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Modeling the Health Benefits of Carbon Emissions Reductions in China[1]

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ABSTRACT

Air pollution from the use of fossil fuel has been recognized to be a cause of serious health problems in China. The use of fossil fuel also produces carbon dioxide, a greenhouse gas thought to be a major contributor to global climate change. In earlier work, we examined the economic effects of limiting CO_2 emissions in China through the use of a carbon tax. In this paper we make a first attempt at estimating the local health benefits of such a tax. We employ a dynamic computable general equilibrium (CGE) model of the Chinese economy, into which we have integrated a sub-model that enables us to capture health effects of burning fossil fuel. Although preliminary, our estimates indicate that a carbon tax that reduces carbon emissions from our base case by 10% in each year could also reduce premature deaths by 7-8% per year. Effects on other health related measures, such as cases of chronic bronchitis, asthma, and hospital emergency room visits, are similar.

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I. Introduction

Air pollution from the use of fossil fuel has been recognized to be a cause of serious health problems in China. Recently, the World Bank (1997) estimated that air pollution caused 178,000 premature deaths in urban China in 1995 and valued health damages at nearly 5% of GDP. The same study estimated that hospital admissions due to pollution-related respiratory illness were 346,000 higher than if China had met its own air pollution standards. In addition, there were 6.8 million more emergency room visits and 4.5 million person-years were lost because of illnesses associated with pollution levels that exceeded standards. The majority of these damages have been attributed to emissions of particulates and sulfur dioxide. These problems are expected to worsen in the near future as rapid growth outpaces efforts to reduce emissions.

While particulate and sulfur dioxide emissions from burning fossil fuel contribute to local air pollution, the use of fossil fuel also produces carbon dioxide, a greenhouse gas thought to be a major contributor to global climate change. In an earlier paper, we examined the effects of limiting CO_2 emissions in China through the use of a carbon tax. In this paper we make a first attempt at estimating the local health benefits of such a tax. Unlike many efforts aimed at estimating health effects, which focus on specific technology policies aimed at reducing pollution, we examine broad-based *economic* policies within an economy-wide framework. We present a preliminary effort, utilizing a number of simplifications, to illustrate this procedure. Our estimates indicate that a carbon tax that reduces carbon emissions by 10% in each year from our base case, could also reduce premature deaths each year by 7-8%. Effects on other health related measures, such as cases of chronic bronchitis, asthma, and hospital emergency room visits, are similar.

In the next section, we briefly describe the computable general equilibrium (CGE) model used in our analysis. We pay particular attention to the environment-health aspects of our model. In section three, we discuss some of the data used. The base case simulation is described in section four. Section five presents the results of simulations of the effects of a carbon tax on human health. Some sensitivity analysis is discussed in section six. The final section presents some conclusions and our plans for future work.

II. The Economy-Energy-Health Model

Our economic modeling framework is based on that described in Garbaccio, Ho, and Jorgenson (1999). We summarize only key features of the economic model here, but provide further details in the appendix. Instead, we describe in some detail the health aspects of our modeling approach. We first estimate the reduction in emissions of local pollutants that might be brought about through policies designed to reduce CO_2 emissions. These changes in emissions are next translated into changes in concentrations of various pollutants in urban areas. Dose-response functions are then used to calculate the effect of reductions in concentrations of pollutants on health outcomes. These include reduced premature mortality, cases of chronic bronchitis, and other health effects. Finally, we utilize commonly used valuation methods to translate the reduced damages to health into *yuan* values, which may be compared to the other costs and benefits of such policies.

The Economic Model

Our 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 1, there are 30 sectors, including five energy sectors. Output is produced using constant returns to scale technology. 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 (and the exogenous government deficit and current account). 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 capital

stock is immobile in any given period, while the market part responds to relative returns. Over time, the plan part is fully depreciated and the entire capital 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. An endogenous terms-of-trade exchange rate clears this equation.

The level of technology is projected exogenously, i.e. we make a guess of how input requirements per unit of 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, and electric power. Non-fossil fuels, including hydropower and nuclear power, are included as part of the electric power sector.

Our carbon tax is a tax on fossil fuels at a rate based on their carbon content. This tax is applied to the output of four industries -- coal mining, crude petroleum, natural gas, and petroleum refining.[1] It is applied to imports while exports are excluded. In the base case, this tax is zero. In our policy simulations, the rate of the carbon tax is set to achieve a desired reduction in carbon emissions. Since the application of this tax will raise revenues above those in the base case, to maintain comparability, we keep government spending and revenues the same by reducing other existing taxes.

The Energy-Health Model

Emissions of local pollutants come from two distinct sources. The first source is the burning of fossil fuels (combustion emissions). The second is from noncombustion processes (process emissions). The later is important because a great deal of dust is produced in industries

[1] There is no double counting of crude and refined petroleum.

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). Analysis of the health effects of other pollutants, such as nitrogen oxides and lead, are left for future work. 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).[2]

Total emissions from industry *j* is the sum of process emissions and combustion emissions from burning coal, oil, and natural gas. Let EM_{jxt} denote the emissions of pollutant *x* from industry *j* in period *t*. Then we have:

$$(1) \qquad EM_{jxt} = s_{jx} QI_{jt} + \sum_f \left(y_{jxf} AF_{jft} \right) \quad ,$$

where x = PM-10, SO_2 , f = coal, oil, gas , j = 1,2, .. , 30, H, G .

s_{jx} is process emissions of pollutant *x* from a unit of sector *j* output and y_{jxf} is the emissions from burning one unit of fuel *f* in sector *j*. QI_{jt} is the quantity of output *j* and AF_{jft} is the quantity of fuel *f* in tons of oil equivalent (*toe*) consumed by sector *j* in period *t*.[3] The model generates intermediate inputs, denoted A_{ijt}, which are measured in constant *yuan*. For the cases where *i* is one of the fuels, these A_{ijt}'s are translated to AF_{jft} which are in *toe* of coal, oil, and natural gas. The *j* index runs over the 30 production sectors and the two nonproduction sectors -- household and government. For the two nonproduction sectors there are zero process emissions (i.e. $s_{jx} = 0$).

The amount of emissions per *yuan* of output, or emissions per *toe* of fuel used, depends on the technology employed and changes as new investments are made. We need to take into account the costs of these new technologies and how much they reduce emissions and energy

[2] Lvovsky and Hughes discuss the choice of PM-10 as their metric. Measurements taken in China have mostly been in TSP (total suspended particles). Health damages, however, are believed to be due mainly to finer particles. Lvovsky and Hughes make an estimate of the share of PM-10 in TSP and use that in making their estimates. Improved data would obviously refine our analysis.

[3] For the petroleum refining sector the input of oil is of course not total purchases of crude, but rather only that part which is burned.

use.[4] However, estimates of these factors have not yet been assembled for many industries in China and so 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 the superscripts "*O*" and "*N*" to denote the old and new coefficients, we have:

$$(2) \qquad y_{jxft} = k_t y^{O}_{jxf} + (1-k_t) y^{N}_{jxf} \quad ,$$

where the weight, k_t, is the share of old capital in the total stock of capital.[5]

Within each of the sectors there is considerable heterogeneity in plant size, vintage, etc. Unfortunately, we are unable to incorporate such detail into this work. However, it is known that, on average, the emissions of different industries enter the atmosphere at different heights. 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 height, and the nonmanufacturing and household sectors as low height. The exact designations by sector are given in Table 1. Denoting the emissions of pollutant *x* at height *c* by E_{cxt} we have:

$$(3) \qquad E_{cxt} = \sum_{j \in c} EM_{jxt} \quad , \qquad \text{where } c = \text{low, medium, and high height.}$$

The next step is to estimate concentrations of pollutants in population centers due to these emissions. The preferred approach would be to disaggregate the emissions by geographic location and feed the data into a separate air dispersion model for each location. This would generate the concentrations at each population center from all sources of emissions. Such an elaborate exercise must be deferred to future work. Again we follow Lvovsky and Hughes and use reduced form coefficients to estimate concentrations. Unlike Lvovsky and Hughes, however,

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

[5] 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. Were such data available, an integrated approach would of course be preferred.

who distinguish between large metropolitan regions and other, less populous cities, we make a further simplification and express the national average urban ambient concentration as:

$$(3) \qquad C_{xt}^{N} = g_{low,x} E_{low,xt} + g_{medium,x} E_{medium,xt} + g_{high,x} E_{high,xt} \quad ,$$

where the g_{cx} coefficients translate emissions at height *c* to concentrations of pollutant *x*.[6]

The formulation described above is rather crude and so we briefly discuss the effects of misspecification of different parts of the procedure. An error in the g_{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. what is the percentage reduction in mortality due to a particular policy?), then an error in g_{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.) We illustrate this numerically in section six below.

There has been much research and debate about the magnitude of the effects a particular concentration of pollutant has on human health and on how the effects of various pollutants interact. 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 and populations with different demographic and health characteristics. This is discussed by Wang and Smith (1999b, Appendix E), who cite a range of estimates for mortality effects ranging from 0.04% to 0.30%, for a one mg/m^3 increase in PM-10 (see their Table 5). In addition, there is also the issue of differential age impacts of these pollutants and the associated difficulty of measuring "quality of life-years."

We are not able to address these important issues here and are forced to make some simple assumptions. 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

[6] Indexing this equation by cities would be more appropriate, but we would have to have 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.

mortality and chronic bronchitis. These effects, indexed by *h*, are given in Table 2 together with the dose-response relationship, DR_{hx}. For mortality, the number 7.1 is interpreted as the number of excess deaths per million people due to an increase in the concentration of PM-10 of one mg/m^3. This is equivalent to a 0.1% mortality effect, which is also the central estimate in Wang and Smith (1999b, Table 5). We use an alternative estimate in our sensitivity analysis in section six.

With these dose-response relationships, the number of cases of health effect *h* in period *t* is then given by:

$$(5) \qquad HE_{ht} = \sum_x \left(DR_{hx} (C_{xt}^N - a_x) POP_t^u er \right) \qquad \text{h = Mortality, RHA, ... ,}$$

where a_x is the World Health Organization (WHO) reference concentration, POP_t^u is the urban population (in millions), and er is the exposure rate (i.e. the share of the urban population exposed to pollution of concentration C_{xt}^N).

Various approaches have been used to value these damages. We use the "willingness to pay" method. The valuation of these damages is a controversial and difficult exercise, with arguments over the idea itself (Heinzerling (1999)), whether the "contingent valuation" method is appropriate (Hammit and Graham (1999)), and how to aggregate willingness to pay (Pratt and Zeckhauser (1996)). For this preliminary effort we again follow Lvovsky and Hughes (1997) and use estimates for willingness to pay in the U.S., but scale them by the ratio of Chinese to U.S. per capita incomes.[7] Using this simple scaling means that we are assuming a linear income effect. The U.S. values associated with each health effect are given in the third column of numbers in Table 2. The next column gives the values scaled using per capita incomes in 1995.

Most studies of health damage valuation have used these estimates for all years of their analysis. However, China is experiencing rapid increases in real incomes. For example, if income rises at an annual rate of 5%, in 25 years it would have risen 3.4 times. In the base case, our model projects an average growth rate of per capita income of 4-5% over the next 40 years. Given this rate of increase, we have chosen a valuation method that changes every period in line

[7] These estimates are from Chapter 2 of the World Bank (1997), which also discusses the use of the "willingness to pay" versus the "human capital" valuation methodology, the method most commonly used in China.

with income growth, again assuming a linear income effect. The values for the year 2020 are given in the last column of Table 2. The national value of damage due to effect *h* is given by:

$$(6) \qquad Damage_{ht} = \sum_{x} V_{ht} HE_{ht} \quad ,$$

where the valuations for 1995, $V_{h,1995}$, are in the third column of Table 2. The value of total damages is simply the sum over all effects:

$$(7) \qquad TD_t = \sum_{h} Damage_{ht} \quad .$$

We should point out that these are the valuations of the people who suffer the health effects. This is not the same as calculating the medical costs, the cost of the lost output of sick workers, the cost of parent's time off to take care of sick children, etc. The personal willingness-to-pay may, or may not, include these costs.

III. Data

In order to implement the model described above, a great deal of economic, environment and health related data is required. Economic data is needed for the base year, parameters of various behavioral functions (e.g. elasticities of substitution in the production functions), and projections of the exogenous variables. These include projections of 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 (2000). A particularly important data source is the 1995 social accounting matrix (SAM) derived from the official 1995 input-output table.[8]

For the health component described in section two above, we obtained the output and energy use from the 1995 input-output table and the various editions of the China Statistical Yearbook. The process emissions coefficients are calculated from the sectoral noncombustion emissions data in the China Environment Yearbook. The energy related emission coefficients

[8] This 1995 SAM was produced in cooperation with the Department of Development Strategy of the Development Research Center. The 1995 I-O table is the official extrapolation of the 1992 benchmark table.

(y_{jxf}) are derived from those in Lvovsky and Hughes (1997) and scaled to the combustion emissions data.[9] Data is given in detail for the mining, manufacturing, and electric power sectors, with summary estimates for other sectors (agriculture, services, and final demand). We distribute the total for the other sectors in proportion to fuel use and scale Lvovsky and Hughes' estimates of the s_{jx} and y_{jxf} coefficients. Lvovsky and Hughes also provided separate estimates of the old and new technology coefficients, y^{O}_{jxf}, y^{N}_{jxf}, s^{O}_{jx}, and s^{N}_{jx}. The estimates for PM-10 for current and low-cost improved technology are given in Tables 3a (combustion emissions) and 3b (process emissions). Lvovsky and Hughes provide coefficients that transform emissions to concentrations separately for each of 11 major cities. We use this information to calculate a national average set of g_{cx}'s. In the 1995 base year, with emissions calibrated to the data for that year, the estimated urban concentration averaged over the cities is 194 mg/m^3.

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 must be projected. We take total population projections from the World Bank (1995). The rate of urbanization in China for 1950-97 is plotted in Figure 1. For comparison we also plot the rate of urbanization in the U.S. over the period 1840-1940.[10] The "medium" urbanization projection assumes that the urban population grows by 0.5% per year, while in the "low" urbanization projection, the rate is assumed to be 0.3% per year. The medium projection is very close to U.S. historical rates. The rate of increase in this projection is slightly lower than that assumed by Lvovsky and Hughes.

IV. The Base Case Simulation

It is important to point out that the aim of this paper is *not* to provide estimates of present and future health damages caused by urban air pollution in China. Rather, the objective of our simulations is to explore the potential effects that policies, such as a carbon tax, might have on

[9] Data on annual sectoral emissions of TSP and SO_2 (including both process and combustion emissions), are given in the China Environment Yearbook. Sinton (1996) provides a convenient English compilation of data up to 1993. Energy conversion coefficients are given on page 18. The TSP data are scaled to produce estimates of PM-10 emissions.

[10] From U.S. Census Bureau publication CPH-2-1, at http://www.census.gov/population/censusdata/ur-def.htm.

economic, environment, and health variables. This caveat should be kept in mind as we discuss our base case simulation.

We start our base case simulation in 1995 and initialize the economy to have the capital stock and working age population of that year. We use the economic model described above to calculate the output of all commodities, consumption by households and the government, exports, and the savings available for investment. Investment in one period augments the next period's capital stock and the exercise is repeated for future years. The level of output (both for specific commodities and total GDP) depends on our projections of population, savings behavior, the evolution of spending patterns with increases in income, the ability to borrow from abroad, improvements in technology, etc. Our results are reported in Table 4 and Figure 2. The 5.8% average GDP growth rate over the next 25 years that results from our assumptions is slightly less optimistic than the 6.7% growth rate projected by the World Bank (1997). But it still implies very rapid growth in per capita income. During this same period, the population is projected to grow at an average annual rate of 0.7%.

The dashed line in Figure 2 shows fossil fuel based energy use in standard coal equivalents (*sce*). Our assumptions on improvements in the efficiency of energy use 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 of 1995.[11] Carbon emissions from fossil fuels are also plotted in Figure 2. The rate of growth of carbon emissions is slower than the growth in energy use. This is mainly due to our assumptions about the shift from coal toward oil.

With the industry outputs and input requirements calculated for each period, we use equations (1) through (7) 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 Table 3). All sources of PM-10 increase emissions, with the largest rise coming from low-height sources. Projected SO_2 emissions rise

[11] Since 1995, official Chinese data shows a dramatic decline in energy use. This is evident not only in the energy-output ratio, but also in the absolute level of energy use. Sinton and Fridley (2000) provide a good discussion of this phenomenon. It may be then that our "fairly optimistic" projections are not sufficiently so.

much faster than particulates due to a less optimistic estimate of changes in the s_{jx} and y_{jxf} coefficients.[12]

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

Of course the fact that our estimates are not all that different from Lvovsky and Hughes' does not mean that either estimate is "good." We report our level estimates to illustrate our simulation procedure and the magnitudes involved. To reiterate, this is not a forecast of emissions, but rather a projection that assumes no changes in policy. Both the government and private sector's behavior will certainly change over time. In the next section we examine how certain government policy choices may impact economic, environmental, and health variables.

V. The Health Benefits of a Carbon Tax

As described in the previous section, the projected growth rate of carbon emissions in our base case, while lower than the growth rate of GDP, is still quite high. The level of emissions doubles in 35 years. A number of policies have been suggested to reduce the growth of emissions of this global pollutant, ranging from specific, detailed policies like importing natural gas or shutting down small-scale coal mines, to broader approaches, such as a carbon tax or emissions trading. In this paper we concentrate on one simple, broad-based policy by imposing a "carbon tax," i.e. a tax on fossil fuels based on their carbon content.[13]

The specifics of this tax, and the detailed economic effects that result from its imposition, are discussed in Garbaccio, Ho, and Jorgenson (1999). In our simulations, we increase the price

[12] The emission coefficients for sulfur dioxide are not reported here but are available from the authors. Given its relatively minor effects on human health (as shown in Table 2), we do not emphasize SO_2 in this study. SO_2 is of course an important cause of other damages, such as acid rain.

[13] We do not deal with other sources of carbon dioxide or greenhouse gases in this study.

of crude petroleum, natural gas, and coal (both domestic and imported), through the carbon tax. In this paper, two carbon targets are examined, 5% and 10% reductions in annual carbon emissions. In our simulations, the level of the tax is calculated endogenously such that emissions in each period are 5% or 10% less than in the base case. This is shown in Figure 3. The revenues from this new tax are used to reduce other existing taxes. The amount of reduction is such that the public deficit (which is exogenous) and real government expenditures (which are endogenous) were kept the same as in the base case.

The results of our carbon tax simulations are given in Table 5 and Figures 3-6. The levels of the carbon tax needed to achieve the reductions are plotted in Figure 4. In the first year, a tax of 17 *yuan* per ton of carbon is required to achieve a 5% reduction in emissions.[14] This is equivalent to a 6% increase in the market price of coal, a 1% increase in the price of crude petroleum, and a 3% increase in the price of natural gas. The higher percentage change for the cleaner natural gas might seem puzzling. However, this is due to the high subsidies in the base year. The subsidy for natural gas means that in 1995, emissions of carbon are about 2.2 kg per one *yuan* of natural gas, compared to 0.7 kg per one *yuan* of oil.[15]

Higher after-tax energy prices reduce demand for fuels and raise the relative prices of energy intensive goods. We assume that the government does not compensate the household sector for the higher prices and so consumption falls in the short run. Because the labor supply is assumed fixed, real wages fall slightly. The compensating reduction in enterprise taxes, however, leaves firms with higher after-tax income, and given our specification, this leads to higher investment. Over time, this leads to a significantly higher capital stock, i.e., higher than in the base case, and thus higher GDP. The higher output allows a level of consumption that exceeds that in the base case soon after the beginning of the simulation period.

As can be seen in Table 5, in the first year of the 5% carbon reduction case, the imposition of the carbon tax leads to a reduction in total particulate emissions of 3.2%. This, however, is an average over three different changes. High height emissions from the electric power sector fall by 5.6%, medium height emissions from manufacturing fall by 2.0%, while low

[14] On average, there are 0.518 tons of carbon emitted per ton of coal. The average price of coal output in 1995, derived by dividing the value in the input-output table by the quantity of coal mined, is about 125 *yuan* per ton. This implies that the carbon tax is about 7% of the price of a ton of coal.

[15] This is derived from applying the conversion coefficients in Sinton (1996) to the quantity data in the China Statistical Yearbook, then combining that with our estimates of the value of output of these sectors.

height emissions fall 3.4%. Sectoral emissions of sulfur dioxide fall by similar amounts. The electric power sector is the most fossil fuel intensive and hence experiences the largest declines in both output and emissions.

This reduction in emissions results in a fall in the average urban concentration of PM-10 by 3.1%. As a consequence, cases of various health effects (i.e. the number of premature deaths, the number of cases of chronic bronchitis, etc.) fall by about 4.1%. The reduction in health effects is bigger than the change in concentration due to the nonproportional nature of equation (5). If we apply these percent changes to the base case estimates in Table 4, this translates to 12,500 fewer excess deaths, and 107,000 fewer cases of chronic bronchitis. Since the valuations are simple multiples (see equation 6) the percent reduction in the *yuan* values of these health damages is also 4.1%.

Over time, as the revenue raised through the carbon tax reduces the income tax burden on enterprises, higher investment leads to a larger capital stock and hence a higher level of GDP. The higher level of output means greater demand for energy and hence requires a higher carbon tax rate to continue to achieve the 5% reduction in carbon emissions. This is shown in the "15th year" column of Table 5 and in Figure 4. The lower tax on crude petroleum in the 15th year is the result of our assumptions about the world price of oil. If we had assumed no imports, the tax on crude petroleum would also have been higher. This twist in fossil fuel prices results in a bigger fall in coal consumption compared to crude petroleum consumption for an unchanged level of GDP. However, the higher demand has a bigger effect than this twist in fuel prices and hence the reduction in emissions in the 15th year is smaller than the initial reduction, 3.0% versus 3.2%. Over time, the reduction in concentrations is correspondingly smaller, as shown in Figure 5.

Another feature of the results that should be pointed out is that the change in concentration is smaller than the change in emissions in future years (see Figure 5). This is due to our classifying emissions by height and the fact that low level emissions are the biggest contributors to concentration (i.e. they have the biggest g_{cx}'s). Different sectors of the economy grow at different rates (e.g. sources of low height emissions are growing the most rapidly) and respond differently to the imposition of the carbon tax. The most responsive sector (i.e. the one that shrinks the most) is electric power generation, which produces high height emissions with the lowest contribution to concentrations. Finally, this path of concentration changes leads to

health effects that become smaller over time, going from a 4.1% reduction in the first year, to a 3.4% reduction in the 15th year, to 3.1% in the 25th year.

When we raise the targeted carbon emissions reductions from 5% to 10% of the base case, the effects are approximately linear. In the "15th year" column of Table 5 we see that the effects on coal prices are less than doubled while the effects on oil prices are more than doubled. The end result for emissions, concentrations, and health effects is an approximate doubling of the percentage change. This seeming linearity would not hold for larger changes.

VI. Sensitivity Analysis

In section three, we discussed the first- and second-order effects of an error in a parameter. To illustrate this, we make an alternative assumption about an exogenous variable, the future urbanization rate. This variable, POP_t^u, enters in equation 4. The base case plotted in Figure 1 assumes that the urban share of the total population rises at 0.5% per year, while in the "low" case it rises at 0.3% per year. We ran the model again with this lower estimate of the exposed population. The number of premature deaths in both the base case and in this alternative simulation are plotted in Figure 7. This is an example of a first-order effect of an error in a parameter or exogenous variable.

Finally, we ran the model with the lower urban population growth rate and again imposed a carbon tax to achieve a 5% reduction in carbon emissions. In the original simulation, this resulted in excess deaths that were 4.1% lower in the first year (see Table 5 and Figure 6). Using the alternative urbanization estimate, mortality again falls by 4.1%. The *percentage* reductions in premature mortality over time for both cases are plotted in Figure 8. They are almost identical.

The wide range of estimates for the dose-response relationship was noted above in section three. For mortality, Lvovsky and Hughes (1997) use 7.14 excess deaths per million per one mg/m^3. If we use a coefficient that is 1.5 times higher, well within the range cited by Wang and Smith (1999b), then the projected excess deaths are simply 50% higher. This is shown in Figure 9.

The sensitivity analysis above illustrates the effects of changing a variable or parameter that has no feedback effect. However, if we change exogenous variables that do have feedbacks,

there will be second-order effects. For example, an alternative guess about the time path of the government deficit will change revenue requirements and taxes and will have an effect on the estimated percentage change. This effect will, however, be minor, merely a second-order effect on the percentage change.

The really crucial parameters have a first-order effect on the percentage change. These include the elasticity of substitution between capital and energy, the elasticity of substitution between coal and oil, and other behavioral parameters. In the case of health effects, if the concentration and dose responses (equations 4 and 5) were not linear then there would be significant changes. Two other examples come to mind. If the health of workers is a factor in the effectiveness of labor input or if urbanization is modeled explicitly, then something like a carbon tax would have a more complex interaction with GDP and health benefits. Examination of these issues is deferred to future work.

VII. Conclusions

This paper presents a preliminary effort to integrate a model of the health effects of fossil fuel use with a multi-sector economy-wide CGE model. In our initial analysis, we look at how policies intended to reduce emissions of greenhouse gasses might simultaneously affect emissions of local pollutants and ultimately human health. Our initial specifications of the linkages between fuel use and emissions of local pollutants and between the emissions of these pollutants and their concentrations in urban areas are very simple. Efforts to improve these specifications are currently under way. However, to the extent that the effects are linear (i.e. as described in equations 4 and 5), our estimates of percentage changes in concentrations and mortality are as good (or bad) as our estimates of sectoral output changes.

The aim of a more detailed modeling effort would be to provide guidance for policy making. One goal of the preliminary effort presented here is to lay out explicitly the assumptions that would be needed to make such an analysis, both with or without better data and more elaborate model specification. Even the incorporation of an elaborate regional air pollution model would still require that projections be made for a multitude of time-dependent exogenous variables, such as total and urban population size, future world oil prices, energy efficiency improvements, etc.

A further goal of this preliminary modeling effort is to highlight areas in which improvements in data collection and model specification could bring the greatest benefit to even a limited analysis. Issues beyond those associated with the economic component of the model include: (1) There is a belief among some researchers that concentrations of very fine particles (i.e. PM-2.5) are a better predictor of the adverse health effects of air pollution than larger particles (i.e. PM-10). Data on emissions, concentrations, and the health effects of these particles in Chinese urban areas would be a useful adjunct to the data currently available for TSP and PM-10. (2) Improved data on concentrations in a greater range of Chinese urban areas would give a better sense of the range of the reduced form coefficients. (3) In the current version of the model, for each industrial sector, emissions are crudely classified by height (low, medium, and high) of discharge. More detailed data on sectoral emissions characteristics would be desirable. (4) Improving the specification of the dose-response functions in our model is a recognized priority. In this regard, we feel that it is particularly important to include an age dimension. This is especially important as we intend to eventually link worker health and labor productivity. (5) Our current valuations of health effects are based on U.S. studies, but scaled to the income level in China. Work is currently underway to obtain Chinese valuations of these damages. When complete, we intend to incorporate this work into our model.

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 (2000). 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.[16] 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:

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

[16] 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.

$$-\sum_i \overline{PS}_i \, \overline{A}_{ij} - \sum_i \tilde{PS}_i \, \tilde{A}_{ij} \quad .$$

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

$\log E_{jt} = \sum_k a_{kj}^E \log A_{kjt}$ and k = coal, oil, gas, electricity, and refined petroleum

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

Here a_{Ej} is the cost share of aggregate energy inputs in the production process and a_{kj}^E is the share of energy of type *k* within the aggregate energy input. Similarly, a_{Mj} is the cost share of aggregate non-energy intermediate inputs and a_{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 a_{Ej} coefficients are indexed by time and are updated exogenously. We set a_{Ej} to fall gradually over the next 40 years while the labor coefficient, a_{Lj}, rises correspondingly. The composition of the aggregate energy input (i.e. the coefficients a_{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.[17] The coefficient *g(t)* in equation A3 represents technical progress and the change in *g(t)* is determined through an exponential function ($\dot{g}_j(t) = A_j \exp(-m_j t)$). This implies technical change that is

[17] 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.

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:

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

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 a_{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:

$$\text{(A11)} \quad Rev = \sum_j t^k (P_j^{KD} KD_j - D_j) + t^V \sum_j (P_j^{KD} KD_j + PL_j LD_j + PT_j TD_j) + \sum_j t_j^t PI_j QI_j$$

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

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:

$$\text{(A12)} \quad t_i^c = t^x q_i \quad ,$$

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

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

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

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

(A14) $PS_i G_i = a_i^G VGG$.

We construct a price index for government purchases as $\log PGG = \sum_i a_i^G \log PS_i$. 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) $\overline{K}_{jt} = (1-d)\overline{K}_{jt-1} + \bar{I}_{jt}$, 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) $\tilde{K}_t = \sum_j \tilde{K}_{jt}$, 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).[18]

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, a_{it}^I:

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

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

Like the a_{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.[19] The total, I_t, can be written as:

(A23) $I_t = \tilde{I}_t + \bar{I}_t = I_{1t}^{a_1^I} I_{2t}^{a_1^I} \ldots I_{nt}^{a_n^I}$.

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

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

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):

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

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

[19] 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.

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

$$\text{(A27)} \quad X_{it} \;=\; EX_{it}\left(\frac{\tilde{PI}_{it}}{e_t(1+s_{it}^{e})PE_{it}^{*}}\right)^{h_i} \quad ,$$

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:

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

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*}):

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

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:

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

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, y_{jt}^{L}. Each industry pays $PL_{jt} \;=\; y_{jt}^{L} PL_t /(1-t_j^{V})$ for a unit of labor. The labor market equilibrium is then given as:

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

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) $KD_{jt} = y_{jt}^{K} K_{jt}$,

where y_{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) $TD_j = T_j$, 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) $S^p + RE + G_INV = VII + \Delta G + CA$.

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, 1995

	Sector	Gross Output (bil. *yuan*)	Energy Use (mil. tn. coal equivalent)	Emission Height Class
1	Agriculture	2034	57	low
2	Coal Mining	170	55	medium
3	Crude Petroleum	163	25	medium
4	Gas Mining	4	3	medium
5	Metal Ore Mining	80	8	medium
6	Other Non-metallic Ore Mining	145	6	medium
7	Food Manufacturing	1057	44	medium
8	Textiles	800	35	medium
9	Apparel & Leather Products	564	6	medium
10	Lumber & Furniture Manufacturing	186	5	medium
11	Paper, Cultural, & Educational Articles	458	24	medium
12	Electric Power	280	79	high
13	Petroleum Refining	277	56	medium
14	Chemicals	1129	195	medium
15	Building Material	662	131	medium
16	Primary Metals	764	214	medium
17	Metal Products	408	10	medium
18	Machinery	792	27	medium
19	Transport Equipment	418	14	medium
20	Electric Machinery & Instruments	423	6	medium
21	Electronic & Communication Equipment	321	3	medium
22	Instruments and Meters	50	1	medium
23	Other Industry	40	12	medium
24	Construction	1340	13	low
25	Transportation & Communications	527	59	low
26	Commerce	1155	20	low
27	Public Utilities	431	20	low
28	Culture, Education, Health, & Research	447	10	low
29	Finance & Insurance	246	4	low
30	Public Administration	340	11	low
	Households		157	low
	Government			---
	Totals	**15710**	**1310**	

Sources: Development Research Center's Social Accounting Matrix for 1995; State Statistical Bureau; and authors' estimates.

Table 2

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

	Health Effect	Cases per 1 mil. people with a 1 $\mu g/m^3$ increase	Valuation in 1995 U.S. $	Valuation in 1995 *yuan 95*	Valuation in 2020 *yuan95*
	Due to PM-10:				
1	Mortality (deaths)	7.14	3,600,000	632,000	2,220,000
2	Respiratory hospital admissions (cases)	12.00	4,750	834	2930
3	Emergency room visits (cases)	235.00	140	25	86
4	Restricted activity days (days)	57,500.00	60	10	37
5	Lower respiratory infection/child asthma (cases)	23.00	50	9	31
6	Asthma attacks (cases)	2,608.00	50	9	31
7	Chronic bronchitis (cases)	61.20	72,000	12,600	44400
8	Respiratory symptoms (cases)	183,000.00	50	9	31
	Due to SO_2:				
9	Chest discomfort	10,000.00	50	9	31
10	Respiratory systems/child	5.00	50	9	31

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

Table 3a

Combustion Particulate Emission Factors

	Sector	Current Emissions by Fuel			Emissions with Low Cost Improvements by Fuel		
		Coal	Oil	Natural Gas	Coal	Oil	Natural Gas
1	Agriculture	59940	225	37	29970	225	37
2	Coal Mining	14201	53	9	7101	53	9
3	Crude Petroleum	14201	53	9	7101	53	9
4	Gas Mining	14201	53	9	7101	53	9
5	Metal Ore Mining	14201	53	9	7101	53	9
6	Other Non-metallic Ore Mining	14201	53	9	7101	53	9
7	Food Manufacturing	31950	120	20	15975	120	20
8	Textiles	18946	71	12	9473	71	12
9	Apparel & Leather Products	4487	17	3	2243	17	3
10	Lumber & Furniture Manufacturing	23555	955	25	10124	955	25
11	Paper, Cultural, & Educational Articles	23555	955	25	10124	955	25
12	Electric Power	31309	522	0	10436	522	0
13	Petroleum Refining	8614	861	14	2871	861	14
14	Chemicals	15138	1514	25	5046	1514	25
15	Building Material	10621	1062	18	3540	1062	18
16	Primary Metals	5460	546	9	1820	546	9
17	Metal Products	3553	13	2	1776	13	2
18	Machinery	12833	48	8	6417	48	8
19	Transport Equipment	12833	48	8	6417	48	8
20	Electric Machinery & Instruments	12833	48	8	6417	48	8
21	Electronic & Communication Equipment	12833	48	8	6417	48	8
22	Instruments and Meters	12833	48	8	6417	48	8
23	Other Industry	39593	148	25	19796	148	25
24	Construction	59940	225	37	29970	225	37
25	Transportation & Communications	59940	7492	37	29970	3746	37
26	Commerce	59940	225	37	29970	225	37
27	Public Utilities	59940	225	37	29970	225	37
28	Culture, Education, Health, & Research	59940	225	37	29970	225	37
29	Finance & Insurance	59940	225	37	29970	225	37
30	Public Administration	59940	225	37	29970	225	37
	Households	29970	599	37	14985	599	37

Note: Coefficients y^{O}_{jxf} and y^{N}_{jxf} in tons of PM-10 per million tons of oil equivalent (toe).

Table 3b

Process Particulate Emission Factors

	Sector	Current Emissions	Emissions with Low Cost Improvements
1	Agriculture	---	---
2	Coal Mining	0.21	0.04
3	Crude Petroleum	0.21	0.04
4	Gas Mining	0.21	0.04
5	Metal Ore Mining	0.21	0.04
6	Other Non-metallic Ore Mining	0.21	0.04
7	Food Manufacturing	0.03	0.03
8	Textiles	0.01	0.01
9	Apparel & Leather Products	---	---
10	Lumber & Furniture Manufacturing	0.04	0.01
11	Paper, Cultural, & Educational Articles	0.04	0.01
12	Electric Power	0.13	0.13
13	Petroleum Refining	0.36	0.36
14	Chemicals	0.17	0.17
15	Building Material	6.99	1.40
16	Primary Metals	1.47	0.29
17	Metal Products	0.01	0.01
18	Machinery	0.03	0.03
19	Transport Equipment	0.03	0.03
20	Electric Machinery & Instruments	0.03	0.03
21	Electronic & Communication Equipment	0.03	0.03
22	Instruments and Meters	0.03	0.03
23	Other Industry	0.43	0.43
24	Construction	---	---
25	Transportation & Communications	---	---
26	Commerce	---	---
27	Public Utilities	---	---
28	Culture, Education, Health, & Research	---	---
29	Finance & Insurance	---	---
30	Public Administration	---	---
	Households	---	---

Note: Coefficients s_{jx}^{O} and s_{jx}^{N} in tons per million 1995 *yuan*.

Table 4

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 5

Effects of a Carbon Tax on Selected Variables
(Percentage Change from Base Case)

	Effect in 1st Year with:		Effect in 15th Year with:	
Variable	**5% CO_2 Emissions Reduction**	**10% CO_2 Emissions Reduction**	**5% CO_2 Emissions Reduction**	**10% CO_2 Emissions Reduction**
GDP	-0.01%	-0.02%	0.07%	0.14%
Primary Energy	-4.78%	-9.54%	-4.72%	-9.46%
Market Price of Coal	5.80%	12.30%	6.07%	12.94%
Market Price of Oil	0.73%	1.50%	0.57%	1.23%
Market Price of Gas	2.88%	6.09%	2.71%	5.79%
Coal Output	-5.79%	-11.55%	-6.00%	-11.98%
Oil Output	-0.69%	-1.42%	-0.56%	-1.20%
Particulate Emissions	-3.18%	-6.35%	-2.98%	-5.97%
From High Height Sources	-5.58%	-11.14%	-5.52%	-11.09%
From Medium Height Sources	-1.96%	-3.92%	-1.86%	-3.68%
From Low Height Sources	-3.37%	-6.76%	-2.83%	-5.68%
Particulate Concentration	-3.09%	-6.20%	-2.73%	-5.49%
SO_2 Concentration	-2.99%	-6.01%	-2.38%	-4.78%
Premature Deaths	-4.11%	-8.24%	-3.44%	-6.90%
Cases of Chronic Bronchitis	-4.11%	-8.24%	-3.44%	-6.90%
Value of Health Damages	-4.11%	-8.24%	-3.44%	-6.90%

Table A1

Selected Parameters and Variables in the Economic Model

	Parameters
s_i^e	export VAT rebate rate on good *i*
t_i^c	carbon tax rate on good *i*
t^k	tax rate on capital income
t^V	Value added tax (VAT) rate
t_i^r	net import tariff rate on good *i*
t_i^t	net indirect tax (output tax less subsidy) rate on good *i*
t^x	unit tax per ton of carbon
	Endogenous Variables
G_I	interest on government bonds paid to households
G_INV	investment through the government budget
G_IR	interest on government bonds paid to the rest of the world
G_transfer	government transfer payments to households
P_i^{KD}	rental price of market capital by sector
PE_i^*	export price in foreign currency for good *i*
PI_i	producer price of good *i*
PI_i^t	purchaser price of good *i* including taxes
PL	average wage
PL_i	wage in sector *i*
PM_i	import price in domestic currency for good *i*
PM_i^*	import price in foreign currency for good *i*
PS_i	supply price of good *i*
PT_i	rental price of land of type *i*
QI_i	total output for sector *i*
QS_i	total supply for sector *i*
$r(B^*)$	payments by enterprises to the rest of the world
R_transfer	transfers to households from the rest of the world

Figure 1: Data and Projections of Urban Population as a Percentage of Total

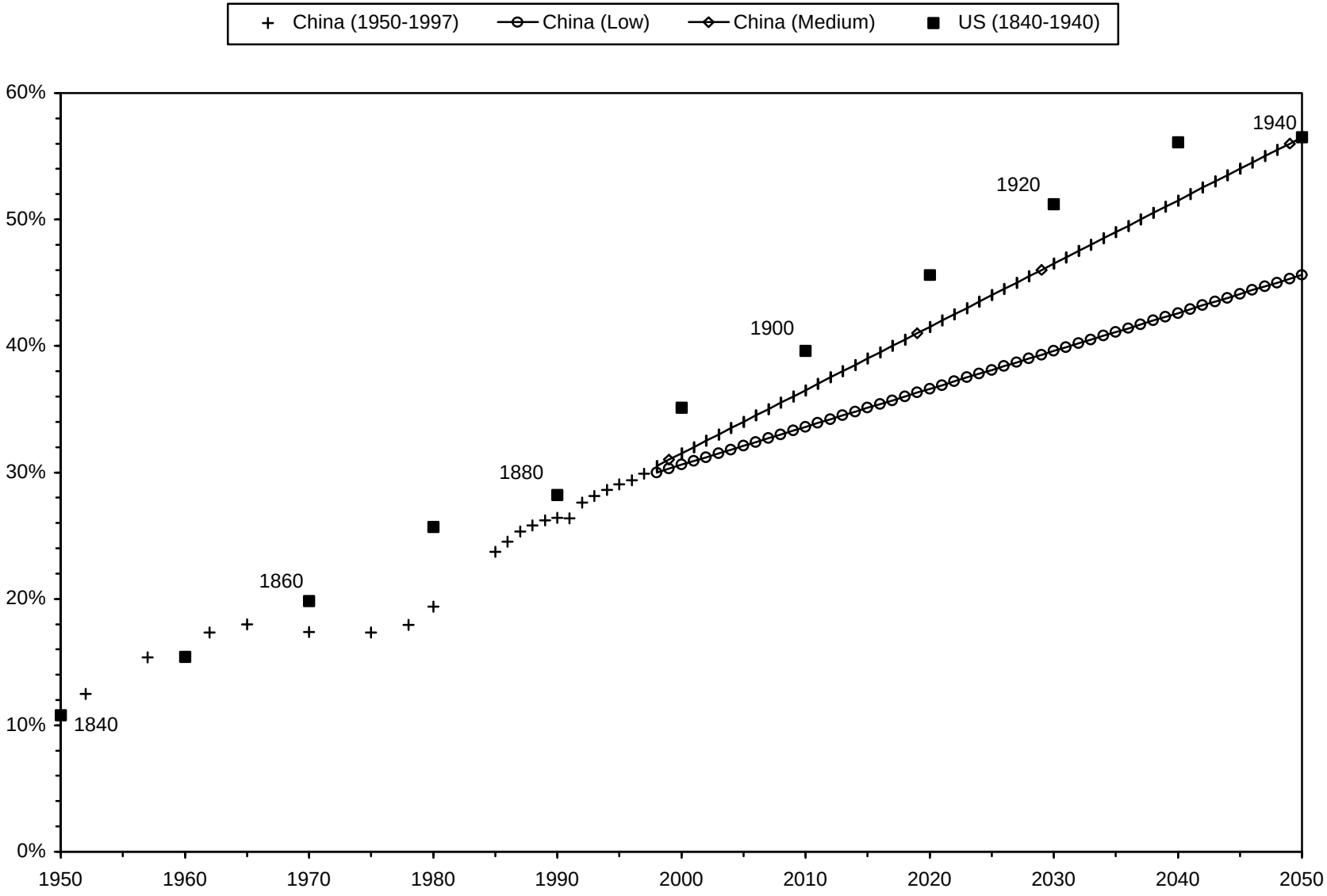
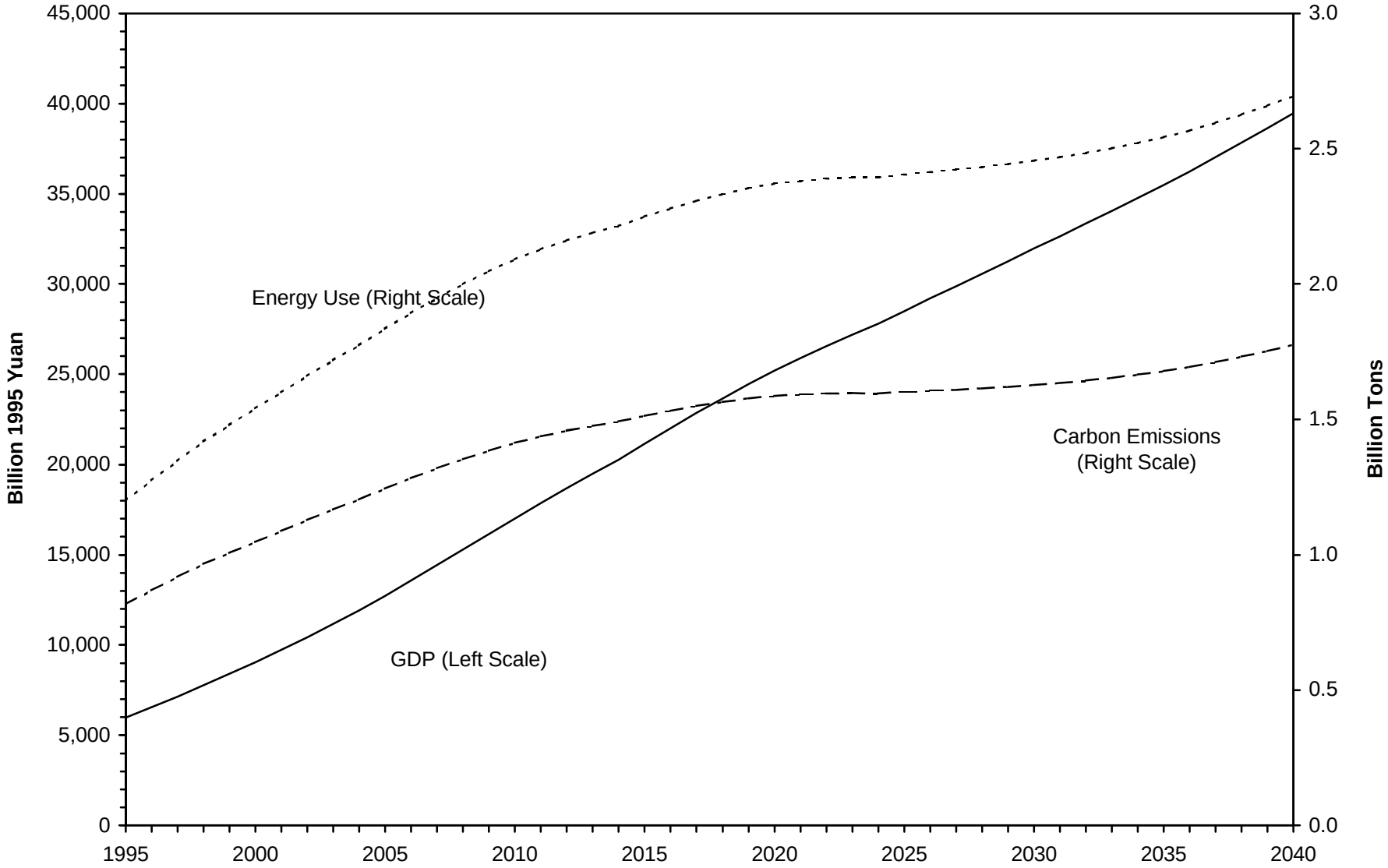


Figure 2: GDP, Energy, and Carbon Emissions 1995-2040



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

Figure 3: Carbon Emissions in Base Case and Counterfactuals

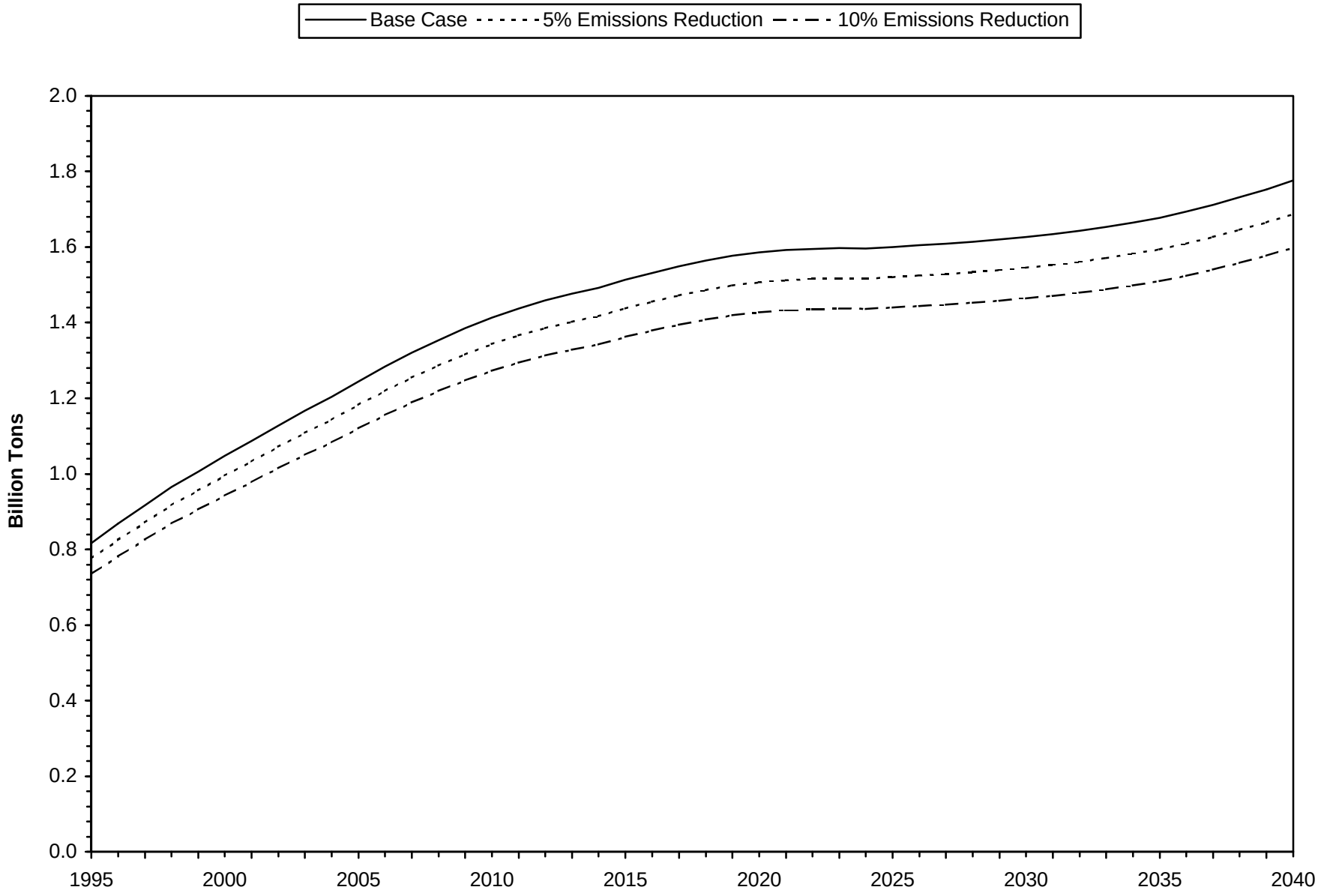


Figure 4: Carbon Taxes Required to Attain a Given Reduction in Emissions

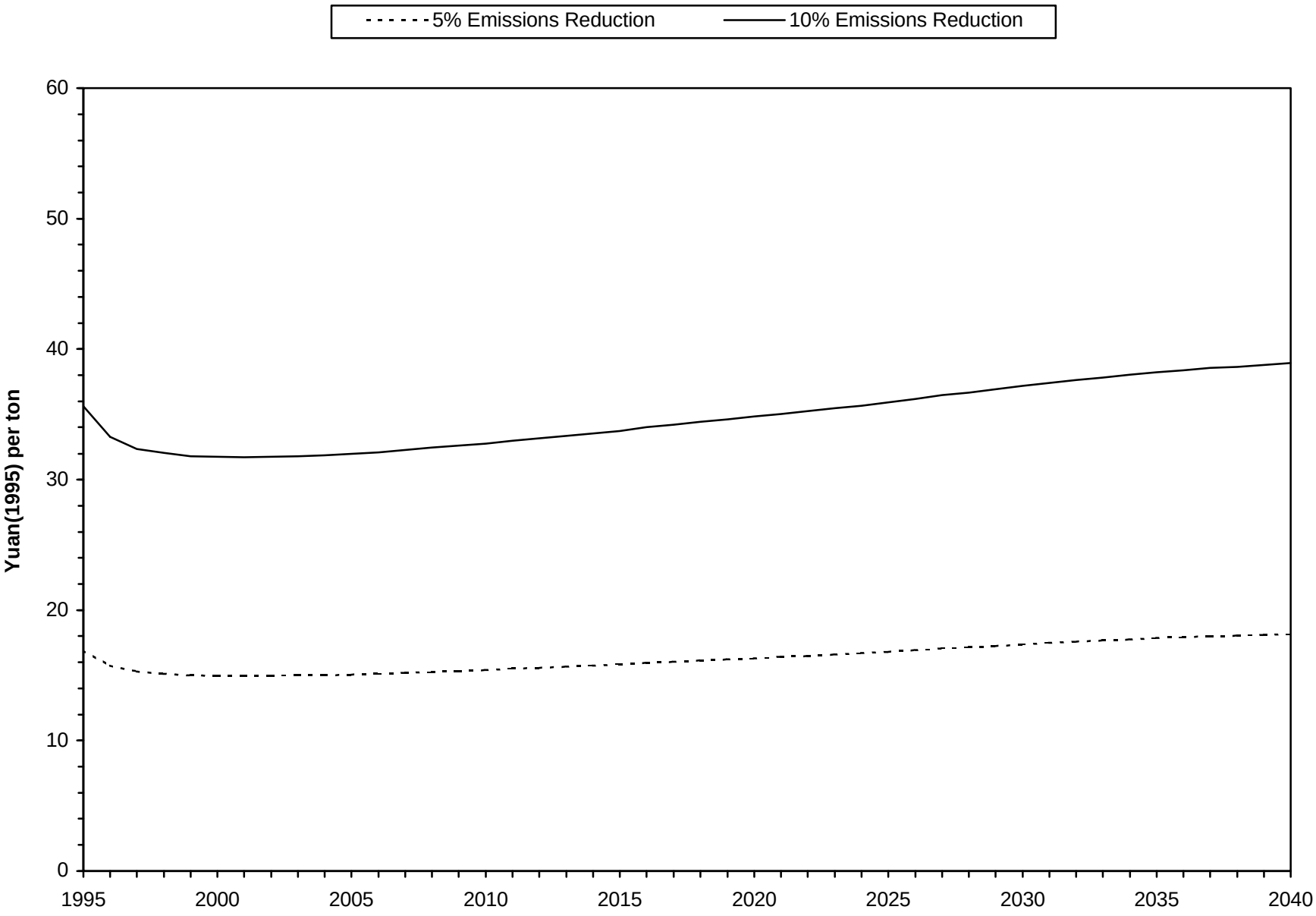


Figure 5: Reduction in PM-10 Emissions and Concentrations Relative to Base

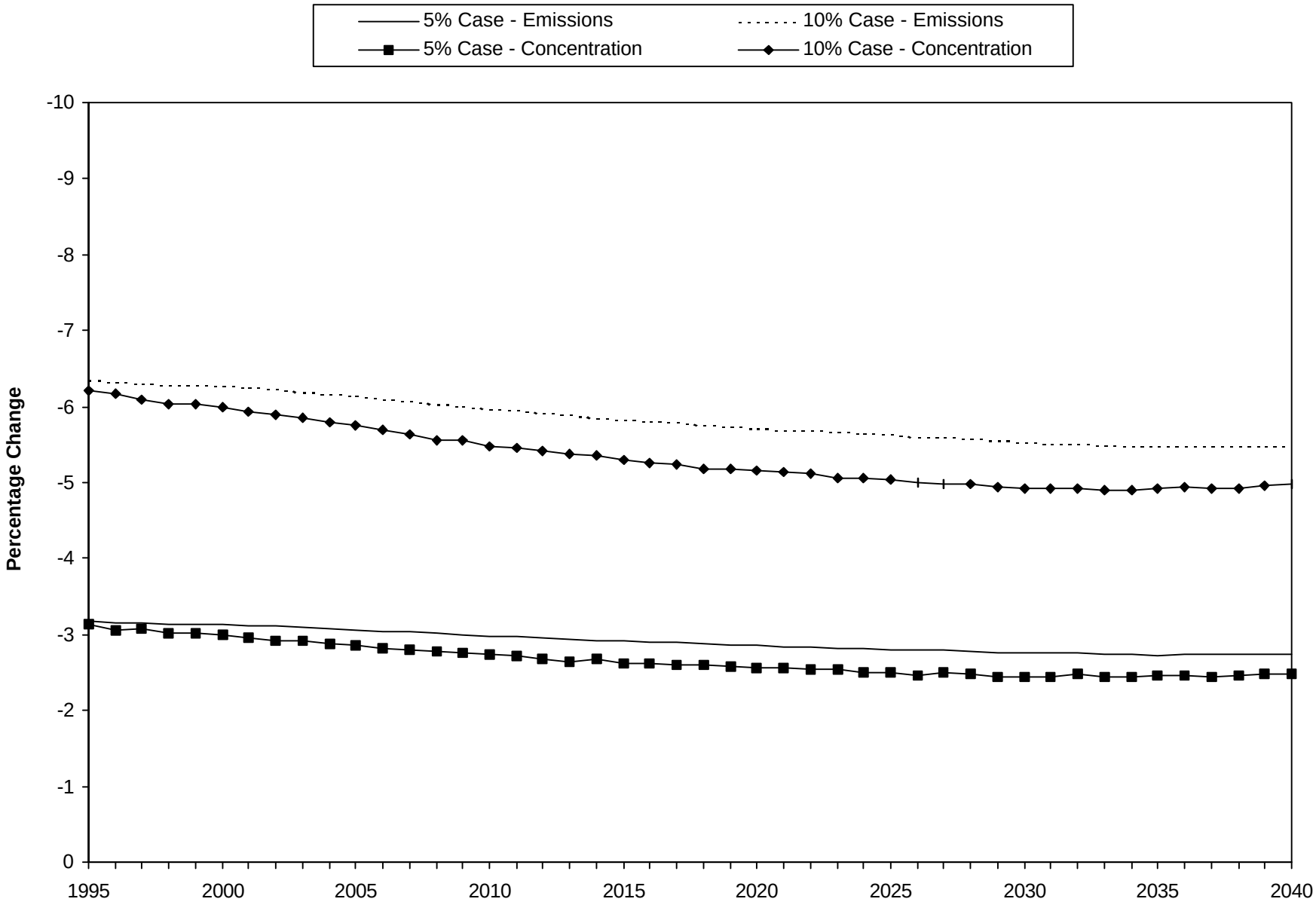


Figure 6: Reduction in Excess Deaths Relative to Base Case

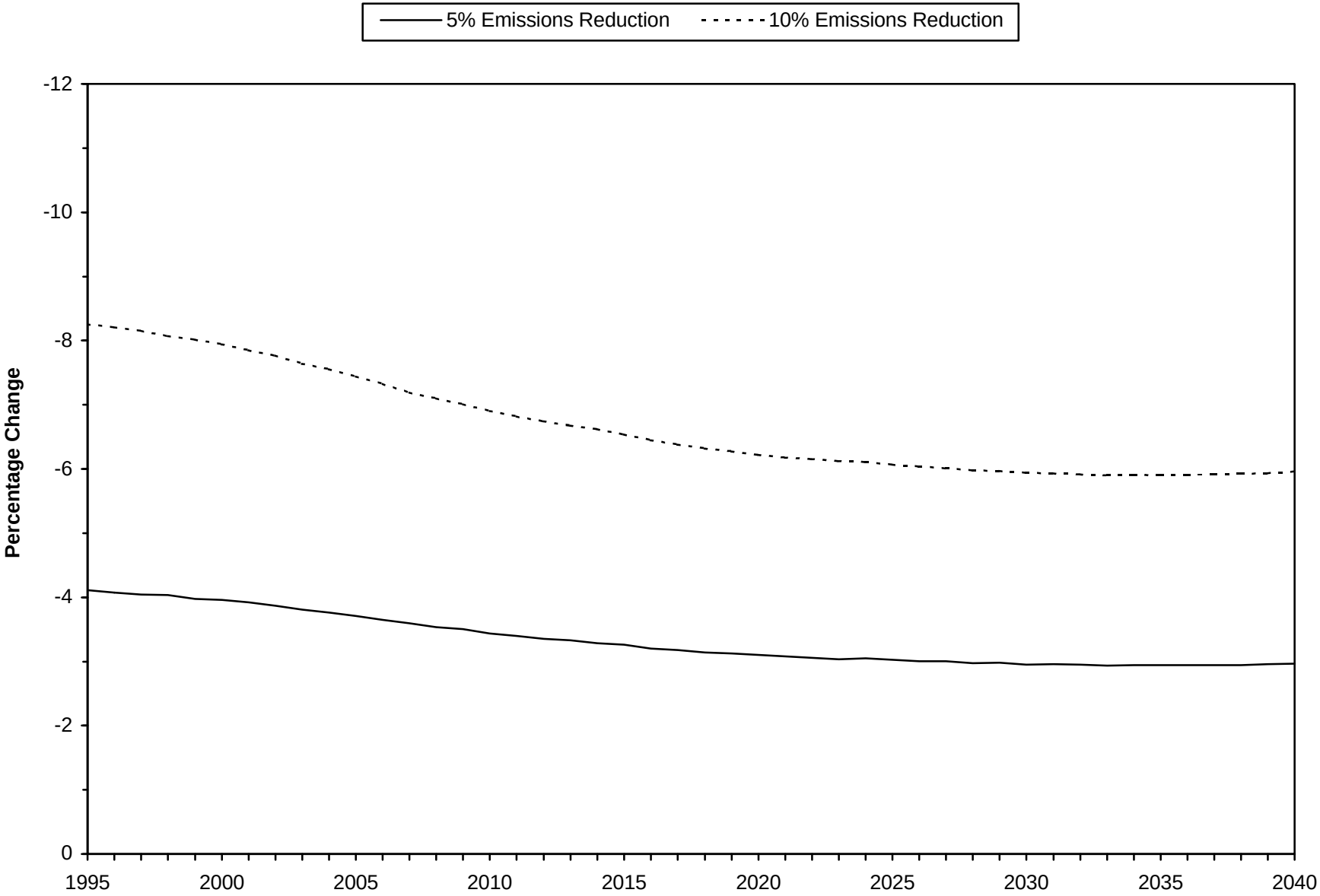
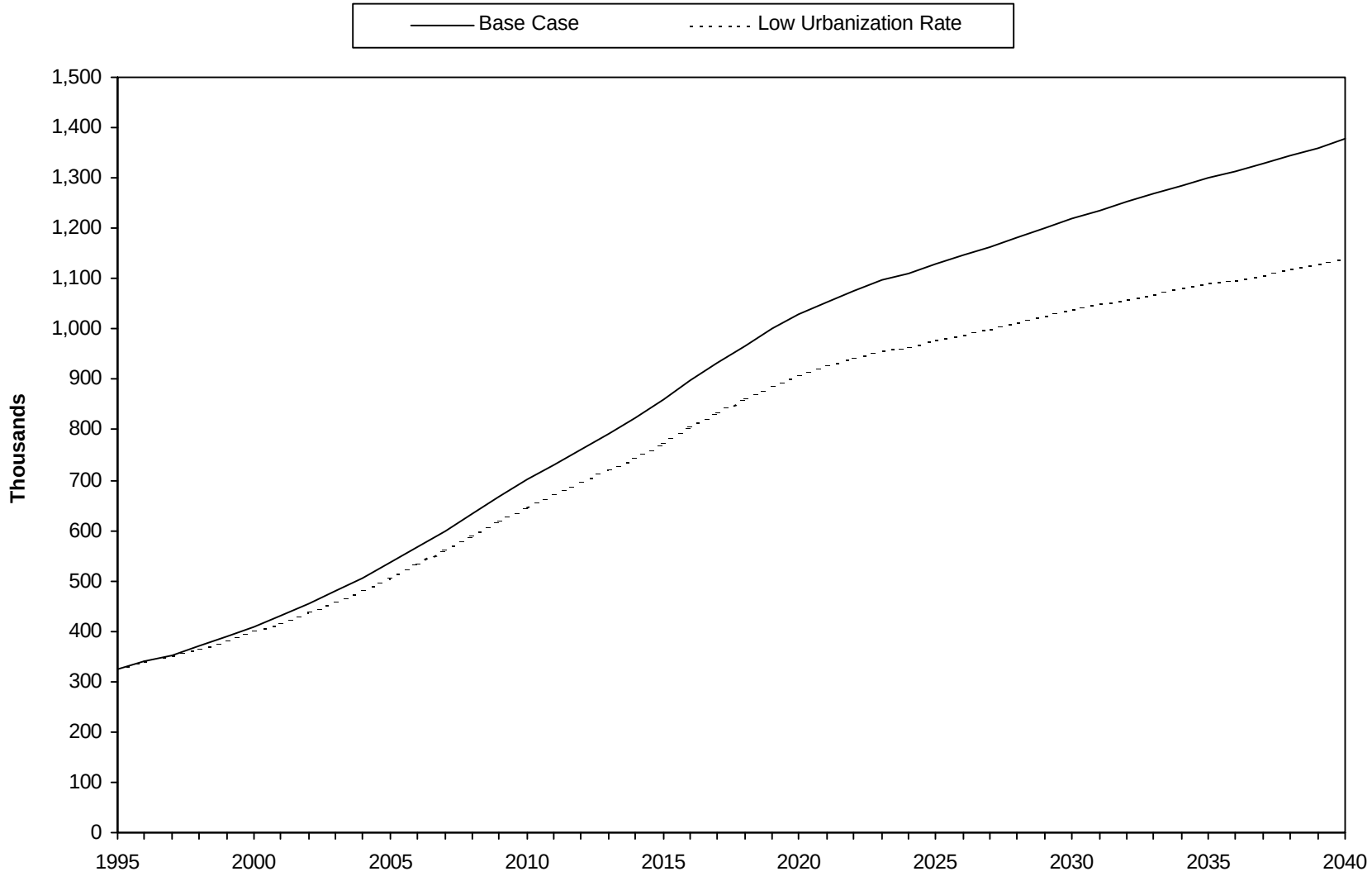
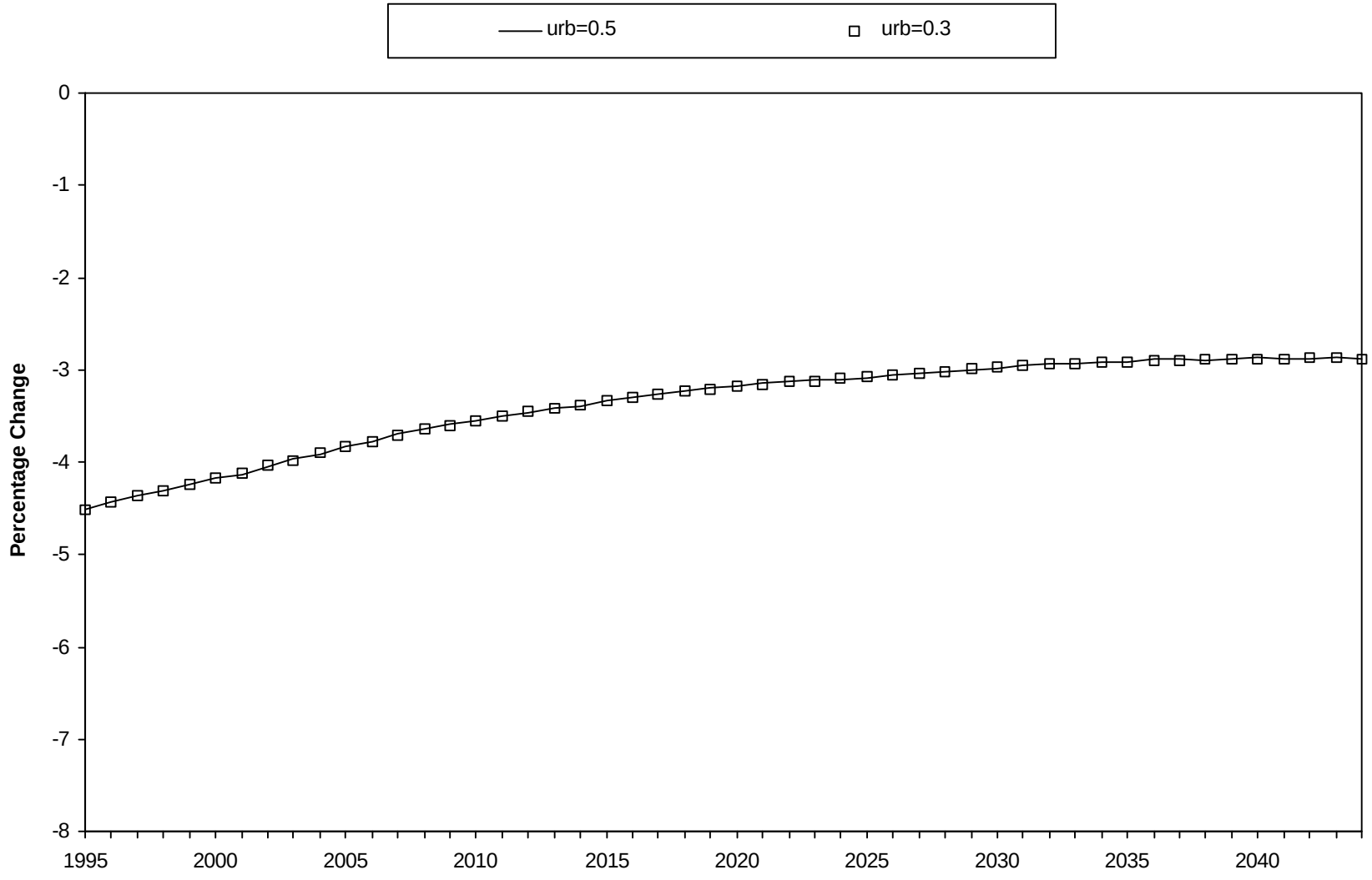


Figure 7: Excess Deaths in Base Case versus Low Urbanization Rate Case



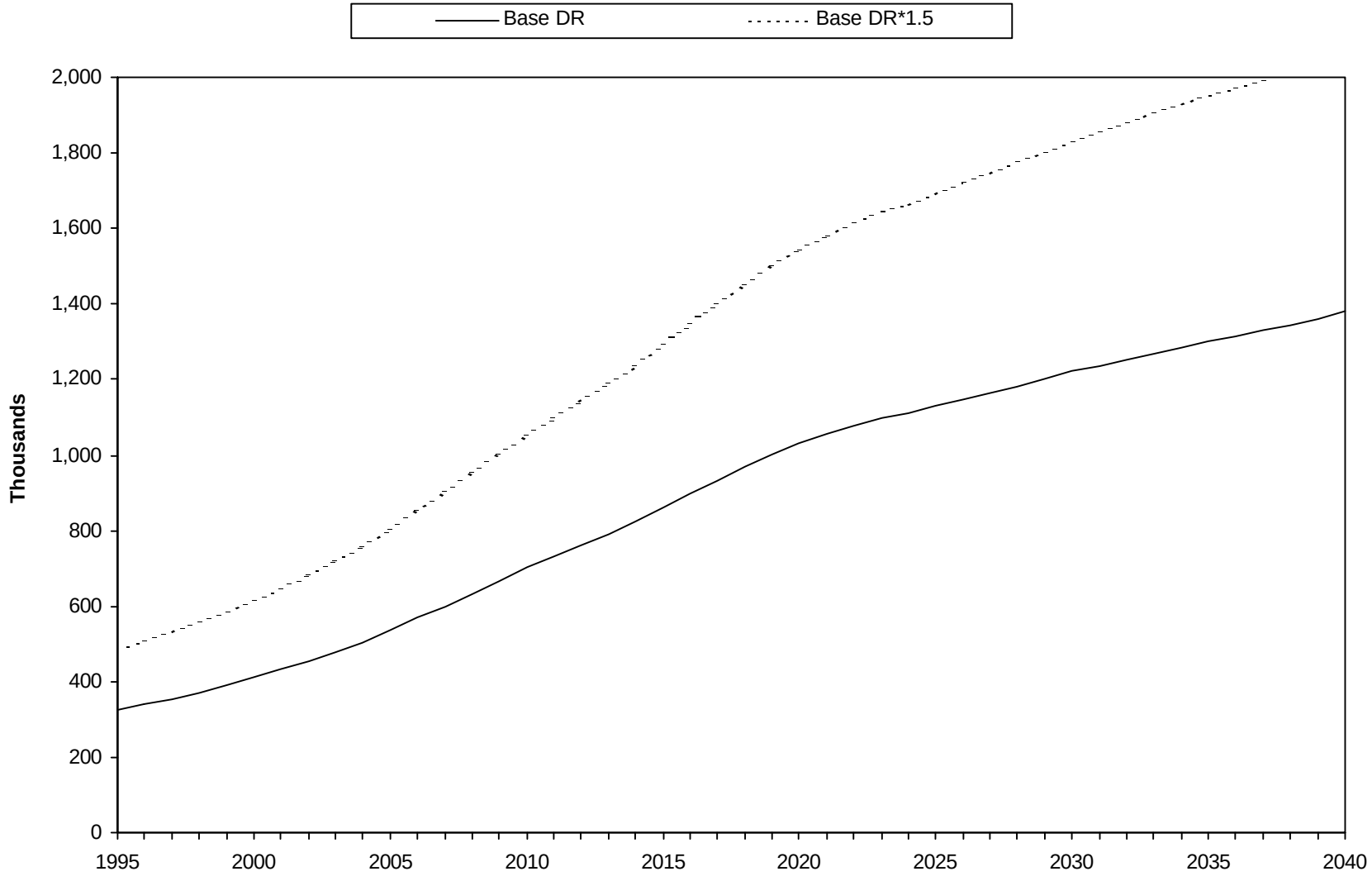
Note: The base case assumes that the urban share of the population is rising at 0.5% a year, in the low case we assume a 0.3% rate.

Figure 8: Change in Excess Deaths, Base versus Low Urbanization Case



Note: Each line represents the effect on premature deaths from a 5% reduction in carbon emissions.

Figure 9: Excess Deaths in Base Case versus High Dose-Response Case



Note: The base case uses the central estimate of the dose desponse to a one microgram/m3 increase in concentration. In the high DR case the value is 1.5 times the base coefficient.