simple linear effect of these emissions :

$$(6) \qquad C^{N}_{xt} = \gamma_{low,x} E^{u}_{low,xt} + \gamma_{medium,x} E^{u}_{medium,xt} + \gamma_{high,x} E^{u}_{high,xt} \, ,$$

where the γ_{cx} coefficients translate emissions at height *c* to concentration of *x*.[7]

This formulation is rather crude and one should be aware of the effects of misspecification of various parts of the procedure. An error in the γ_{cx} reduced form coefficients has a first-order effect on the level of concentration, which will have a first-order effect on the estimate of health effects. 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 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.)

Eight separate health effects are identified for PM-10 and two for SO_2, these are given in Table 1, ranging from premature mortality to respiratory symptoms. The most important of these effects in terms of the monetary valuations are mortality and chronic bronchitis. The number of

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[7] In the original calculations of Lvovsky and Hughes this equation was calculated separately for 11 cities. Since our model does not have regional detail we aggregated it to a national one. This is described in greater detail in HJ around eqs. (5-6).

cases of health effect *h* in period *t* is assumed to be a linear function of the concentration given in eq. (6):

$$(7) \qquad HE_{ht} = \sum_{x} \left(DR_{hx} (C_{xt}^{N} - \alpha_{x}) POP_{t}^{u} er \right) \qquad h = \text{Mortality, RHA,...}$$

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 central estimates of the dose-response coefficients are reproduced in Table 1 from Table 8 in HJ.

The applicability of this linear formulation in estimating *total* damage is discussed in HUCE (2002, Chapter 2). For our purposes here of estimating the *change* in damages due to a policy change it is sufficient that this linear approximation is valid just for the range of concentrations realized under the policies. (HUCE 2002, Chapter 1 gives the concentrations of the recent years). We shall not be considering extreme reductions to, say, the low levels seen in the rich countries.

(ii) The iF Method

The intake fraction (*iF*) method was implemented for the sectors with the highest emissions to provide a more precise estimate of exposures to pollution. This research was done by the Harvard University Center for the Environment as described in HUCE (2002). This approach estimates the fraction of emissions that is breathed in by using a simple air dispersion model on typical sources (stacks) in the selected sectors. The use of *iF*'s to estimate marginal damages is described in Ho and Jorgenson (2003a) in eqs. 17-22.

We shall briefly summarize the discussions in that companion report. The total national dosage, or intake, of pollutant *x* due to sector *j* is given by multiplying the intake fraction with total emissions and dividing by the breathing rate, $iF_{xj}^N EM_{xj} / BR$. The health effects due to sector *j* is the dosage multiplied by the dose-response coefficient and summed over all pollutants :

$$(8) \qquad HE^{S}_{hj} = \sum_{x} \left(DR_{hx} \frac{iF^{N}_{xj} EM_{xj}}{BR} \right) \qquad h = \text{Mortality, RHA,...}$$

These sector health effects (denoted by superscript S) were estimated for chemicals, nonmetal mineral products, metals smelting and electricity from samples drawn from 5 cities and nationally. A simpler estimate was also made for the transportation sector.

After estimating the health effects from both methods, the next step is to value these health damages in order to compare with the costs of reducing them. The value of damages due to *h* is given by:

$$(9) \qquad Damage_{ht} = V_{ht} HE_{ht}$$

The central estimates of the valuations, V_{ht}, are reproduced in Table 1 from Table 8 of HJ which also report alternative estimates and describe the sources of the data.

Some studies of health damage valuation use a fixed V_{ht} for all years of their analysis[8]. 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. Instead of calculating an income effect endogenously[9] within the model, we simply index *V* by time and scale it to lagged changes in per capita incomes, assuming a linear income effect. In the base case, our model projects an average growth rate of 4-5% in per capita incomes over the next 40 years producing substantial revaluations as illustrated in the last two columns of Table 1.

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

$$(10) \qquad TD^{N}_{t} = \sum_{h} Damage_{ht} \quad .$$

In analyzing the effects of corrective taxes we are interested, not in the total damages, but in the marginal damage. For the LH method, the marginal damage for each unit of emissions in sector *j* is derived as (this is eq. 12 in HJ) :

$$(11) \qquad MDX_{jx} = \sum_{h} V_{ht} DR_{hx} \gamma_{j} POP^{u}_{t} er$$

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[8] That is, they do not have health explicitly in an utility index, and combine the consumption of normal goods with health using a fixed relative price (V_{ht}) that is independent of income.

[9] A variable in the model is said to be *endogenous* if it is determined within the model simultaneously with other variables. On the other hand, an *exogenous* variable is predetermined before any model solution, e.g. population size.

The marginal damage from producing one unit of sector *j*'s output is the weighted sum over all pollutants of these MD_{jx}'s:

$$(12) \qquad MD_{jt}^{O} = \sum_{x} \left(MDX_{jx} \frac{\upsilon_j EM_{jxt}}{QI_{jt}} \right)$$

The weights are the emissions. The superscript O is to denote that it is an output measure.

We made the calculations for these marginal damages in Ho and Jorgenson (2003a) separately for total and combustion only emissions given the uncertainty surrounding the non-combustion emissions. Here too we conduct our policy analysis for both cases. The combustion only counterpart to the marginal damage per unit output is :

$$(13) \qquad MD_{jt}^{O,C} = \sum_{x} \left(MDX_{jx} \frac{\upsilon_j EM_{jxt}^{C}}{QI_{jt}} \right)$$

where the combustion emissions of pollutant *x*, EM_{jxt}^{C} , is given in eq. (1).

For the estimates using the *iF* method, the marginal damage from the last unit of output is derived as (eq. 24 in HJ) :

$$(14) \qquad MD_{jt}^{O} = \sum_{h} V_{ht} \sum_{x} \left(DR_{hx} \frac{iF_{xj}^{N} EM_{xj}}{BR.QI_{jt}} \right)$$

2.2 The Economic Model

The environment-health model described above requires as inputs industry output and fuel use. These are generated by our model of the Chinese economy. We summarize the key features of the model here, further details are in Appendix F. (For further description and applications see Garbaccio, Ho and Jorgenson 2001.) It is a standard multi-sector Solow growth model (dynamic recursive[10]) for one country that is modified to recognize the two-tier plan-market nature of the Chinese economy. This version is based on the 1997 input output table where 33 sectors are identified, including six energy industries. Sector output, value added, and energy use are given in HJ Tables 2 and 3. The largest sector in terms of employment and output is agriculture, the largest user of coal is electricity, while the largest emitter of TSP is nonmetal mineral products.

The household sector maximizes a utility function that has all 33 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 the current account surplus. The investment in period *t* increases the stock of capital that is used for production in future periods.

Labor is supplied inelastically[11] 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 (the *g(t)* term in appendix eq. F.3) is projected exogenously, i.e. we make a guess of how input requirements per unit output fall over time, including energy requirements. The latter 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.

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[10] The terms "Solow" and "dynamic recursive" refers to the feature that certain fixed rules determine investment, that there is no forward-looking behavior where expected changes in future policies can affect behavior today. This is simpler than models with intertemporal equilibrium and such features.

[11] By inelastic labor supply we mean that the total hours worked is a predetermined number not affected by economic events. The alternative formulation of having hours worked depending on the wage rate seems to us to be

2.3 Marginal damages and Pigovian taxes

With the above economic model and the environment-health submodel we now have the pieces to analyze the costs and benefits of two taxes to reduce pollution damages. The first is a tax on output proportional to the damages, and the second is a tax on fuels.

a) *Policy of using Output taxes*

To implement corrective output taxes one needs the marginal damage per unit output of each sector. These are calculated above in eqs. 12-14. The values for these marginal damages are calculated in Ho and Jorgenson (2003a). (Tables 10 and 11 in HJ gives the *MD*'s for the LH method, and Table 13 for the *iF* method. Table 10 gives the damages due to all emissions while Table 11 is for combustion emissions only.) We have noted that the main difference between the two is the non-combustion (process) emissions of the cement sector. As discussed in the companion report, health damage is believed to be due to very fine particles, however, there is no information on the particle size distribution of these cement emissions. That is, we do not know if these process TSP are equally harmful as the combustion ones, or not harmful at all, or something in between.

We therefore conduct our analysis separately for both sets of emissions -- combustion only and total. Considering only combustion emissions, the highest health damage producing sector is nonmetal mineral products with a rate of 0.048 yuan of damages per *yuan* of output, followed by transportation with 0.046. When both combustion and noncombustion emissions are considered to be equally damaging then the damage rate for nonmetal mineral products is a very high 0.248. Comparing the damages from PM versus those from SO2, we see that our central parameter assumptions lead to a trivial portion attributed to SO2, essentially total $MD_{jt}^{O} = MDX_{j,x=PM,t}^{O}$.

In this policy simulation the externality tax for period *t* is set proportional to the marginal damage of the previous period :

(15a) $t_{jt}^{x} = \lambda MD_{jt-1}^{O,C}$ (15b) $t_{jt}^{x} = \lambda MD_{jt-1}^{O}$

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too elaborate to implement sensibly for the current Chinese economy with its large pool of underemployed workers. A more elaborate model with heterogenous workers might change the details but not the overall result.

This tax, t_j^x, is applied to the price of output of sector j and thus the dirtiest sector has the biggest increase in price (for details, see appendix F eq. F4). In the other simulation where we consider all emissions we set the tax at $t_{jt}^x = \lambda MD_{jt-1}^O$.

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 next consider a policy of taxing fuels in proportion to the marginal damages produced using the base case technologies. 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. The higher overall cost of energy will also induce substitution from energy to capital and other inputs.

To implement a simple national tax on each primary fuel we use the damage per unit fossil fuel calculated in HJ, eq. 18. To summarize, the average marginal damage of fuel *f*, averaged over all sectors, in the base year, *tb*, is given by:

$$(16) \qquad AMD_f = \frac{\sum_j MD_{fj}^F FT_{jf,tb}}{\sum_j FT_{jf,tb}}$$

where the sector specific marginal damage of fuel *f* is $MD_{fj}^F = \sum_x \left(MDX_{jx} \psi_{jxf} \theta_f \right)$. The damage per unit pollutant, MDX_{jx}, is given in eq. 11.

The *AMD* is in *yuan* per physical unit (per ton of coal or ton of oil) and is given in HJ, Table 12. They are quite substantial, up to 153 yuan per ton of coal. To give a better idea of these magnitudes, we also expressed the damages in terms of a *yuan* of fuel:

$$(17) \qquad t_{ft}^{xv} = \xi_f AMD_{ft}$$

where $1/\xi_f$ is the price of a physical unit of fuel. (These value ratios are given in the last column of HJ Table 12 in the companion report, under t_f^{xv}). For coal the value of damages almost equal the value of the coal itself, $t_{f,1997}^{xv}$ was 0.938 *yuan* of damage per *yuan* of coal. In contrast, the damage rate for oil is only 0.028.

If a tax rate equaling the *AMD* is applied, the price of coal will double. As we have discussed above, large changes are not well analyzed with marginal methods and linearity assumptions that we employ here. When analyzing this policy we set the externality tax to some small fraction, λ, of this damage:

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

c) Externality tax revenue offsets

Our approach to analyzing the effects of externality taxes as given in equations 14 and 17 is to first simulate a base case under the current tax system without these pollution taxes[12]. We then apply the externality taxes and simulate a counterfactual case. The revenue from an ad-valorem externality tax on output is the sum over all sectors :

(19) $R\_EXT_t = \sum_j t_{jt}^{xv} PI_{jt} QI_{jt}$

PI_{jt} denotes the seller's price of the output of *j*. (The superscript *v* on the tax rate denote that it is an ad-valorem tax, as opposed to a unit tax).

To maintain revenue neutrality (hence keeping real government spending constant) we cut the VAT, the capital income tax and the sales tax (Appendix F eqn. F11-F16 describes the government accounts). Using superscript C to denote the counterfactual simulation, the new tax rates are a fraction α of the base case rates :

(20) $t_t^{v,C} = \alpha_t t_t^v$, $t_t^{k,C} = \alpha_t t_t^k$, $t_t^{t,C} = \alpha_t t_t^t$

In the counterfactual simulation α_t is endogenously chosen such that total government revenue is equal to that found in the base case for each period. The economic and health outcomes in the two cases are then compared, e.g. how much is the GDP higher or lower in the counterfactual?

3 The Base Case Simulation

The central aim of our methodology is to provide estimates of the *change* in damages and economic performance due to implementing some pollution control policy. This requires a projection of the future Chinese economy. We now describe the base case projection of the main variables in order to give the reader a clear idea of how our approach works, it is not our aim to give the most sophisticated forecast possible. The projections are made in a relatively simple manner, involving many assumptions regarding population growth, technical progress, changes in preferences and changes in the world economy. We shall briefly describe our assumptions, they only have second order effects on the percentage change in costs and benefits that we are trying to estimate[13].

We start the simulation in 1997 and so we initialize the economy to have the capital stocks that were available at the start of 1997, and have the working age population of 1997 supplying labor.[14] The economic model then calculates, for this period, the output of all commodities, the purchases of intermediate inputs including energy, the consumption by households, government, exports, and the savings available for investment[15]. This investment augments the capital stock for the next period, and using the projected population for the next period we solve the model again. This exercise is repeated for the subsequent T periods. The level of output (of 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.

The main variables for the base case are reported in Table 2 for the first, tenth and 30th years. The 5.1% growth rate of GDP over the next 30 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 slow 0.6% annual rate during this period.

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 2026 that is about 60%

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[12] In the current system there are various fees and fines on waste water and other discharges amounting to 6 billion yuan. These are not explicitly taken into account in the model. Our pollution taxes should be viewed as new taxes on top of the existing charges.

[13] The datails of the projections of exogenous variables are discussed in more detail in Appendix F, section F7.

[14] The choice of the starting year also have small effects on the percentage change calculation. It would have a big effect if there have been dramatic changes in pollution ratios or structure of the economy. Like the assumptions about projections of exogenous variables, the choice of the initial period affects the level, but the effect on the percent change is small.

[15] Specifically, we solve the model to find an equilibrium set of prices. That is, find a set of prices such that the demand of each commodity equals the supply, the demand for labor equals the exogenously specified work force, the demand for capital equals the stock of capital, and the government accounts meet the specified deficit.

that of 1997.[16,17] There is a big fall in the use of coal per unit output, but a rise in oil and electricity use about equal to that of GDP growth, and a big rise in the use of gas. These changes are due to our assumptions about changes in transportation demand, in electricity generation technologies, in space heating technologies and improvements in energy efficiency. This shift from coal to oil and gas results in the rate of growth of carbon emissions even slower than the growth in energy use (3.1% vs. 3.3% per year over 30 years).[18]

With the industry output and input requirements calculated for each period, we use equations (1)-(8) to calculate the total emission of pollutants, the urban concentration of pollutants, and the health effects of these pollutants. Total PM-10 emissions actually fall (at a 1.44% rate) despite the increase in energy use. The time paths of GDP, energy use and emissions are plotted in Fig. 1.

This fall in PM is due to the sharp difference in the assumed emission coefficients for new and old capital (see eq. 4) and the shift from coal to oil. Medium height sources of PM-10, mostly manufacturing sources, fall dramatically, while low-height emissions from transportation, construction and services rise. High height emissions from electric power generation fall and then rise due to the opposing trends of lower emissions per unit output and rapidly rising total electricity use. As a result of these opposing trends the fall in urban concentrations of PM is only 0.73% per year. 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} emission coefficients. However, there is still a substantial projected improvement, while coal use rises at 2.3% per year, SO_2 emissions rise only at 1.85% over this 30-year period.

Our base case estimate of premature mortality in 1997 is 250,000 deaths. This is a little higher than World Bank (1997) estimate of 230,000 for 1992 and is due to the increased urban populations and the change in concentration. The growth rate of health effects from our more optimistic assumptions of energy trends are much lower that projected by Lvovsky and Hughes

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[16] As explained in Appendix F we assume that the input-output structure gradually changes towards a structure similar to the US in 1982. It is not identical, the Chinese economy would still use more coal per unit output than the U.S. in 1982.

[17] The official data since 1997 shows a decline in energy consumption 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, however, one should consider if these recent trends are real, and sustainable.

[18] Our base case is similar to the "current trends" scenario in Sathaye, Monahan and Sanstad (1996) for growth rates of GDP (4.9%) and carbon emissions (3.1%) over the 30-year period.

(1997), e.g., after 25 years our estimated excess deaths are 1.2 times the first year level, compared to their 3.7 times. Premature mortality first falls and then rises due to the initial reductions in emission factors being bigger than the increased urbanization, but over time the higher transportation pollution and greater urbanization becomes more dominant. The higher death rate multiplied by valuations that rise with per capita incomes means that the health damage:GDP ratio rises quite rapidly.

To reiterate our cautionary note, this description of the base case is not intended as a forecast of economic activity and 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 in ways that are not captured. The emphasis of our analysis will be on the changes at the margin due to specific policy changes, no one expects all pollution to be removed in the next year. This is what we turn to next.

4 Controlling Local Pollution with Corrective Taxes

4.1 Effects of taxes on output based on damages

This policy imposes taxes on the gross output of each sector in proportion to the local health damage caused by the marginal unit of output, as described above in section 2.3a. The effects of this policy is analyzed first using the estimates from the LH method for all sectors, and then with the *iF* estimates for the 5 sectors. We focus on combustion emissions and briefly report the case when all emissions are considered.

We first run a counterfactual simulation where the externality tax is set according to eq. 15a above, i.e. a tax on output equal to the marginal damage with $\lambda = 1$, and using the LH marginal damages for combustion (MDX_j^O) in HJ Table 11. (Other values of λ has been used to examine the possible nonlinearities in the system. The results of varying λ in a setup similar to this one are reported in Ho, Jorgenson and Di 2002).

Given the estimates of MDX_j^O, this policy is one which imposes an addition to the existing sales tax on nonmetal mineral products, transportation, services and electricity of about 2-5% and a much smaller addition on the other commodities. The economy wide effects of using these output taxes are given in Table 3 in the columns marked "LH Method," for the first and

20th years. The sector effects in the first year are given in Table 4, and the time paths plotted in Fig. 2. The initial effect of the taxes is to raise the prices of these dirty commodities by about 2-4%, and to lower those on the cleaner items such as finance, commerce and mining by about 1%. Both investment goods such as cement and construction, and consumption items such as services and transportation, are subject to the higher tax rates. This pattern leads to a small change in GDP and the composition of aggregate demand. GDP falls a tiny 0.03% with total real consumption falling marginally and investment hardly changed. Recall that government spending is held fixed across all scenarios.[19]

The output of the dirty sectors – nonmetal mineral products, transportation, and metals smelting - are lowered by 2-5%, and this leads to a reduction in the demand for electricity and coal. Electricity use falls by 2.3% even though the price only rose by 0.9%. Coal use falls by 2.2% even as its price falls a little. Inputs released from these sectors go to the cleaner industries leading to an expansion in finance, food products, apparel by about 0.5-1%. (The ability to trace these indirect effects comes from using our input-output general equilibrium framework. The alternative method of using "partial equilibrium" analysis only captures the direct effects.)

Aggregate GDP falls by 0.03% and this tiny reduction comes from the assumptions of full employment and labor mobility. Workers and other inputs are assumed to immediately find employment in the expanding sectors. A more sophisticated economic model with adjustment costs, where it takes some time to reallocate the inputs that are released, will cause aggregate output to fall by a greater amount during the transition years. However, in the longer run, after the economy adjusts, our model will give the appropriate GDP effects.[20]

These changes lead to a reduction in total particulate emissions of 3.3%, with the medium height group of manufacturing industries (including cement and metals smelting) having the biggest reduction, 3.6%, while low height emissions only fall 1.5%. This pattern arises because total emissions includes both combustion and process types, and the latter is dominated by cement emissions. Counting only combustion emissions, they fall by 2.7%. The effect of these reductions is to lower the urban concentration of PM by 3.0%. This is a bit less than the fall in

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[19] This somewhat surprising pattern is due to the high estimated combustion emissions from space heating in the service sectors in our base year 1997, as discussed in HJ. These emissions are assumed to be low height, i.e., highly damaging emissions.

[20] Why does GDP fall when all labor and capital remain fully employed? Real GDP is defined as an aggregate over "final demand" commodities, i.e. over goods that make up consumption, invesment, government and exports. The

total emissions because of the small reduction in low height PM that contributes the most to concentration (the highest γ_{cx}). Similarly, while total SO2 emissions fall by 2.3%, its concentration is only reduced by 1.7% because of the relatively smaller reduction in low height emissions. The changes in relative industry outputs is also the cause of seeing PM emissions fall by more than coal use, 3.3% vs. 2.2%.

The change in PM concentration gives a reduction in *marginal* health effects of the same 3.0%, which translates into a 4.3% reduction in total health damages (due to the threshold assumption in eq. 7). That is, there is a fall of 4.3% in estimated excess deaths, cases of chronic bronchitis, etc. The value of this reduction in damages in the first year comes to about 0.17% of GDP of that year. This is a very modest reduction compared to the total estimated health damages of 3.9% of GDP (last row of Table 2)[21].

The revenue raised from this broad based tax is substantial, some 13.2% of total revenues in year one. This allows a reduction in value-added and capital income taxes of 11.9%. This tax cut eventually leads to higher retained earnings and hence investment. The higher rate of investment leads to a higher stock of capital and a greater productive capacity for the whole economy. As shown in the column marked "20th year" in Table 3, GDP is 0.15% higher than the base case by the twentieth year. The lower taxes and higher GDP allowed investment to be 0.6% higher while consumption is reduced by only 0.09%. The lower consumption is due to the higher goods prices and the assumption that the tax cut goes entirely to enterprises instead of households.

With this higher level of counterfactual economic activity more emissions are generated and the reduction in emissions and damages due to the externality tax becomes smaller. By the 20th year, the reduction in damages compared to the base case is only 1.59% compared to 4.33% in the first year. As described in section 3 above the base case assumptions lead to a high productivity growth rate, i.e. inputs, in particular fuels, per unit output is falling rapidly. In addition, emissions per unit fuel are falling. These two trends led to a sharp reduction in emissions per unit output (see Fig. 1), that is, a sharp reduction in marginal damages. The lower

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aggregation procedure uses both values and prices of these commodities. Given a particular set of prices, two baskets of goods made by the same number of workers will have a different aggregate value.

[21] This is about 300 billion yuan and correspond to that reported in HJ, Table 9. This calculation uses total emissions in determining concentration (eq. 6), giving equal weight to process and combustion emissions. If the observed concentration is attributed entirely to combustion emissions only, then the marginal damage estimates and tax rates would be roughly doubled.

MD_{jt}^{O}'s lead to a lower tax, and hence smaller adjustments in the future economy and smaller reductions in health damages. The value of this damage reduction as a share of GDP falls even more since the higher GDP per capita means higher future valuations in the counterfactual case.

The emissions of the greenhouse gas carbon dioxide is related to the local pollutants. In the first year carbon emissions from fossil fuels fall by 1.98%, a little less than the fall in coal use since there is some switching towards oil and gas. This is a relatively inefficient policy to reduce emissions of either carbon or PM, and we shall consider another policy below.

4.2 Sensitivity analysis of output taxes

Role of non-combustion emissions

To test the implications of assuming that combustion and process emissions are equally damaging, we repeated the exercise setting the pollution tax according to eq. 15b., i.e. according to the marginal damages in HJ Table 10. This is essentially a big tax on nonmetal mineral products and a moderate tax on transportation, services and metals smelting. The results are reported in Table 5. There are some big differences compared to the combustion-only case. The huge tax on cement raise the price of investment goods substantially, and the higher marginal damages (MD^{O}) means higher overall pollution revenue and tax cuts. The result is a fall in initial real investment of 1.3%, and a rise in consumption of 0.47%. Again the reduction in the output of the dirty sectors lead to a reduction in the use of coal and electricity. PM emissions fall by 12.3% in the first year which lowers the ambient concentration by 11.2%. This reduces total health damages by a large 15.9% compared to the 4.3% in the combustion-only case. The large initial reduction in investment lead to a smaller capital stock and GDP for many years in this scenario despite the lower capital income taxes. GDP does not catch up to base case levels until after the 30th year in this case with such a large distortion of goods prices.

Using intake fractions estimated for individual industries

The marginal damages used in the above counterfactual simulations are based on the simple approximations in the Lvovsky-Hughes method reported in HJ Table 11. The LH method treat all of manufacturing symmetrically and put a very small weight on emissions from the power sector. In the next exercise we employ the marginal damage rates based on the *iF* calculations given in HJ Table 13. That is, the $MD_j^{O,C}$'s in eq. 15a are replaced by the estimates based on the dispersion and damage calculations in HUCE (2002) for chemicals, nonmetal mineral products, metals smelting, electricity, and transportation. We consider the combustion emissions only case, and use the simple approximation for damages in the "extended range" damage as twice the 50km. range. While we use different tax rates in this exercise, for simplicity, the concentration and total damage calculations are still based on the LH formulas in eqs. 6 and 7.

Comparing the marginal damages per unit output in HJ Table 11 with HJ Table 13 we see that in the *iF* case, the taxes will be much smaller on chemicals, cement and metals smelting but much larger for transportation and a bit larger for electricity. On average they are a little lower than those imposed in the LH counterfactual. The results are reported in Tables 3 and 4 in the columns marked "iF Method" for comparison with the adjacent "LH Method".

The effects of this set of pollution taxes are easily explained given our discussion of the LH results. The industry pattern of price changes in the initial year are identical to the LH case but different in magnitude. The output of nonmetal mineral products and metals smelting also falls, but since they are taxed less in this case they suffer a smaller reduction in output. On the other hand the price of electricity and transportation rise more and suffer a bigger reduction in output (Table 4). Transportation falls by 5.65% in this *iF* case where it is taxed at 7.5% compared to a fall of 3.75% when taxed at 4.6% in the LH case. The other sectors are affected in the same direction but to a smaller extent.

These changes lead to a rise in the price of construction which is smaller than the LH case and thus the price of investment is affected less. This leads, at the aggregate level, to a rise in investment of 0.22% and a fall in consumption of 0.14% compared to the negligible changes earlier. That is, the tax cuts in the *iF* case give a boost to investment spending that exceeds the increase in prices of investment goods. The price of consumption goods rise on average and this lowers real household consumption in the initial year.

The changes in output composition lead to a fall in total PM emissions of 1.56% in the first year, with a large reduction in low height emissions and small reduction in medium height emissions from manufacturing sources. These changes deliver a 1.48% reduction in ambient PM concentration. Health damages fall by 2.15% in this *iF* case compared to 4.33% in the LH method. These are not exactly parallel since much of the reductions in the LH case comes from the cement sector which is classified as medium height and produce only moderate health damage. The bigger reductions in low height emissions in the *iF* simulation results in bigger reductions in health damage for each unit reduction in total emissions.

The pollution tax revenue is bit smaller initially, 11.4% of total government revenues instead of 13.2% earlier. But because of the smaller increase in investment goods prices real investment is higher in this *iF* case and over time GDP growth is faster. Real consumption is lower initially because of the higher prices but over time as GDP rises faster the consumption gap closes as the economy produces more of everything. This includes producing more pollution. There was a large fall in PM emissions over time in the LH case, but in the *iF* case the future reduction is much smaller due to the higher GDP growth rate.

The lesson from this sensitivity analysis is not that our intake fraction estimates are good, but that it is very important to get sector specific estimates of the damages when considering national policies. A different attribution of the total damages result in different policy instruments, in this case tax rates, which have different sector and aggregate effects.

4.3 Effects of taxes on fuels based on damages

Emissions is a function of output levels, fuel choice, energy efficiency and control strategies. We now consider a more sharply targeted air pollution control policy, a tax on fossil fuels in proportion to the health damage caused as a result of using current technologies. A counterfactual simulation is run with taxes set according to the average marginal damages of the fuels (AMD_{ft}) as described in eq. 17. As we have discussed above, the damage rate for coal is very high and a full tax equal to the estimated AMD_{ft} will be almost 100%, something that is neither realistic nor well analyzed by our methodology.

We therefore begin at a relatively modest level, taxing coal, oil and gas at a rate equal to 20% of their estimated health damage, i.e. $\lambda = 0.2$ in eq. 17. Given the high values of the marginal damage (HJ Table 12), this would produce a 19% tax rate on the price of coal. The effects of these taxes on the economy and pollution are shown in Tables 6 and 7. These results are quite different from the previous output tax policy experiments.

The heavy tax on coal reduce its use by 14% initially, while the moderate tax on oil reduces the refining output by 1.1%. The heavy users of these fuels have to raise their output prices to compensate and that causes a reduction in demand for these goods. Electricity price rise by 2.5% and its output fall by 2.8%. Metals smelting and nonmetal mineral products are other big coal users and their output fall by 0.8 and 0.6% respectively. The reduction in output of these sectors is much smaller than the reduction in coal input because the production functions that we employed allows an easy substitution among inputs. (See Appendix F, eq. F3). Resources released from these shrinking energy intensive sectors go to the clean ones such as finance, commerce and food.

The total additional tax burden is relatively small, pollution tax revenue comes to only 2.75% of total revenue and the offsetting tax cuts for VAT and capital income correspondingly small. The small additional retained earnings of enterprises allow aggregate investment to rise by 0.07% in the first year. This is accompanied by a fall in real consumption of 0.07% as households face mostly higher goods prices. The changes in composition of aggregate output leads GDP to fall by small 0.04% (see footnote 20 about measuring real GDP).

These changes in consumption patterns reduce total PM emissions by 6.2%, with high height emissions from electricity falling the most, 13.0%, and medium height the least, 4.0%. This reduce the base case concentration of PM by 6.1%, which leads to a reduction in total health damages of 8.8%. Since only the three fossil fuels are taxed, the pollution tax revenue is only 2.75% of total government revenue in year one. This is in contrast to the 13.2% collected in the output tax policy which taxes all commodities. However, the output tax (combustion only) case only generated a 4.3% reduction in health damages.

That is, a narrowly based, but well targeted, tax that raises only a modest amount of revenue leads to a sizable reduction of pollution and related health damages. This large estimated effect is due in part to our characterization of technology with high elasticities of substitution as we have mentioned. That is, substitution of one fuel for another, and substitution between energy and capital, labor and nonenergy intermediate inputs. While this may be regarded as overly optimistic in the short run, it is reasonable to think that this level of fuel substitution could be achieved over time. As we can see from the results for the 20th year, the long run reductions in health damages are even bigger.

The pattern of emission reduction here is quite different from that of the output tax policy. Here low height (i.e. high damage) emissions are cut much more than the medium height emissions relative to the output tax cases. This is because all sectors can reduce coal use and reduce combustion emissions. In the output tax case we see only a shift in demand from dirty to cleaner inputs, those cleaner sectors still use fuels in a manner similar to the base case usage since the taxes on fuels are not particularly high (burning coal is polluting, but coal mining is not particularly so). Another reason is that the household sector is also hit by the fuel tax whereas they are not directly affected by the output tax. This sector is an important source of low height emissions (HJ Table 2). In addition, the process emissions from the cement sector is not reduced substantially by this fuel tax and thus total medium height emissions is cut by only 4.0% compared to 11.5% for low height emissions. High height emissions from Electricity is cut by a large amount, 13.0%, due to the direct effect of higher coal prices and the indirect effect of reduced demand for expensive electricity.

The patterns over time is very different from the product tax case, here the reduction in emissions and damages rise over time as shown in Figure 3, and comparing the "20th year" column with the "1st year" in Table 6. By the 20th year even though GDP is 0.04% higher than the base case, the reduction in total PM emissions is 7.4%, greater than the 6.2% reduction in the first year when GDP fell. Correspondingly, concentration of PM is 8.3% lower by year 20, greater than the initial fall of 6.1%. The value of health damages, given by concentration and urban population, falls even more, by the 20th year the reduction is 13.3%.

The main cause of this time path is the assumed changes in technology. We have rapid technical progress which lead to much higher output using the same inputs, hence lower marginal damage per unit output over time. For the fuel tax case, the emission per unit fuel is assumed to fall but at a more modest rate than the assumed rate of technical change. While emissions per unit fuel is falling, the urban population exposed to pollution is rising rapidly and so the value of the marginal damages per unit fuel is rising after the first few years. This means that the pollution tax is raised over time and induce more fuel switching and conservation. However, since the economy is growing even faster, the total pollution tax revenue is falling as a share of all tax revenue.

Considering the emissions of the coincident global pollutant, carbon dioxide, we see that the reduction in carbon emissions is smaller than the fall in coal use due to the switch to the lower taxed fuels, oil and gas. In the first year when coal falls by 13.8% carbon falls only by 11.1%. Over time as the tax rises, the carbon share from oil rises even more, the reduction in year 20 of carbon is only 10.3% while coal use falls 15.1%. While one may see this as an inefficient instrument to reduce carbon, it is actually a very good second best instrument even if one ignores the very important health benefits. In our view we should see these substantial reductions in carbon emissions as an important side benefit, to China and the world, of dealing with the urgent issue of local air quality and public health.

4.4 Sensitivity Analysis

Effect of Nonlinearities

To examine the nonlinearities in the system we compare the above results to the effects of a higher fuel tax, equal to 30% of estimated marginal damage per unit fuel, i.e. $\lambda = 0.3$. The results are also reported in Tables 6 and 7 in columns marked "30%". As one can see, the changes are less than one and a half times those estimated for the $\lambda = 0.2$ case. Concentration in the first year is down 8.7% compared to 6.1% in the low tax case. Damages are reduced by 12.4% compared to 8.8%. The effect of sector prices are close to linear but the quantities change by less. Coal output is 19.3% lower with a 30% tax compared to being 13.8% lower with a 20% tax. The higher tax revenues allow a greater cut in existing taxes and hence a higher rate of investment.

One has to exercise caution in evaluating the relative merits of these two tax rates. While the higher rate delivers more pollution reduction and more investment, consumption is lower for many periods. Furthermore, the short run adjustment costs that we have ignored could be more than proportionally higher in the high tax case. The point of our exercise here is to show the value of using an explicit general equilibrium analysis to estimate the costs and benefits in contrast to partial equilibrium calculations that are often based on linearizations.

Effects of different dose-response coefficients and valuations

In Ho and Jorgenson (2003a) we have discussed how the unit damages depend on the parameter values for the dose-response and health end-point valuations (HJ section 5, Table 15). When we use the low end of the range of estimates for DR_{hx} and V_h the damages are about a third of those using the central values. Here we examine how varying these two important parameters affect our analysis of pollution tax effects.

A new base case simulation is first run using the low end values of dose-response and health valuations given in HJ Table 8. This have the same GDP and emissions as the original base case reported in Table 2, but the estimated health effects are 55% of the central case, and damage values are 29%. We then repeated the fuel tax experiment where a tax equal to 20% of estimated marginal damages is placed on coal, oil and gas. Since these damages are only 29% of the central estimates, the taxes now are correspondingly lower. We compare the counterfactual tax results with the new base case and the differences between the two are given in Table 8 in the columns marked "low end parameters." For comparison, the earlier results in Table 6 are reproduced in the "central parameters" column.[22]

As a result of the much lower taxes, coal use falls by only 4.4% compared to 13.8% in the central case. Electricity, the big user of coal, falls by 0.86% compared to 2.80%. That is, the changes are about 30% of the central case. Emissions and concentration effects are also about 30%. The value of health damages is reduced by 2.9% with this low fuel tax which adds less than 1% to total government revenues. The changes in consumption, investment and aggregate GDP are in the same direction as the central case, the tax cuts allow a higher investment which leads to a higher future GDP. Consumption is reduced in the earlier years but also catch up when the GDP expands faster. Consumption is lower by 0.02% in the first year in this case compared to a 0.07% reduction in the central case.

To summarize these results, using the central values of these parameters, a fuel tax amounting to less than 3% of revenues may be expected to deliver a reduction in health damages of 8.8%, and at the same time reduce consumption quite trivially. If one wishes to be conservative and use the low end values of the dose-response and health valuations, then a fuel tax amounting to less than 1% of revenues may be expected to deliver a reduction in health damages of 2.9% and reduce consumption trivially. In other words, the ratio of benefits to revenues are both about 3, and the ratio of benefits to long-run GDP or consumption foregone is large.

4.5 Comparisons to earlier estimates

The results here are somewhat different from those reported in Ho, Jorgenson and Di (2002), and in the simpler analysis in HUCE (2002, Chapter 8). In this version we have used the more recent estimates of non-industrial emissions which are much lower than those reported for

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[22] Given the small role of oil compared to coal, this experiment is similar to the test of nonlinearities above. In this case, lowering the estimates of *AMD*'s in eq. 8.18 is very similar, though not identical, to lowering λ.

1997. This means a lower estimate of the marginal damages of the service and household sectors. Another major change is the separation of total emissions into urban and non-urban sources. Since the urban ratio for the 33 industries are different, the different output response to the taxes mean some changes in the urban emissions relative to total emissions.

5 Discussion of policy choices

We have only considered two national policies here. These are chosen because they rely on market instruments that are likely to be more efficient and relatively easy to apply compared to technology regulations or industrial policies. A few lessons stand out even from this brief analysis.

First, the benefit of reducing air pollution likely far exceeds the consumption foregone. While we have not modeled the short run adjustment costs these may be mitigated by phasing in the taxes gradually.

Secondly, the conclusion that long run net benefits are positive is robust to many of the uncertainties in the parameters underlying this, and other similar, analysis. It is certainly desirable to have bigger samples and wider coverage to sharpen the estimates, in particular the relative damages by the various sectors. But the overall conclusion that coal use be discouraged remains valid.

Thirdly, there may be tradeoffs between effectiveness of an instrument and the ease of implementing it. A broad based tax may be easier to gain acceptance since the pain is shared by many, but is not very effective. A narrow tax targeted at the main polluters or fuels is more efficient but requires a large adjustment on their part. One may try to encourage or require the removal of dust and SO2 (which form secondary particles) from the existing level of fuel use, however, the reduction of coal use is an important part of a pollution policy package. This might require the closure of some coal producers. The transition cost of making this happen -- the costs of relocating miners, the cost of replacing coal stoves with gas stoves, etc. -- should be an urgent topic of research.

Fourthly, the use of pollution tax instruments may deliver sizable new revenues to the government. This should ease the reform of public finances in China.

6. Conclusions

We have analyzed the use of corrective fees for controlling pollution externalities in China using relatively simple instruments and model. Nevertheless, we believe our analysis have some useful lessons. First, the long run benefits of applying externality taxes on pollution are much larger than the costs. If one believes that the short run adjustment costs that we have not considered are large then the way to proceed is to ease adjustment costs by imposing the corrective taxes gradually. Secondly, this high benefit-cost ratio estimate is robust to the many uncertainties underlying the effort to estimate health damage due to air pollution. That is, even if one is concerned about the large range of uncertainty surrounding the health damage valuation estimates, a conservative approach would still recommend imposing pollution charges but perhaps at a lower level. Third, the revenue from some externality taxes could be substantial, this may be an opportunity to move towards a more efficient tax system.

A more complete analysis of the effects of pollution fees would try to estimate the cost functions for reducing particulate and sulfur 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 which are also a function of the effort to reduce them. A specification of the costs of these efforts would be the next step in refining policy choices.

An important factor determining welfare costs of policy changes is the substitution elasticities. This ability to substitute capital for energy is highlighted in our methodology where it is set explicitly for each industry. A less substitutable technology means higher costs. It is thus important for analysis of energy and environmental policies, not just our study here, to have good estimates of these elasticities for the various sectors. Making these estimates requires a time series of input and output data. An example of this work for the U.S. is Jorgenson et. al. (2000). An important item on our research agenda is thus the construction of these industry-level data and the econometric estimation of the elasticities.

Turning to the environmental aspects of our methodology, the contrast in the results using damages estimated from the LH method, which treat all the manufacturing sectors symmetrically, and those from the intake fraction method, highlight the need for obtaining human exposure estimates based on detailed individual sector data. The estimates of *iF*'s in

HUCE (2002, Chapters 4-6) that we use in here were based on a sample of actual locations and local conditions. A wider sample for these highly polluting sectors, and including more sectors in the detailed analysis would improve the precision of such estimates.

As we have briefly alluded to in section 2, many recent studies ask if the traditional policy of setting taxes equal to the marginal damage, the Pigovian tax, is appropriate in a complex world with many pre-existing tax distortions. This question has to be answered in an explicit framework, i.e., in a clearly specified economic model like the one used here with an explicit welfare function. This approach requires a well specified welfare function that includes both the usual goods and health effects. Such an extension to the existing model is on our research agenda.

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Table 1 Dose-Response and Valuation Estimates for PM-10 and SO_2

	Health Effect	**Cases per 1 mil. people for a 1 $\mu g/m^3$ 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 2 Selected Variables from Base Case Simulation, years 1,10 and 30.

Variable	1997	2006	2026	30-year growth
Population (mil.)	1,230	1,318	1,464	0.58%
Urban population (mil.)	368	432	568	1.46%
GDP (bil. 1997 *yuan*)	7,630	15,000	33,500	5.06%
Energy Use (fossil fuels, mil. tons sce)	1,340	2,220	3,590	3.34%
Coal Use (mil. tons)	1,390	2,090	2,750	2.30%
Oil Use (mil. tons)	210	440	960	5.16%
Carbon Emissions (mil. tons)	900	1,460	2,260	3.12%
Particulate Emissions (mil. tons)	24.23	17.00	15.69	-1.44%
From High Height Sources	4.25	3.10	3.57	-0.58%
From Medium Height Sources	17.94	11.66	9.07	-2.25%
From Low Height Sources	2.04	2.24	3.06	1.35%
Urban Combustion PM (mil. tons)	7.17	5.20	4.95	-1.23%
SO_2 Emissions (mil. tons)	19.98	25.76	34.59	1.85%
Concentration of urban PM ($\mu g/m^3$)	168	133	135	-0.73%
Premature Deaths (1,000)	250	205	277	0.35%
Health Damage/GDP	3.8%	2.9%	3.6%	

Table 3 Effects of an output tax based on damages (combustion emissions only), full tax (λ =1).

Variable	LH Method Effect in 1st Year	LH Method Effect in 20th Year	iF Method Effect in 1st Year	iF Method Effect in 20th Year
GDP	-0.03%	+0.15%	-0.02%	+0.27%
Consumption	-0.01%	-0.09%	-0.14%	-0.08%
Investment	0.00%	+0.62%	+0.22%	+0.86%
Coal use	-2.22%	-0.71%	-1.65%	-1.53%
Carbon emissions	-1.98%	-0.44%	-1.51%	-1.10%
Particulate Emissions (total)	-3.33%	-0.97%	-1.56%	-1.48%
High Height Sources	-3.20%	-0.97%	-3.27%	-3.07%
Medium Height Sources	-3.58%	-0.94%	-1.10%	-0.83%
Low Height Sources	-1.47%	-1.10%	-2.00%	-1.99%
PM emissions (combustion)	-2.72%	-0.91%	-1.94%	-1.93%
Particulate Concentration	-3.03%	-1.06%	-1.48%	-1.51%
SO2 Emissions	-2.30%	-0.79%	-1.93%	-1.95%
SO_2 Concentration	-1.70%	-0.84%	-1.59%	-1.54%
Premature Deaths	-4.34%	-1.78%	-2.13%	-2.50%
Value of Health Damages	-4.33%	-1.59%	-2.15%	-2.23%
Change in other tax rates	-11.9%	-7.4%	-10.0%	-9.8%
Reduction in Damages/GDP	0.17%	0.05%	0.08%	0.07%
Pollution tax/Total tax revenue	13.2%	7.3%	11.4%	9.6%

Notes: The entries are % changes between the counterfactual tax case and the base case. The last two rows are % shares. In the counterfactual case a tax proportional to the marginal damage per yuan of output, given by eq. (15a), is applied.

Table 4 Sector Effects of an output tax based on damages (combustion emissions only), % change year 1.

		LH Method		iF Method	
	Sector	**Price**	**Quantity**	**Price**	**Quantity**
1	Agriculture	-0.11	0.22	-0.05	0.14
2	Coal mining and processing	-0.31	-2.17	-0.15	-1.61
3	Crude petroleum mining	-0.83	-0.39	-0.71	-0.41
4	Natural Gas Mining	-0.73	-0.33	-0.43	0.07
5	Metal ore mining	-0.28	-1.11	-0.07	-0.4
6	Non-ferrous mineral mining	-0.40	-1.25	-0.26	-0.47
7	Food products, tobacco	-0.68	0.81	-0.47	0.54
8	Textile goods	-0.43	0.16	-0.27	0.1
9	Apparel, leather	-0.57	0.52	-0.43	0.38
10	Sawmills and furniture	0.04	-0.48	0.14	-0.64
11	Paper products, printing	0.06	-1.25	0.21	-1.04
12	Petroleum refining & coking	-0.80	-0.99	-0.65	-1.22
13	Chemical	-0.08	-0.75	-0.32	-0.01
14	Nonmetal mineral products	3.44	-4.56	0.86	-1.39
15	Metals smelting & pressing	0.76	-1.9	0.1	-0.59
16	Metal products	-0.01	-0.54	-0.11	-0.21
17	Machinery and equipment	-0.15	-0.05	-0.16	0.02
18	Transport equipment	-0.31	-0.06	-0.33	-0.27
19	Electrical machinery	-0.13	-0.2	-0.24	-0.05
20	Electronic & telecom. equip	-0.32	0.07	-0.33	0.15
21	Instruments	-0.26	-0.46	-0.25	-0.31
22	Other manufacturing	-0.07	-0.88	0.01	-0.61
23	Electricity, steam, hot water	0.92	-2.31	1.63	-2.41
24	Gas production and supply	0.96	-1.71	1.13	-1.85
25	Construction	1.43	-0.76	0.8	-0.29
26	Transport & warehousing	2.62	-3.75	4.86	-5.65
27	Post & telecommunication	-0.31	-0.25	-0.19	-0.23
28	Commerce & Restaurants	-1.06	0.52	-0.69	0.33
29	Finance and insurance	-1.64	1.06	-1.22	0.76
30	Real estate	0.99	-1.03	0.92	-0.98
31	Social services	1.98	-2.4	2.14	-2.5
32	Health, Educ., other services	4.05	-2.6	4.11	-2.6
33	Public administration	2.09	0.76	2.24	0.73

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

Table 5 Effects of an output tax based on damages (process and combustion emissions), full tax (λ =1).

Variable	**Effect in 1^{st} Year**	**Effect in 20^{th} Year**
GDP	-0.27%	-0.14%
Consumption	+0.47%	-0.19%
Investment	-1.32%	+0.35%
Coal use	-5.46%	-2.07%
Carbon emissions	-4.75%	-1.50%
Particulate Emissions (total)	-12.3%	-4.4%
High Height Sources	-4.8%	-1.7%
Medium Height Sources	-15.3%	-6.1%
Low Height Sources	-1.0%	-1.3%
PM emissions (combustion)	-7.2%	-2.5%
Particulate Concentration	-11.2%	-3.7%
SO2 Emissions	-4.9%	-1.9%
SO_2 Concentration	-3.1%	-1.6%
Premature Deaths	-15.9%	-6.0%
Value of Health Damages	-15.9%	-5.8%
Change in other tax rates	-23.3%	-10.8%
Reduction in Damages/GDP	0.61%	0.19%
Pollution tax/Total tax revenue	24.2%	10.5%

Notes: The entries are % changes between the counterfactual tax case and the base case. The last two rows are % shares. In the counterfactual case a tax proportional to the marginal damage per yuan of output, given by eq. (15b), is applied.

Table 6 Effects of a fuel tax based on damages

	Effect in 1st Year with:		Effect in 20th Year with:	
Variable	**tax rate = 20% of damages**	**tax rate = 30% of damages**	**tax rate = 20% of damages**	**tax rate = 30% of damages**
GDP	-0.04%	-0.07%	+0.04%	+0.04%
Consumption	-0.07%	-0.11%	-0.01%	-0.04%
Investment	+0.07%	+0.07%	+0.15%	+0.20%
Coal use	-13.8%	-15.1%	-19.2%	-21.1%
Carbon emissions	-11.1%	-15.6%	-10.3%	-14.4%
Particulate Emissions	-6.2%	-8.8%	-7.4%	-10.4%
High Height Sources	-13.0%	-18.2%	-13.5%	-18.8%
Medium Height Sources	-4.0%	-5.7%	-4.1%	-5.7%
Low Height Sources	-11.5%	-16.1%	-12.6%	-17.7%
PM emissions (combustion)	-12.1%	-16.9%	-13.3%	-18.7%
Particulate Concentration	-6.1%	-8.7%	-8.3%	-11.7%
SO2 Emissions	-10.7%	-15.0%	-11.6%	-16.2%
SO_2 Concentration	-9.4%	-13.1%	-10.0%	-13.9%
Premature Deaths	-8.8%	-12.3%	-13.4%	-18.8%
Value of Health Damages	-8.8%	-12.4%	-13.3%	-18.7%
Change in other tax rates	-2.8%	-3.9%	-1.6%	-2.3%
Reduction in Damages/GDP	0.34%	0.48%	0.43%	0.60%
Pollution tax/Total tax revenue	2.75%	3.83%	1.54%	2.15%

Notes: The entries are % changes between the counterfactual tax case and the base case. The last two rows are % shares. The columns marked “20%” correspond to having $\lambda = 0.2$ in eq. 8.18, while “30%” correspond to $\lambda = 0.3$.

Table 7 Sector Effects of an fuel tax based on damages, % change year 1

		tax=20%damages		tax=30%damages	
	Sector	**Price**	**Quantity**	**Price**	**Quantity**
1	Agriculture	0.08	0.06	0.12	0.08
2	Coal mining and processing	14.84	-13.82	22.16	-19.33
3	Crude petroleum mining	0.05	-0.41	0.08	-0.61
4	Natural Gas Mining	0.24	-0.13	0.35	-0.21
5	Metal ore mining	0.37	-0.4	0.54	-0.59
6	Non-ferrous mineral mining	0.27	-0.87	0.41	-1.24
7	Food products, tobacco	-0.05	0.2	-0.05	0.27
8	Textile goods	0.06	0.09	0.1	0.1
9	Apparel, leather	0.02	0.05	0.04	0.06
10	Sawmills and furniture	0.15	-0.01	0.23	-0.04
11	Paper products, printing	0.18	-0.06	0.28	-0.1
12	Petroleum refining & coking	0.9	-1.07	1.34	-1.58
13	Chemical	0.35	-0.35	0.53	-0.52
14	Nonmetal mineral products	0.8	-0.59	1.17	-0.88
15	Metals smelting & pressing	0.52	-0.81	0.77	-1.17
16	Metal products	0.29	-0.31	0.43	-0.46
17	Machinery and equipment	0.21	-0.21	0.31	-0.32
18	Transport equipment	0.19	-0.05	0.28	-0.09
19	Electrical machinery	0.19	-0.24	0.28	-0.36
20	Electronic & telecom. equip	0.09	0.02	0.14	0.01
21	Instruments	0.12	-0.16	0.18	-0.25
22	Other manufacturing	0.19	-0.35	0.28	-0.5
23	Electricity, steam, hot water	2.51	-2.8	3.66	-4.02
24	Gas production and supply	2.64	-2.86	3.85	-4.13
25	Construction	0.3	-0.01	0.45	-0.04
26	Transport & warehousing	0.14	-0.19	0.21	-0.28
27	Post & telecommunication	0.07	-0.08	0.12	-0.13
28	Commerce & Restaurants	-0.3	0.32	-0.41	0.44
29	Finance and insurance	-0.38	0.4	-0.52	0.55
30	Real estate	0.17	-0.06	0.25	-0.1
31	Social services	0.13	-0.09	0.2	-0.14
32	Health, Educ., other services	0.24	-0.18	0.35	-0.26
33	Public administration	0.17	0.03	0.25	0.04

Note: This is the % change in output prices (purchaser's price) and quantities in the first year due to a tax on fossil fuels. Two simulations are reported, one where the tax is 20% of the marginal damage of a unit of fuel, and other is 30%.

Table 8 Sensitivity analysis of varying Dose-response and Health Valuation parameters.
Effects of a fuel tax equal to 20% of marginal damages, central vs. low-end parameters.

	Central parameters		**Low-end parameters**	
Variable	**1st year effects**	**20th year effects**	**1st year effects**	**20th year effects**
GDP	-0.04%	+0.04%	-0.00%	+0.02%
Consumption	-0.07%	-0.01%	-0.02%	+0.01%
Investment	+0.07%	+0.15%	+0.03%	+0.06%
Coal use	-13.8%	-19.2%	-4.4%	-4.9%
Carbon emissions	-11.1%	-10.3%	-3.6%	-3.4%
Particulate Emissions	-6.2%	-7.4%	-2.0%	-2.4%
High Height Sources	-13.0%	-13.5%	-4.1%	-4.4%
Medium Height Sources	-4.0%	-4.1%	-1.3%	-1.3%
Low Height Sources	-11.5%	-12.6%	-3.7%	-4.1%
PM emissions (combustion)	-12.1%	-13.3%	-3.8%	-4.3%
Particulate Concentration	-6.1%	-8.3%	-1.9%	-2.6%
SO2 Emissions	-10.7%	-11.6%	-3.3%	-3.7%
SO_2 Concentration	-9.4%	-10.0%	-3.1%	-3.2%
Premature Deaths	-8.8%	-13.4%	-2.8%	-4.3%
Value of Health Damages	-8.8%	-13.3%	-2.9%	-4.3%
Change in other tax rates	-2.8%	-1.6%	-0.9%	-0.5%
Reduction in Damages/GDP	0.34%	0.43%	0.03%	0.04%
Pollution tax/Total tax revenue	2.75%	1.54%	0.88%	0.50%

Notes: The entries are % changes between the counterfactual tax case and the base case.
The last two rows are % shares. The "central" and "low-end" parameter values for dose-response and health valuations are given in Table 8 of Ho and Jorgenson (2003a).

Figure 1: GDP, Energy and Emissions Projected in Base Case

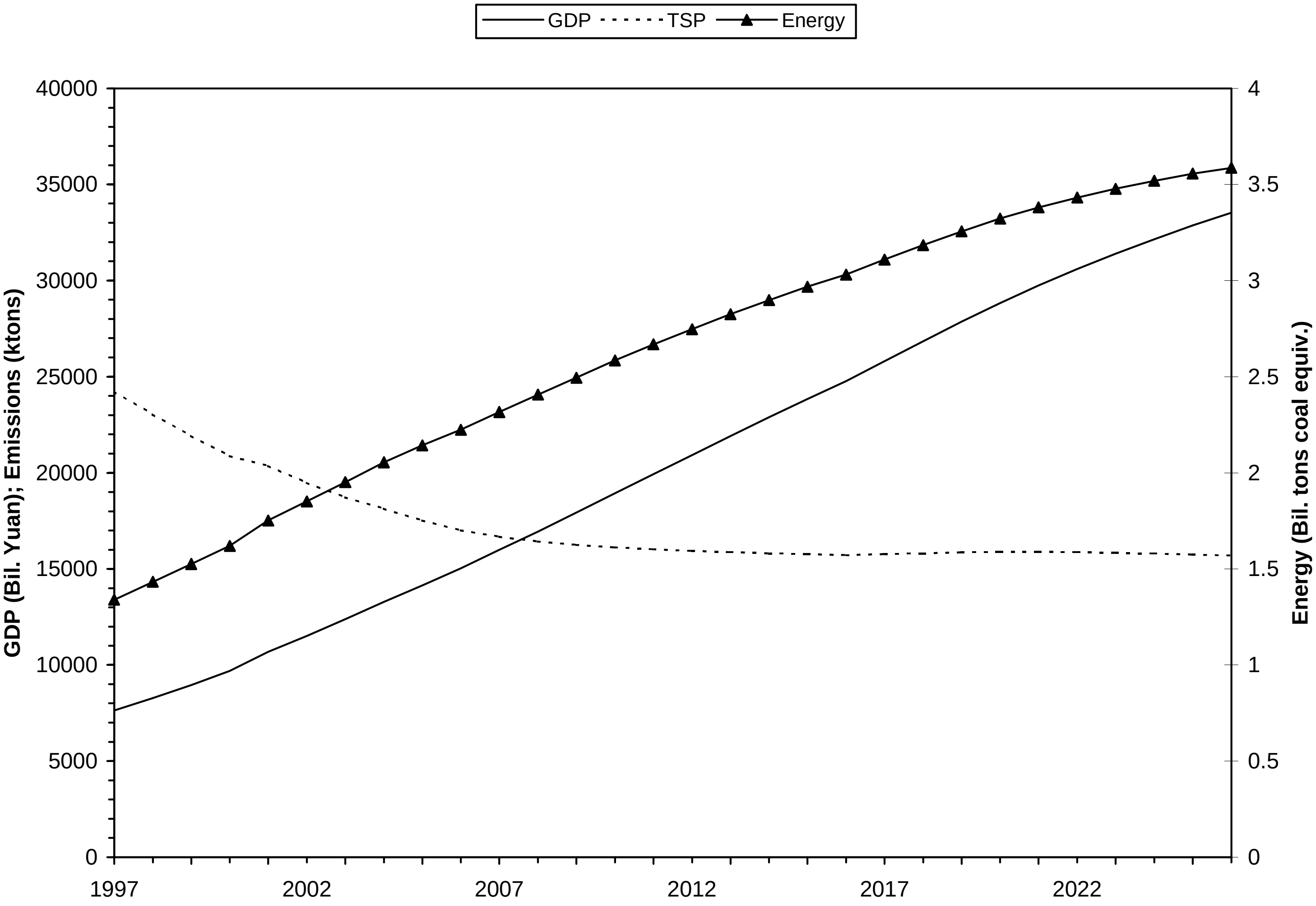

Figure 2: Change in Emissions and Concentrations due to a pollution tax on output

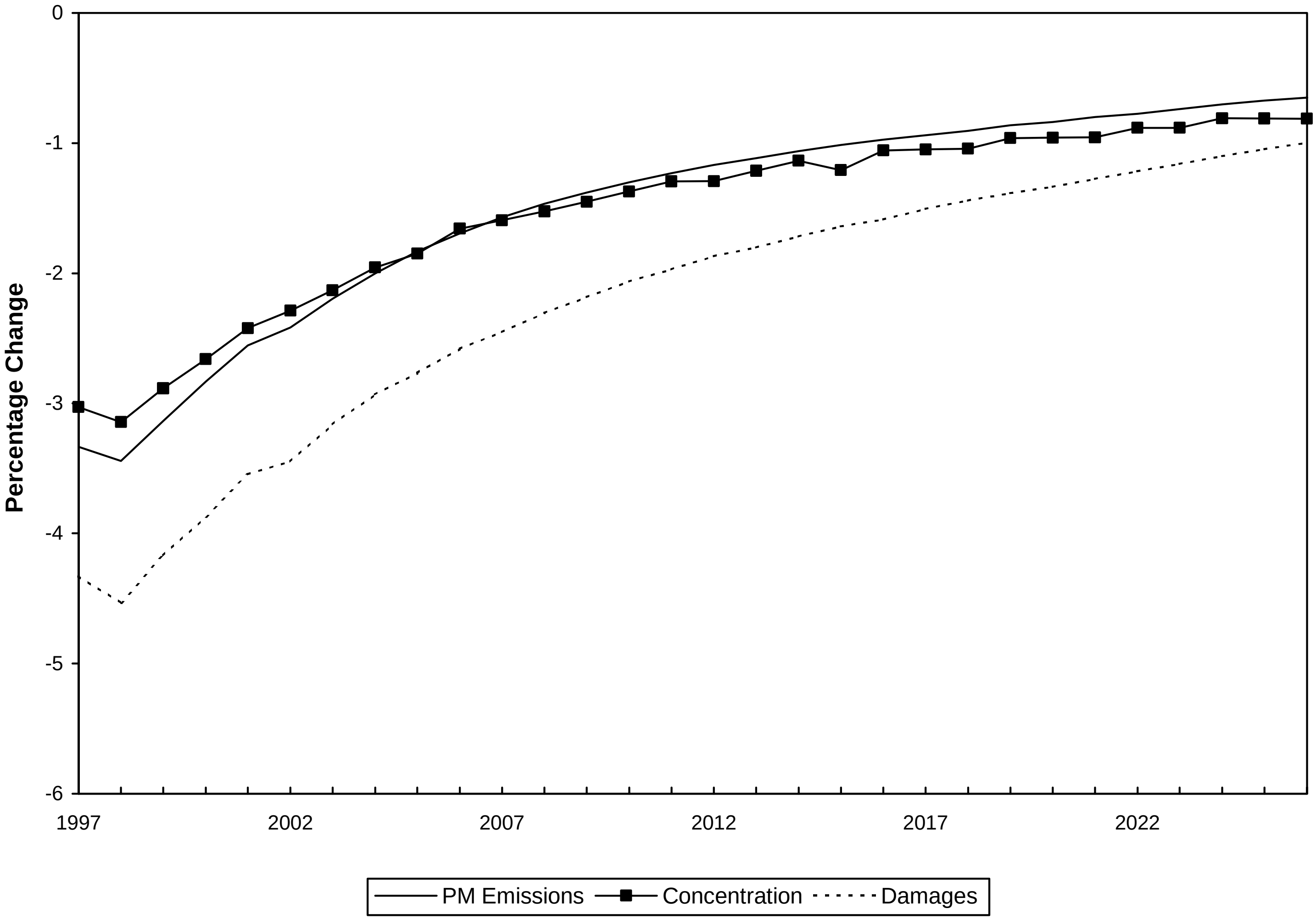

Figure 3: Change in PM Emissions and Concentrations due to a pollution tax on fuels