THE HEALTH BENEFITS OF CONTROLLING CARBON EMISSIONS IN CHINA[1]

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1. Introduction

Air pollution from rapid industrialization and the use of energy has been recognized to be a cause of serious health problems in urban China. For example, 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, there were 6.8 million additional emergency room visits, and 4.5 million additional person-years were lost because of illnesses associated with pollution levels that exceeded standards. Much of this damage has been attributed to emissions of particulates and sulfur dioxide. Furthermore, this problem is expected to grow in the near future as rapid growth outpaces efforts to reduce emissions.

While particulate and sulfur dioxide emissions from burning fossil fuel contributes to local pollution, the use of fossil fuels also produces carbon dioxide, a greenhouse gas thought to be a major contributor to global climate change. The issue of climate change has engaged policy makers for some time now and is the focus of much current research.

As part of this research, in a previous 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 policies. Unlike many other efforts aimed at estimating health effects, which focus on specific technological policies to reduce pollution, here we examine broad based *economic* policies within a framework which includes all sectors of the economy. We present a preliminary effort, utilizing a number of simplifications, to illustrate the procedure. We plan to use more sophisticated air quality modelling techniques in future work.

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Our simple estimates, nevertheless, are instructive. We find that a policy which reduces carbon emissions by 5% every year from our base case will also reduce premature deaths by some 3.5 to 4.5%. If we apply commonly used valuation methods, the health damage caused by air pollution in the first year is about 5% of GDP. A policy to modestly reduce carbon emissions would therefore reduce local health losses by some 0.2% of GDP annually.

2. The economy-energy-health model

Our economic modeling framework is described in Garbaccio, Ho, and Jorgenson (1999). We summarize only key features of the model here. Instead, we describe in some detail the health aspects of our model. Our approach is to first estimate the reduction in emissions of local pollutants due to policies to reduce CO_2 emissions. These changes in emissions are 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, fewer 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.

2.1 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 29 sectors, including four 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 29 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 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 enterprise income, 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 output fall over time, including energy requirements. For the later, this is sometimes called the AEEI (autonomous energy efficiency improvement). In the model, there are separate sectors for coal mining, crude petroleum, petroleum refining, and electric power. Non-fossil fuels, including hydropower and nuclear power, are included as part of the electric power sector.

Table 1. **Sectoral characteristics for China, 1992**

	Sector	**Gross Output (bil. *yuan*)**	**Energy Use (mil. tn. coal equivalent)**	**Emission Height Class**
1	Agriculture	909	50	low
2	Coal Mining	76	44	medium
3	Crude Petroleum	69	22	medium
4	Metal Ore Mining	24	6	medium
5	Other Non-metallic Ore Mining	66	13	medium
6	Food Manufacturing	408	36	medium
7	Textiles	380	33	medium
8	Apparel & Leather Products	149	5	medium
9	Lumber & Furniture Manufacturing	50	20	medium
10	Paper, Cultural, & Educational Articles	176	19	medium
11	Electric Power	115	49	high
12	Petroleum Refining	108	32	medium
13	Chemicals	473	138	medium
14	Building Material	254	109	medium
15	Primary Metals	321	119	medium
16	Metal Products	141	23	medium
17	Machinery	390	34	medium
18	Transport Equipment	163	5	medium
19	Electric Machinery & Instruments	155	9	medium
20	Electronic & Communication Equipment	107	2	medium
21	Instruments and Meters	24	1	medium
22	Other Industry	75	7	medium
23	Construction	520	14	low
24	Transportation & Communications	267	51	low
25	Commerce	635	14	low
26	Public Utilities	205	17	low
27	Culture, Education, Health, & Research	227	19	low
28	Finance & Insurance	171	1	low
29	Public Administration	191	7	low
	Households			low
	Government			-
	Totals	**6,846**	**900**	

Source: Development Research Center Social Accounting Matrix for 1992; State Statistical Bureau; and author's estimates.

A carbon tax is a tax on fossil fuels at a rate based on their carbon content. This tax is applied to the output of three industries – coal mining, crude petroleum, and petroleum refining. It is applied to imports while exports are excluded. In the base case this tax is zero. In the policy simulations the carbon tax rate 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.

2.2 The environment-health aspects

Emissions of local pollutants comes from two distinct sources, the first is due to the burning of fossil fuels (combustion emissions), the other from non-combustion processes (process emissions). A great deal of dust is produced in industries like cement production and building construction that is not related to the amount of fuel used. In this paper we concentrate on two pollutants, particulate matter less than 10 microns (PM-10) and sulfur dioxide (SO_2). The 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 non-combustion 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 gas. Let EM_{jxt} denote the emissions of pollutant *x* from industry *j* in period *t*. Then we have:

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

where x = PM-10, SO_2 , f = coal, oil, gas , $j = 1,2, .. , 29, H, G$.

σ_{jx} is process emissions of pollutant *x* from a unit of sector *j* output and ψ_{jxf} is the emissions from burning one unit of fuel *f* in sector *j*. 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*. 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 tons of oil equivalent of coal, oil, and natural gas. The *j* index runs over the 29 production sectors and the non-production sectors (household and government). For the two non-production sectors there are zero process emissions ($\sigma_{jx} = 0$).

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

The amount of emissions per *yuan* of output, or emissions per toe of fuel used, depends on the technology employed and will change as new investments are made. A proper study should take into account the costs of these new technologies and how much they reduce emissions and energy use.[3] Estimates of these factors have not yet been assembled for many industries in China and we use a simple mechanism to represent such changes. Lvovsky and Hughes (1997) make an estimate of the emission levels of "new" technology and write the actual emission coefficients as a weighted sum of the coefficients from the existing and new technologies. Using superscripts "*O*" and "*N*" to denote the old and new coefficients we have:

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

where the weight, k_t, is the share of old capital in the total stock of capital.[4]

Within each of the sectors there is considerable heterogeneity in plant size, vintage, etc. Unfortunately, we are unable to incorporate such a high level of detail into this work. However, we do note that, on average, different industries emissions enter the atmosphere at different levels. Following Lvovsky and Hughes we classify emission sources as low, medium, and high height. As a first approximation, emissions from the electric power sector are classified as high height, most of the manufacturing industries are classified as medium, and the non-manufacturing and household sectors as low. The exact designations by sector are given in Table 1. Denoting the emissions of pollutant *x* at height *c* by E_{cxt} we have:

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

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

$$(4) \qquad C^{N}_{xt} = \gamma_{low,x} E_{low,xt} + \gamma_{medium,x} E_{medium,xt} + \gamma_{high,x} E_{high,xt} \quad ,$$

where the γ_{cx} coefficients translate emissions at height *c* to concentration of *x*.[5]

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[3] 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.

[4] 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.

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

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

Much debate and research is ongoing about the magnitude of the effect a particular level of concentration of a 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 in Wang and Smith (1999b, Appendix E) who also cite a range of estimates for mortality effects ranging from 0.04% to 0.30% for a one $\mu g / m^3$ increase in PM-10 (see their Table 5). In addition, there is the issue of differential age impacts of these pollutants and the associated difficulty of measuring the "quality of life-years."

We will not be able to address these important issues here and choose only a simple formulation. In our base case we follow Lvovsky and Hughes (1997) who identify eight separate health effects for PM-10 and two for SO_2. The most important of these effects are mortality and chronic bronchitis. These effects, indexed by *h*, are given in Table 2 together with the dose-response relationship, DR_{hx}. The 7.1 number for mortality is interpreted as the number of excess deaths per million people due to an increase in the concentration of PM-10 of one $\mu g / m^3$. This is equivalent to a 0.1% mortality effect, which is also the central estimate in Wang and Smith (1999b, Table 5). 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:

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

where α_x is the WHO 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).

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 works [Hammit and Graham (1999)], and how to aggregate the 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. and scale them by the ratio of per capita incomes in China and the U.S.[6] 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 would use 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%, it would have risen 3.4 times in 25 years. In the base case, our model projects an average growth rate of 4-5% in per capita incomes over the next 40 years. Given this rate of increase, we have chosen a valuation method that changes every period in line with income growth, again assuming a linear income effect. The values for 2020 are given in the last column of Table 2. The national value of damage due to effect *h* is given by:

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

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:

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

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

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

Table 2. **Dose-Response and Valuation Estimates for PM-10 and SO_2**

	Health Effect	**Cases per 1 mil. people with a 1 μg/m^3 increase**	**Valuation in 1995 U.S. $**	**Valuation in 1995 *yuan***	**Valuation in 2020 *yuan***
	Due to PM-10:				
		7.14	3,600,000	82,700.00	289,000.00
2	Respiratory hospital admissions (cases)	12.00	4,750	110.00	380.00
3	Emergency room visits (cases)	235.00	140	3.20	11.20
4	Restricted activity days (days)	57,500.00	60	1.40	4.90
5	Lower respiratory infection/child asthma	23.00	50	1.10	4.00
6	Asthma attacks (cases)	2,608.00	50	1.10	4.00
7	Chronic bronchitis (cases)	61.20	72,000	1,650.00	5,770.00
8	Respiratory symptoms (cases)	183,000.00	50	1.10	4.00
	Due to SO_2:				
9		10,000.00	50	1.10	4.00
10	Respiratory systems/child	5.00	50	1.10	4.00

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

2.3 Data

Obviously, to implement the model described above, a great deal of economic and health related data is required. We need economic data for the base year, the parameters of the various behavioral functions (e.g. elasticities of substitution in the production functions), and projections of the exogenous variables. This includes projections of the population, the savings rate, productivity growth, import prices, the government deficit, etc. These data and forecasts for the economic component of the model are described in Garbaccio, Ho, and Jorgenson (1999). A particularly important data source is the 1992 Chinese input-output table.

For the health component described in section two above we obtained the output and energy use from the 1992 input-output table and Sinton (1996). The process emissions coefficients are calculated from the sectoral non-combustion emissions data in Sinton (1996). The energy related emission coefficients (ψ_{jxf}) are derived from those in Lvovsky and Hughes (1997) and scaled to equal the combustion emissions data.[7] Data is given in detail for the mining, manufacturing, and electric power sectors, with summary estimates for the 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 these σ_{jx} and ψ_{jxf} coefficients. Lvovsky and Hughes also provided separate estimates of ψ^{O}_{jxf} and ψ^{N}_{jxf} and for process coefficients, σ^{O}_{jx} and σ^{N}_{jx}. The estimates for PM-10 for current and low-cost improved technology are given in Table 3a for combustion emissions and in Table 3b for process emissions.

Lvovsky and Hughes (1997) give coefficients that transform emissions to concentrations separately for each of 11 major cities. We use this information to calculate a national average set of γ_{cx} 's. In the 1992 base year, with emissions calibrated to the data from Sinton (1996), the estimated urban concentration averaged over the cities is 194 $\mu g / m^3$.

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 have to be projected. We take total population projections the from World Bank (1995). The rate of urbanization in China for 1950-97 is plotted in Figure A1. For comparison we also plot the rate of urbanization in the U.S. over the period 1840-1940.[8] The "medium" urbanization projection is produced by letting the urbanization rate rise at 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. Lvovsky and Hughes (1997) assume a rate of urbanization slightly higher than our medium projection.

2.4 The base case simulation

It is *not* the aim of this paper to provide estimates of the damage caused by urban air pollution, but rather the changes in the damage caused by some policy. It is only to give a clear idea of how our approach works that we describe our base case simulation, i.e. a simulation of the economy and health effects using current policy parameters.

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[7] Sinton (1996) provides a convenient English compilation from various Chinese sources including the China Environmental Yearbook. Page 18 gives the energy conversion coefficients. Table VIII-4 gives the emissions by sector from both combustion and noncombustion sources.

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

We start the simulation in 1995 and so we initialize the economy to have the capital stocks that were available at the start of 1995 and the working age population of 1995 supplying labor. The economic model described in the appendix calculates the output of all commodities, consumption by households and the government, exports, and the savings available for investment. This investment augments the capital stock for the next period and we repeat the exercise. The level of output (specific commodities and total GDP) thus calculated depends on our projections of the population, savings behavior, changes in spending patterns as incomes rise, the ability to borrow from abroad, improvements in technology, etc. Our results are reported in Table 4 and Figure A2. The 5.9% growth rate of GDP over the next 25 years that results from our assumptions is slightly less optimistic than the 6.7% growth rate projected recently for China by the World Bank (1997), but still implies a very rapid growth in per capita income. The population is projected to rise at a 0.7% annual rate during these 25 years.

Table 3a. **Combustion particulate emissions**

		Current Emissions by Fuel			*Emissions with Low Cost Improvements by Fuel*		
	Sector	**Coal**	**Oil**	**Natural Gas**	**Coal**	**Oil**	**Natural Gas**
1	Agriculture	42,560	160	27	21,280	160	27
2	Coal Mining	38,182	143	24	19,091	143	24
3	Crude Petroleum	38,182	143	24	19,091	143	24
4	Metal Ore Mining	38,182	143	24	19,091	143	24
5	Other Non-metallic Ore Mining	38,182	143	24	19,091	143	24
6	Food Manufacturing	32,983	124	21	16,492	124	21
7	Textiles	18,505	69	12	9,253	69	12
8	Apparel & Leather Products	7,678	29	5	3,839	29	5
9	Lumber & Furniture Manufacturing	25,629	949	27	10,990	949	27
10	Paper, Cultural, & Educational Articles	25,629	949	27	10,990	949	27
11	Electric Power	32,642	544	0	10,881	544	0
12	Petroleum Refining	7,235	723	12	2,412	723	12
13	Chemicals	17,898	1,790	30	5,966	1,790	30
14	Building Material	13,454	1,345	22	4,485	1,345	22
15	Primary Metals	6,379	638	11	2,126	638	11
16	Metal Products	8,814	33	6	4,407	33	6
17	Machinery	11,970	45	7	5,985	45	7
18	Transport Equipment	11,970	45	7	5,985	45	7
19	Electric Machinery & Instruments	11,970	45	7	5,985	45	7
20	Electronic & Communication Equipment	11,970	45	7	5,985	45	7
21	Instruments and Meters	11,970	45	7	5,985	45	7
22	Other Industry	46,872	176	29	23,436	176	29
23	Construction	42,560	160	27	21,280	160	27
24	Transportation & Communications	42,560	5,320	27	21,280	2,660	27
25	Commerce	42,560	160	27	21,280	160	27
26	Public Utilities	42,560	160	27	21,280	160	27
27	Culture, Education, Health, & Research	42,560	160	27	21,280	160	27
28	Finance & Insurance	42,560	160	27	21,280	160	27
29	Public Administration	42,560	160	27	21,280	160	27
	Households	21,280	426	27	10,640	426	27

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

Table 3b. **Process Particulate Emissions**

	Sector	Current Emissions	Emissions with Low Cost Improvements
1	Agriculture	-	-
2	Coal Mining	0.81	0.16
3	Crude Petroleum	0.81	0.16
4	Metal Ore Mining	0.81	0.16
5	Other Non-metallic Ore Mining	0.81	0.16
6	Food Manufacturing	0.09	0.09
7	Textiles	0.04	0.04
8	Apparel & Leather Products	--	--
9	Lumber & Furniture Manufacturing	0.12	0.02
10	Paper, Cultural, & Educational Articles	0.12	0.02
11	Electric Power	0.72	0.72
12	Petroleum Refining	0.57	0.57
13	Chemicals	0.71	0.71
14	Building Material	14.92	2.98
15	Primary Metals	3.17	0.63
16	Metal Products	0.05	0.05
17	Machinery	0.11	0.11
18	Transport Equipment	0.11	0.11
19	Electric Machinery & Instruments	0.11	0.11
20	Electronic & Communication Equipment	0.11	0.11
21	Instruments and Meters	0.11	0.11
22	Other Industry	1.53	1.53
23	Construction	--	--
24	Transportation & Communications	--	--
25	Commerce	--	--
26	Public Utilities	--	--
27	Culture, Education, Health, & Research	--	--
28	Finance & Insurance	--	--
29	Public Administration	--	--
	Households	--	--

Note: Coefficients σ_{jx}^{O} and σ_{jx}^{N} in tons per million 1992 *yuan*.

Table 4. **Selected Variables from Base Case Simulation**

Variable	**1995**	**2010**	**2030**
Population (mil.)	1,200.00	1,348.00	1,500.00
GDP (bil. 1992 *yuan*)	3,560.00	10,200.00	18,600.00
Energy Use (mil. tons sce)	1,190.00	2,490.00	3,280.00
Coal Use (mil. tons)	1,270.00	2,580.00	3,090.00
Oil Use (mil. tons)	180.00	420.00	690.00
Carbon Emissions (mil. tons)	810.00	1,670.00	2,160.00
Particulate Emissions (mil. tons)	21.55	26.78	33.84
From High Height Sources	3.94	4.81	6.80
From Medium Height Sources	11.30	12.48	15.99
From Low Height Sources	6.32	9.49	11.05
SO_2 Emissions (mil. tons)	21.80	42.40	57.90
Premature Deaths (1,000)	320.00	700.00	1,200.00
Health Damage (bil. *yuan*)	180.00	1,000.00	2,800.00
Health Damage/GDP	5.10%	9.80%	15.30%

The dashed line in Figure A2 shows the fossil fuel based energy use in standard coal equivalents (sce) on the right-hand axis. Our assumptions on energy use improvements are fairly optimistic and together with changes in the structure of the economy, result in an energy-GDP ratio in 2030 that is almost half that in 1995. The carbon emissions from fossil fuels are also plotted using the right-hand axis. The rate of growth of carbon emissions is even slower than the growth in energy use. This is mainly due to our assumptions on the shift from coal to oil.

With the industry outputs and input requirements calculated for each period we use equations (1)-(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 much faster than particulates due to a less optimistic estimate of the improvement in the σ_{jx} and ψ_{jxf} coefficients.[9]

In this base case we assume no increase in emission reduction efforts over time. This differs from Lvovsky and Hughes' (1997) BAU case which assumes that the largest 11 cities will choose what they call the "high investment" option. The result is that our estimate of current premature mortality is higher, 320,000 versus 230,000. The growth rate of health effects from our simulations, however, are quite close. By 2020 our estimated excess deaths are 3.1 times the 1995 level, compared to the 3.7 times calculated in Lvovsky and Hughes' BAU case.

Of course the fact that our estimates are close does not mean that either estimate is "good." We report the level estimates to explain our simulation procedure and to illustrate the magnitudes involved. To reiterate, this is not a forecast of emissions, but rather a projection if no changes in policy are made. We expect both the government and private sectors to have policies and investments that are different from today's. The important issue is policy choices and the estimation of the effects of different policies. This is where we turn next.

2.5 Health effects of a carbon tax

As described in the previous section, our projected growth of carbon emissions in the base case, while lower than the growth of GDP, is still very high. The level of emissions doubles in 15 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 coal plants, to broader approaches, such as carbon taxes and emissions trading. In this paper we concentrate on the simplest broad based policy by imposing a "carbon tax," i.e. a tax on fossil fuels based on their carbon content.[10]

The specifics of this tax, and the detailed economic effects, are discussed in Garbaccio, Ho, and Jorgenson (1999). In our simulations we raise the price of crude petroleum and coal, both domestic and imported, by this carbon tax. In this paper, two carbon targets are examined, 5% and 10% reductions in annual carbon emissions. 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 1. The revenues from this new tax are used to reduce other existing taxes. The amount of reduction is such that the public deficit (exogenous) and real government expenditures (endogenous) were kept the same as the base case.

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[9] The emission coefficients for sulphur dioxide are not reported here but are available from the authors. Given the relatively minor role in human health (as shown in Table 2), we do not emphasize SO_2 in this study. It is of course an important cause of other damages, e.g. acid rain.

[10] In this study we ignore both other sources of carbon dioxide and other greenhouse gases.

The results of these carbon tax simulations are given in Table 5 and Figures 1-4. The amount of carbon tax needed to achieve these reductions is plotted in Figure 2. In the first year, a tax of 8.8 *yuan* per ton is required to achieve a 5% reduction in emissions.[11] This is equivalent to a 6% increase in the factory gate price of coal and a 1% increase in the price of crude petroleum. These higher 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. This 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 3.5%. This, however, is an average over three different changes. High height emissions from the electric power sector fell by 5.6%, medium height emissions from manufacturing fell 2.7%, while low height emissions fell 3.7%. Sectoral emissions of sulfur dioxide fell by similar amounts. The electric power sector is the most fossil fuel intensive and hence experiences the largest fall in output and emissions.

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[11] There are 0.518 tons of carbon emitted per ton of average coal. The average price of coal output in 1992, derived by dividing the value in the input-output table by the quantity of coal mined, is about 68 *yuan* per ton. This implies a tax on coal of about 7 percent.

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	-0.00%	-0.00%	0.21%	0.42%
Primary Energy	-4.72%	-9.45%	-4.68%	-9.35%
Market Price of Coal	6.03%	12.80%	6.29%	13.40%
Market Price of Oil	0.95%	2.01%	0.71%	1.53%
Coal Output	-5.93%	-11.80%	-6.14%	-12.20%
Oil Output	-0.81%	-1.71%	-0.59%	-1.29%
Particulate Emissions	-3.50%	-6.97%	-3.11%	-6.20%
From High Height Sources	-3.67%	-7.37%	-3.09%	-6.21%
From Medium Height Sources	-2.66%	-5.29%	-2.22%	-4.40%
From Low Height Sources	-5.59%	-11.20%	-5.44%	-10.90%
Particulate Concentration	-3.45%	-6.92%	-2.95%	-5.92%
SO_2 Concentration	-3.43%	-6.88%	-2.78%	-5.59%
Premature Deaths	-4.52%	-9.04%	-3.55%	-7.10%
Cases of Chronic Bronchitis	-4.52%	-9.04%	-3.55%	-7.10%
Value of Health Damages	-4.52%	-9.04%	-3.55%	-7.11%

Figure 1. **Carbon emissions in base case and simulations**

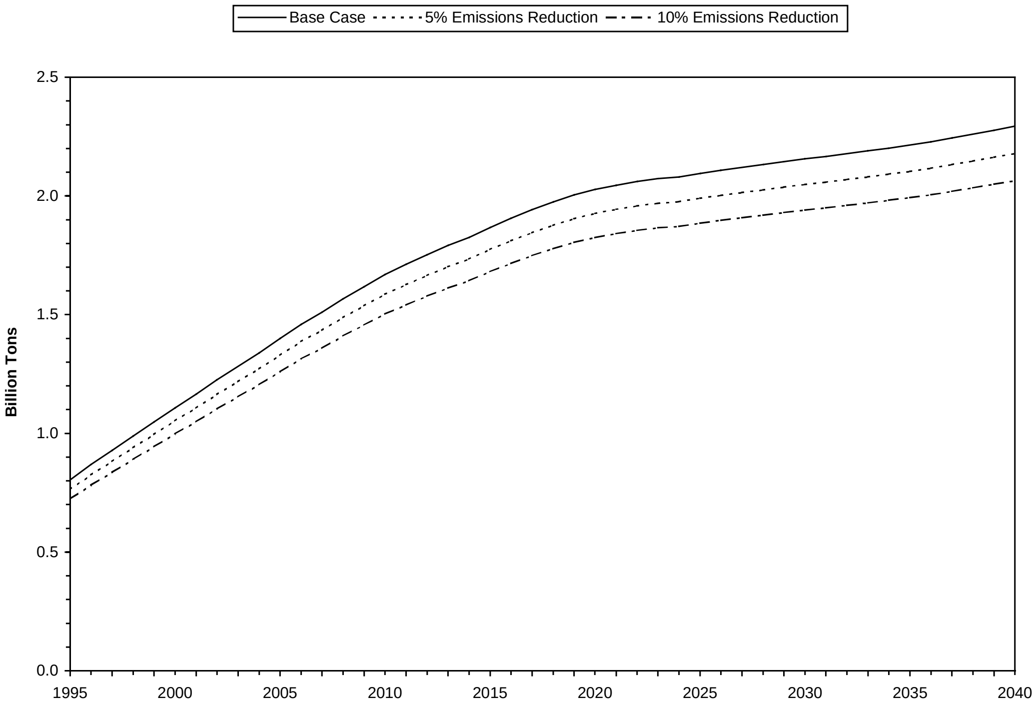


Figure 2. **Carbon taxes required to attain a given reduction in emissions**

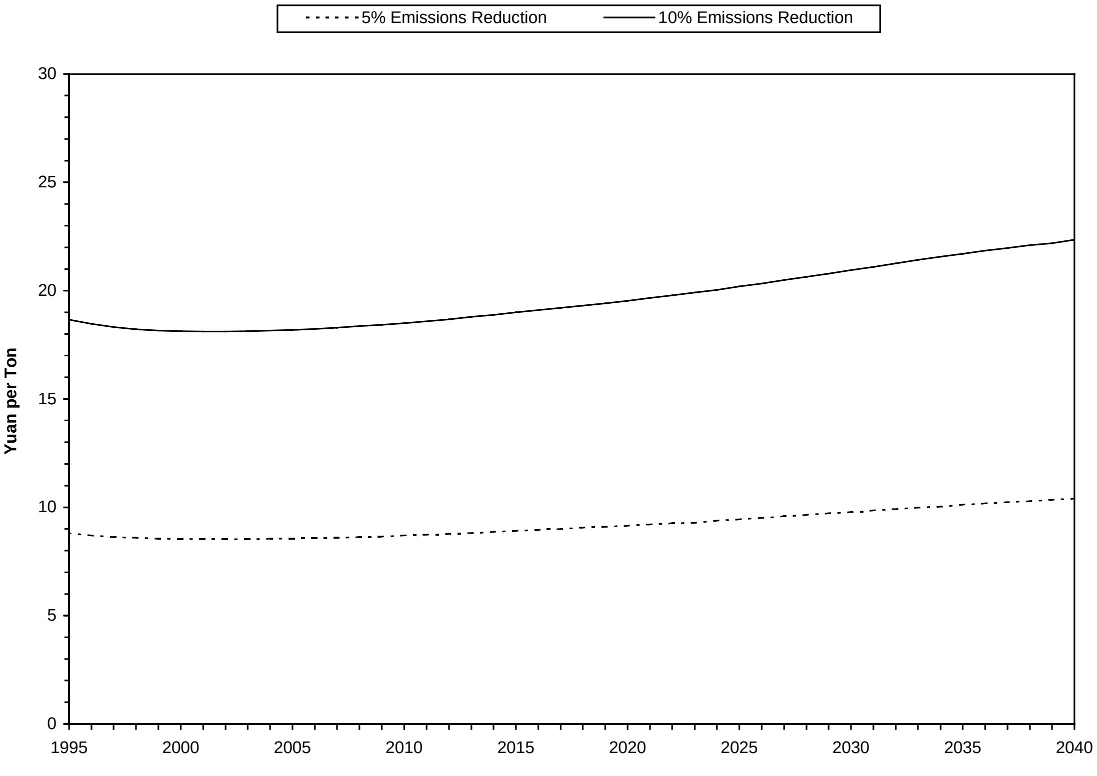


Figure 3. **Reduction in PM-10 emissions and concentrations relative to base**

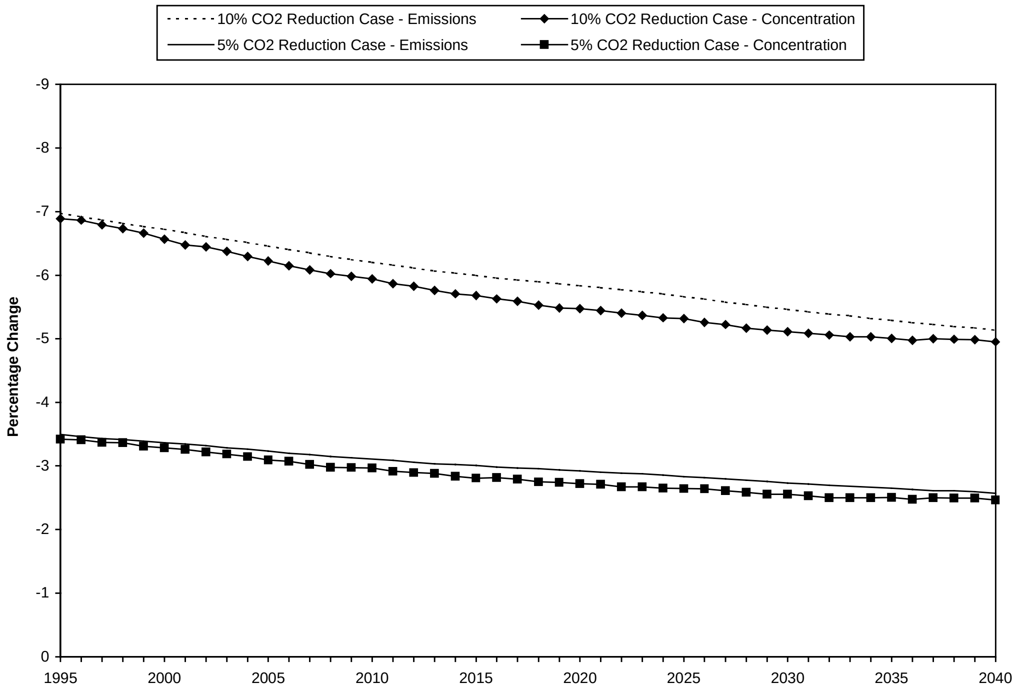
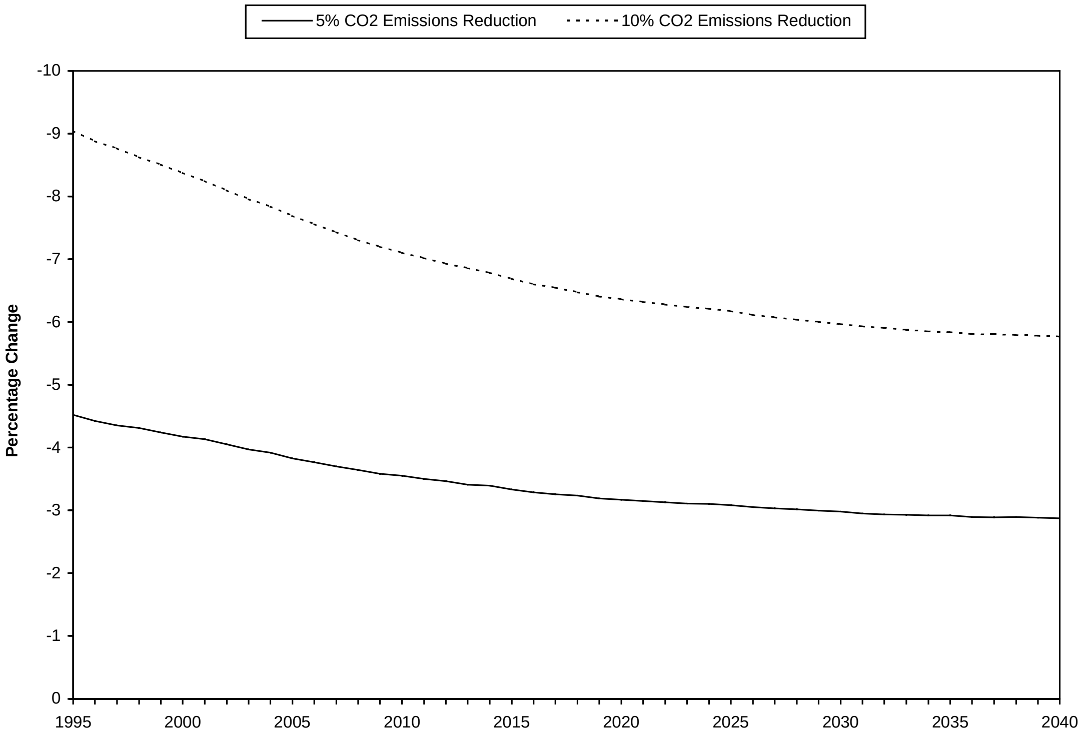


Figure 4. **Reduction in excess deaths relative to base case**



This reduction in emissions results in a fall in the average urban concentration of PM-10 by 3.4%. As a consequence, cases of various health effects fall by about 4.5% (i.e. the number of premature deaths, the number of cases of chronic bronchitis, etc.). The reduction in health effects is bigger than the change in concentration due to the non-proportional nature of equation 5. If we apply these percent changes to the base case estimates in Table 4, this translates to 14,000 fewer excess deaths, and 126,000 fewer cases of chronic bronchitis. Since the valuations are simple multiples (see equation 6) the percent change in *yuan* values of this health damage is also -4.5%.

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 achieve the 5% reduction in carbon emissions. This is shown in the “15th year” column of Table 5 and in Figure 2. The lower tax on crude petroleum in the 15th year is due to our assumption on the price of world 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 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, 3.1% versus 3.5%. The reduction in concentrations over time is correspondingly smaller, as shown in Figure 3.

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 3). This is due to our classifying emissions by height and that low level emissions are the biggest contributors to concentration (i.e. the biggest γ_{cx}‘s). Different sectors of the economy are growing at different rates (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, from a 4.5% reduction in the first year, to a 3.6% reduction in the 15th year, to 3.2% 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 on emissions, concentrations, and health effects is a simple doubling of the percentage change. This seeming linearity would not hold for larger changes.

2.6 Sensitivity analysis

In section three above we discuss first- and second-order effects of an error in a parameter. To illustrate this we use 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 A1 has the urban share of total population rising at 0.5% per year, the “low” case 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 A3. 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 4.5% lower in the first year (see Table 5 and Figure 4). Using the alternative urbanization estimate, mortality again falls by 4.5%. The *percentage* reductions in premature mortality over time for both cases are plotted in Figure A4. They are almost identical.

The wide range of estimates for the dose-response relationship was noted in section three above. For mortality, Lvovsky and Hughes (1997) use 7.14 excess deaths per million per $\mu g / m^3$. 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 A5.

The above illustrates the effect 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 studies.

2.7 Conclusions

This paper presents a preliminary effort to integrate a model of health effects from 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 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 (as described in equations 4 and 5), our estimates of the percent changes in concentrations and mortality would be 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 this preliminary effort is to lay out explicitly the assumptions that need to go into making such an analysis, even with better data and more elaborate model specification. A complex regional air pollution model would still require that projections be made about total and urban population size, future world oil prices, energy efficiency improvements, and all the other time-dependent exogenous variables discussed previously.

Another goal of this preliminary modelling effort is to highlight in which areas improvements in data collection and modelling would bring the greatest benefit to even a limited analysis. Issues beyond those associated with the economic part of the model include: (i) Health damage from air pollution is believed to be due to very fine particles. Data on that would be important. (ii) Data on concentrations in different urban areas and the modelling of these concentrations in a sample of cities would give a sense of the range of the reduced form coefficients. (iii) We have crudely classified emissions by low, medium, and high heights for different industries. Having more refined data on industry emissions characteristics would improve the modelling in item (ii). (iv) Getting better dose-response functions is already a recognized priority. We would urge consideration of including an age dimension in the research. This would be especially important in attempting to link worker’s health back to labor productivity.

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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 (1997). 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 frequently. 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.

Table 1A. **Selected Parameters and Variables in the Economic Model**

Parameters

s_i^e	export subsidy rate on good *i*
t_i^c	carbon tax rate on good *i*
t^k	tax rate on capital income
t^L	tax rate on labor income
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

A.1 Production

Each of the 29 industries is assumed to produce its output using a constant returns to scale technology. For each sector *j* this can be expressed as:

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

where KD_j, LD_j, TD_j, and A_{ij} are capital, labor, land, and intermediate inputs, respectively.[12] 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 return to the owners of fixed capital in sector *j* is:

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

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

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

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

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

---

[12] 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.

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

To allow for biased technical change, the α_{Ej} coefficients are indexed by time and are updated exogenously. We set α_{Ej} to fall gradually over the next 40 years while the labor coefficient, α_{Lj}, rises correspondingly. The composition of the aggregate energy input (i.e. the coefficients α_{kj}^{E}) are also allowed to change over time. These coefficients are adjusted gradually so that they come close to resembling the U.S. use patterns of 1992. The exception is that the Chinese coefficients for coal for most industries will not vanish as they have in the U.S.[13] The coefficient *g(t)* in equation A3 represents technical progress and the change in *g(t)* is determined through an exponential function ($\dot{g}_j(t) = A_j \exp(-\mu_j t)$). This implies technical change that is rapid initially, but gradually declines toward zero. The price to buyers of this output includes the indirect tax on output and the carbon tax:

$$\text{(A4)} \qquad PI_i^t = (1+t_i^t)PI_i + t_i^c \quad .$$

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:

$$\text{(A5)} \qquad Y^p = YL + DIV + G\_I + G\_transfer + R\_transfer - FEE \quad ,$$

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

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

---

[13] 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 2032 will mirror the U.S. economy of 1992, 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.

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:

$$\text{(A7)} \qquad LS_t \;=\; POP_t^w \, hr_t \, q_t^L \quad .$$

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):

$$\text{(A8)} \qquad S_t^p \;=\; s_t Y_t^p \;=\; Y_t^p \;-\; VCC_t \quad .$$

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

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

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

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

We use a Cobb-Douglas utility function because we currently lack the disaggregated data to estimate an income elastic functional form. However, one would expect demand patterns to change with rising incomes and this is implemented by allowing the α_{it}^C coefficients to change over time. These future demand patterns are projected using the U.S. use patterns of 1992.

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 and labor, indirect taxes on output, tariffs on imports, the carbon tax, and other non-tax receipts:

$$\text{(A11)} \quad Rev \;=\; \sum_j t^k (P_j^{KD} KD_j - D_j) \;+\; t^L \sum_j PL_j LD_j \;+\; \sum_j t_j^t PI_j QI_j \;+\; \sum_i t_i^r PM_i^* M_i$$

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

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

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

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

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

(A13) $$Expend = VGG + G\_INV + \sum s_i^e PI_i X_i + G\_I + G\_IR + G\_transfer$$

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

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

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

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

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) $$\Delta G_t = Expend_t - Rev_t \quad ,$$

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

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

The plan portion evolves with plan investment and depreciation:

$$\text{(A19)} \qquad \bar{K}_{jt} = (1-\delta)\bar{K}_{jt-1} + \bar{I}_{jt} \qquad , \qquad t = 1, 2, \ldots, T .$$

In this formulation, $\bar{K}_{j0}$ 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, $\tilde{K}_t$:

$$\text{(A20)} \qquad \tilde{K}_t = \sum\nolimits_j \tilde{K}_{jt} \qquad , \quad \text{where} \quad \tilde{K}_{ji} > 0 \quad .$$

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 two sectors, agriculture and crude petroleum, "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:

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

where $tax(k)$ is total direct taxes on capital (the first term on the right hand side of equation A11).[14]

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

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

Like the α_{it}^C coefficients in the consumption function, the investment coefficients are indexed by time and projected using U.S. patterns for 1992. 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.[15] The total, I_t, can be written as:

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

[15] 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.

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

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

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

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):

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

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*:

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

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

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

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:

$$\text{(A28)} \qquad CA \;=\; \sum_i \frac{PI_i X_i}{(1+s_i^e)} \;-\; \sum_i PM_i M_i \;-\; r(B^*) \;-\; G\_IR \;+\; R\_transfer \qquad ,$$

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

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

A.6 Markets

The economy is in equilibrium in period t when the market prices clear the markets for the 29 commodities and the two factors. The supply of commodity i must satisfy the total of intermediate and final demands:

(A30) $$QS_i = \sum_j A_{ij} + C_i + I_i + G_i + X_i \quad , \quad i = 1, 2, \ldots, 29.$$

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

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

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

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

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

(A33) $$TD_j = T_j \quad , \quad \text{where } j = \text{“agriculture” and “petroleum extraction.”}$$

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

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

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

Figure A1. **Data and projections of Urban population as a percentage of total**

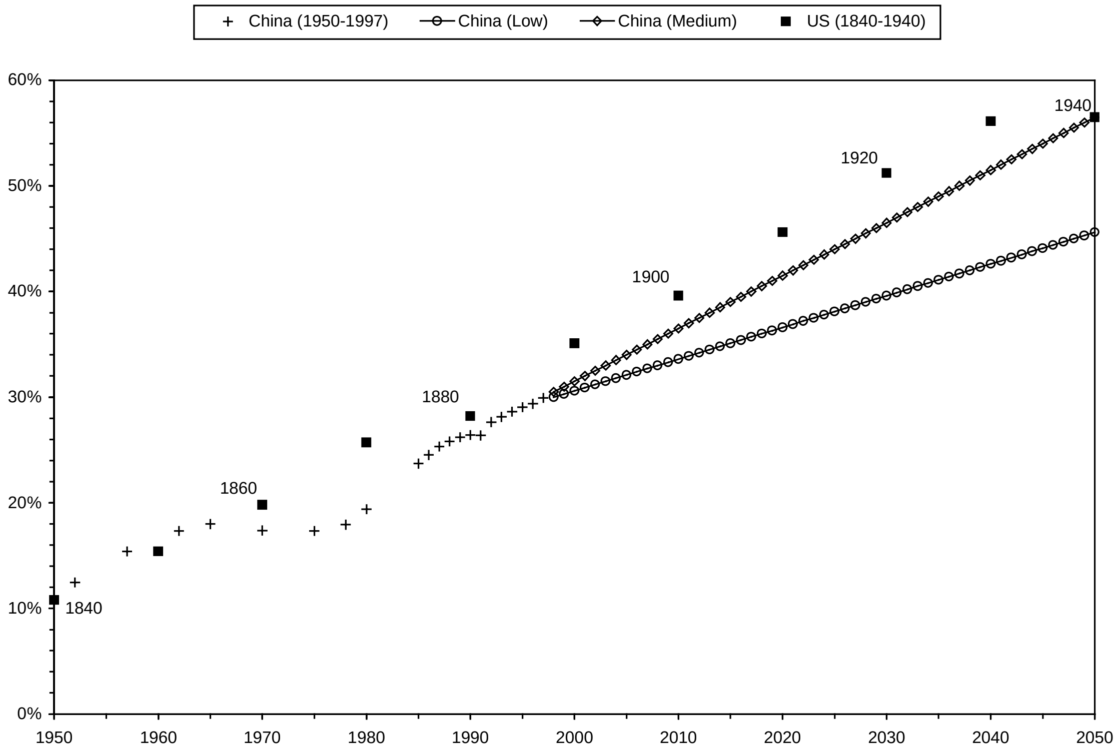
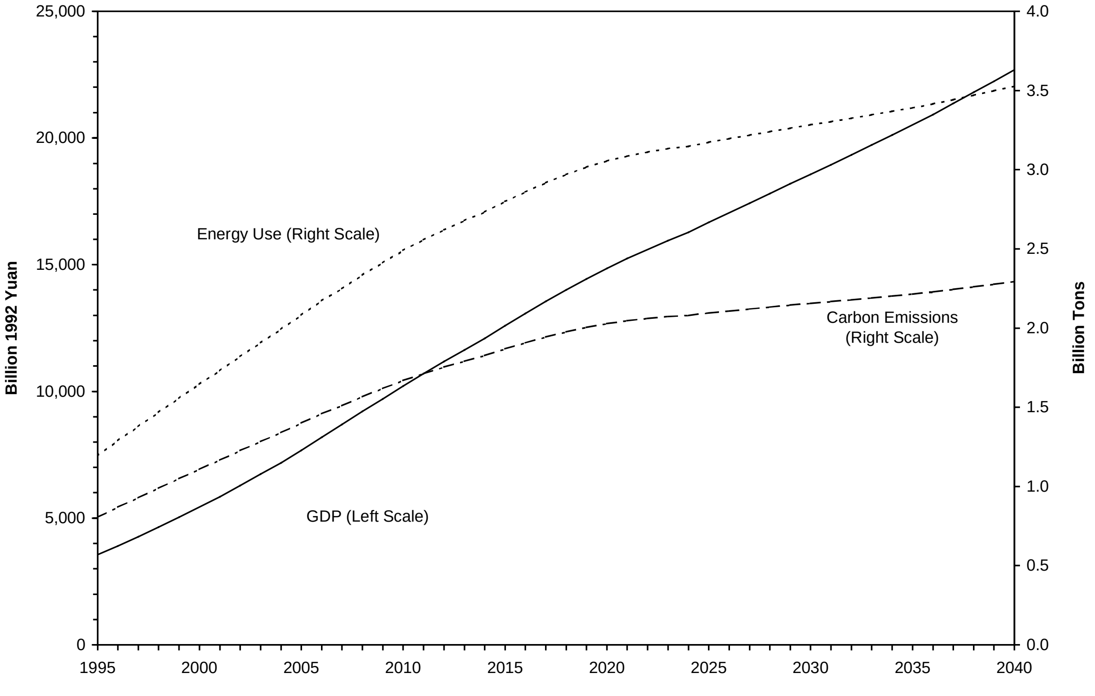
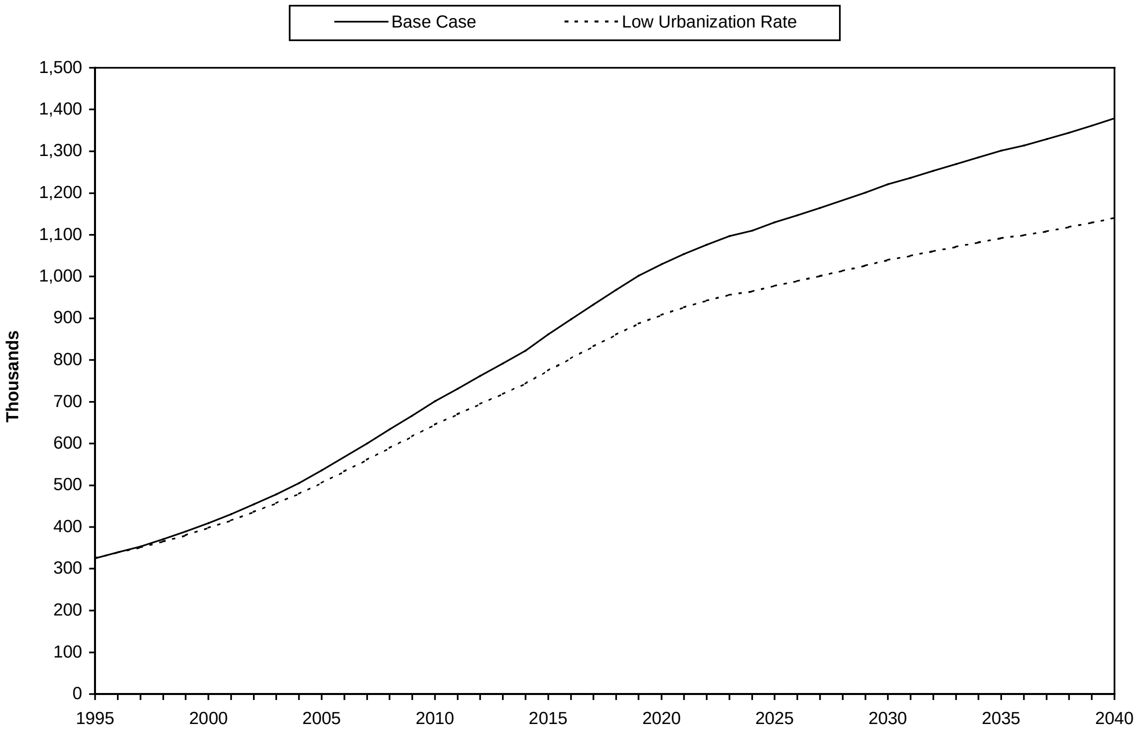


Figure A2. **Projected GDP, energy and carbon emissions, 1995-2040**



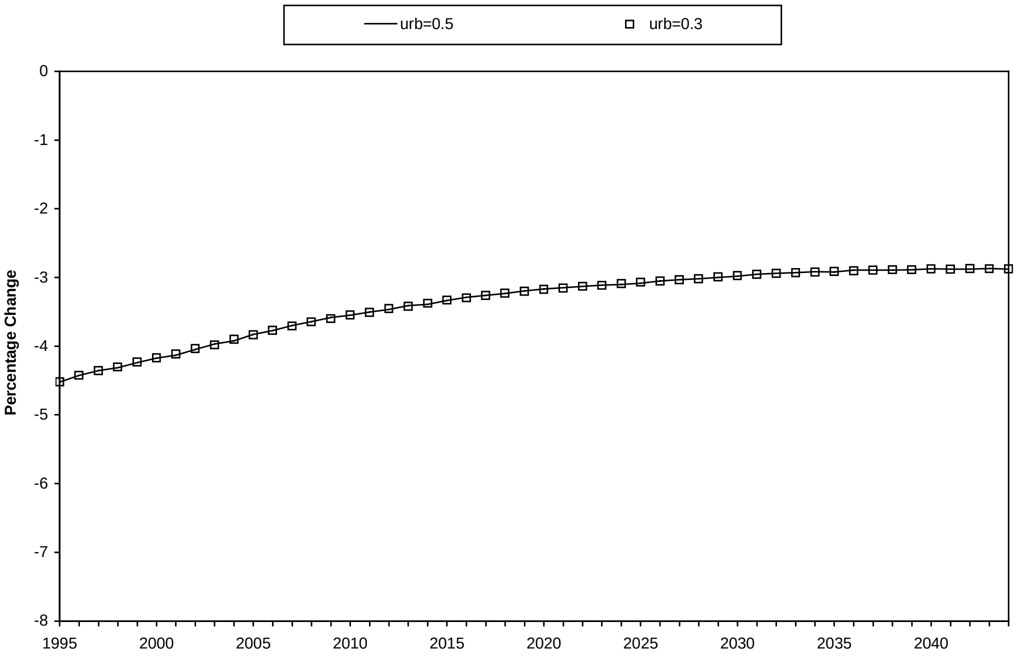
Note: Energy use is in standard coal equivalents (soe).

Figure A3. **Excess deaths in base case versus low urbanization rate**



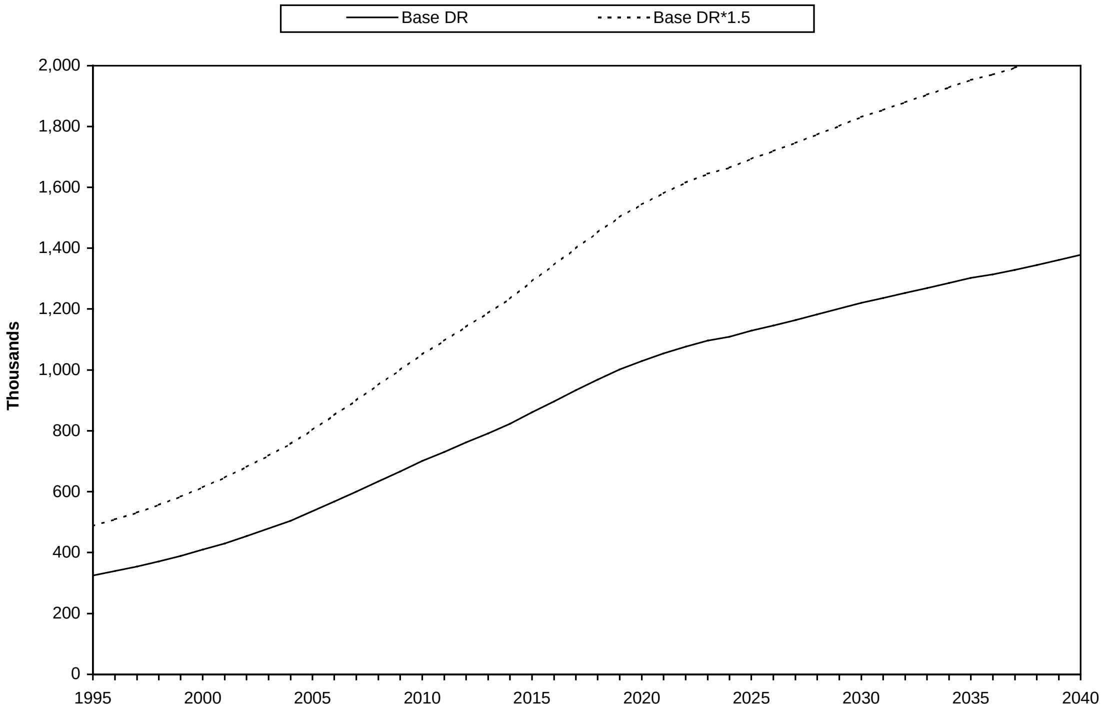
Note: The base case assumes that the urban share of the population is rising at 0.5% a year, in the low case we assume a 0.3% rate.

Figure A4. **Change in excess deaths, base versus low urbanization case**



Note: Each line represents the effect on premature deaths due to a 5% carbon reduction policy.

Figure A5. **Excess deaths in base case versus high dose-response case**



Note: The base case uses the central estimate of the dose response to a 1 microgram/m3 increase in concentration. In the high DR case the value is 1.5 times the base coefficient.