Environment for Development

Discussion Paper Series

April 2008 ■ EfD DP 08-10

"Co-benefits" of Greenhouse Gas Mitigation Policies in China

An Integrated Top-Down and Bottom-Up Modeling Analysis

Jing Cao, Mun S. Ho, and Dale W. Jorgenson

Environment for Development

RESOURCES FOR THE FUTURE

Environment for Development

The **Environment for Development** (EfD) initiative is an environmental economics program focused on international research collaboration, policy advice, and academic training. It supports centers in Central America, China, Ethiopia, Kenya, South Africa, and Tanzania, in partnership with the Environmental Economics Unit at the University of Gothenburg in Sweden and Resources for the Future in Washington, DC. Financial support for the program is provided by the Swedish International Development Cooperation Agency (Sida). Read more about the program at www.efdinitiative.org or contact info@efdinitiative.org.

Central America
Environment for Development Program for Central America
Centro Agronómico Tropical de Investigacíon y Ensenanza (CATIE)
Email: centralamerica@efdinitiative.org

China
Environmental Economics Program in China (EEPC)
Peking University
Email: EEPC@pku.edu.cn

Ethiopia
Environmental Economics Policy Forum for Ethiopia (EEPFE)
Ethiopian Development Research Institute (EDRI/AAU)
Email: ethiopia@efdinitiative.org

Kenya
Environment for Development Kenya
Kenya Institute for Public Policy Research and Analysis (KIPPRA)
Nairobi University
Email: kenya@efdinitiative.org

South Africa
Environmental Policy Research Unit (EPRU)
University of Cape Town
Email: southafrica@efdinitiative.org

Tanzania
Environment for Development Tanzania
University of Dar es Salaam
Email: tanzania@efdinitiative.org

“Co-benefits” of Greenhouse Gas Mitigation Policies in China: An Integrated Top-Down and Bottom-Up Modeling Analysis

Jing Cao, Mun S. Ho, and Dale W. Jorgenson

Abstract

Many greenhouse gas mitigation policies that shift fossil fuel use are accompanied by some hidden environmental benefits, so called “co-benefits” or “ancillary benefits.” Since these “co-benefits” are often overlooked by government policy makers, there tends to be a bias in the policy analysis of various environmental policies and government strategies on global warming. To achieve a plausible estimate of the magnitude of these co-benefits of potential carbon reduction policies in China, this paper applied an integrated modeling approach by combining a top-down recursive dynamic CGE (computable general equilibrium) model with a bottom-up electricity sector model, to simulate three macro-level environmental tax policies: output tax, fuel tax, and carbon tax, as well as national-sectoral mixed policies (a national tax policy with emission caps in the electricity sector).

Based on the integrated model simulations, the estimated ancillary health benefits from the three taxes are quite significant. Under the revenue neutrality condition, it is very likely that China would obtain a “win-win” solution with respect to carbon mitigation, especially if these co-benefits are included in the policy-making cost-benefit analysis. The integrated modeling approach also provides a useful way to examine a complicated mixed policy, such as a national tax policy combined with sectoral-level emission cap policies. In order to achieve both objectives regarding local co-benefits and induce technology change, this model suggests that the preferred policy for China is either a national level fuel tax or carbon tax imposed at the national level with carbon emission caps in the electricity sector.

Key Words: Co-benefits, climate change, CGE model, bottom-up model, top-down model

JEL Classification Numbers: C68, D62, H23

Contents

"Co-benefits of Greenhouse Gas Mitigation Policies in China: An Integrated Top-Down and Bottom-Up Modeling Analysis

Jing Cao, Mun S. Ho, and Dale W. Jorgenson*

Introduction

Greenhouse gas mitigation policies are typically deemed by policy makers to be unnecessary financial burdens that could stifle economic competition, especially for developing countries like China. However, changes in the earth's climate will not only directly affect human welfare through climate itself, but also indirectly affect public health, land use, and ecosystems—requiring action in this arena by all countries. Of particular significance is the discovery by scientists and economists that greenhouse-gas mitigation policies that shift fossil fuel uses toward cleaner energy (or improve cleaner production) can generate hidden environmental "co-benefits" or "ancillary benefits." These co-benefits—such as reductions in local particulate matters (PM), and sulfur dioxide (SO_2) and nitrogen oxide (NOx) emissions—can reduce the overall environmental health damages. Currently, most of the climate change or broader environmental policies are, to a large extent, evaluated only for their potential to reduce carbon and ignore these hidden co-benefits. This may bias various environmental and economic policy analyses, which in turn may sway governments to postpone actions to mitigate greenhouse gases. To draw a more complete picture of possible consequences of potential climate policies in China, one needs to estimate the magnitude of these co-benefits on both the environment and the

* Jing Cao, School of Economics and Management, Tsinghua University, (tel) 86-10-62772410, (email) caojing@sem.tsinghua.edu.cn; Mun S. Ho, Harvard University and Resources for the Future, (tel) 1-202-328-5153, (email) ho@rff.org; Dale W. Jorgenson, Department of Economics and IQSS, Harvard University, (tel) 1-617-495-4661, (email) djorgenson@harvard.edu.

This study is the second chapter of Jing Cao's PhD dissertation at John F. Kennedy School of Government, Harvard University. This integrated top-down and bottom-up model project was supported by the China Project, Harvard University Center for the Environment, and Luce Foundation. The authors are deeply indebted to Professor Peter Rogers for sharing his electricity-sector bottom-up model and research support, and to Professors Robert Stavins and William Hogan for their helpful comments. We are also grateful to Chris Nielsen, executive director of the Harvard China Project, for coordinating this project and funding support, and to Bingjiang Liu and Duan Ling for electricity-sector data support. This paper also benefited from the discussions with Wenhua Di, Lori Snyder, Cynthia Lin, Kate Emans, Jie Lin, Shuxiao Wang, Wang Yuxuan, Li Li, Fan Zhang, and other participants at the Harvard Environmental Economics Seminar and China Project Seminar, and discussions at the Center for Industrial Development and Environmental Governance (CIDEG) seminar at Tsinghua University, Beijing (2007), the Global Institute China-Russia Conference Series (2007), and Pace Conference in Washington, DC (2007).

economic systems. There are two important questions to answer: how large will these "co-benefits" be, and are these co-benefits significant enough that China's state and local government should act to abate carbon emissions immediately?

Several studies have examined the co-benefits of greenhouse gas emission reduction in China. (See, for example, O'Connor et al. 2003, 2001, 2000; Aunan et al. 2000; Garbaccio, Ho, and Jorgenson 2000.) These studies indicate that China, a non-Annex I party to the United Nations Framework Convention on Climate Change (with no mandatory carbon emission targets) should still see substantial gains from the "no regrets" carbon mitigation policies. Consideration of these benefits by the Chinese government may become more important, since, after Russia ratified the Kyoto Protocol, the international climate change negotiations have shifted to a "beyond Kyoto" focus where China's emissions are highlighted. In addition, one reason that the United States opted out of the Kyoto Protocol was its argument that China and India—as large, carbon-emitting, developing countries—were not taking action to mitigate greenhouse gases. All of these international political pressures raise the issue: should China take mitigation action right now or later?

Furthermore, given the "first-mover" advantage and market-share strategy, it may also be important for China to take the lead in implementing greenhouse gas mitigation activities and compete with other developing countries for potential CDM investments in the Kyoto "flexible mechanisms"[1] market. If China steps forward in this area, several relevant policy questions are raised: what are the opportunities and costs for national and local government in China, and how should China adjust its current carbon mitigation policies at both national and sector levels? As the largest and fastest developing country in the world, China is undergoing significant structural transformation. At the current stage of reform, economic development and the welfare of the Chinese people are the primary goals and are given the highest priority in policy reform debates. If the co-benefits and Kyoto flexible mechanisms have significant effects, China may find some "win-win" solutions that meet local and global environmental needs at the same time.

For these reasons, one needs a reliable estimate of the hidden co-benefits of potential climate policies, which can also provide useful information for future environmental policy reform. In particular, it can shed light on how to coordinate both local and global costs and

[1] The Kyoto Protocol provides three "flexible mechanisms" to contribute to the country's development objectives, such as the CDM (clean development mechanisms). These provide outside financial resources for local development projects.

benefits. This paper describes an integrated modeling approach to combine a top-down, recursive computable general equilibrium (CGE) model with a bottom-up electricity-sector model to simulate two categories of policies. The first category assesses three national-level environmental tax policies: carbon tax, fuel tax, and output tax. The second category analyzes several mixed national policies with sectoral-level non-price emission caps. The potential co-benefits for China are significant. In addition, the fuel tax or carbon tax, combined with a sector-specific carbon-emission cap policy would be the most effective in terms of the joint objectives on carbon abatement, health co-benefits, and induced technology change.

This organization of this paper begins in section 2 with a brief methodology review of current literature estimating "co-benefits" and case studies, and discusses current modeling attempts with top-down and bottom-up approaches, as well as integrated or "hybrid" modeling approaches. Section 3 looks at the integrated model in detail, i.e., a top-down Solow recursive CGE model for China, a bottom-up model for China's electricity sector,[2] and an integrating methodology that combines the two specific models for policy analysis as well as the co-benefit estimation methodologies. Section 4 gives the simulation results of the three national-level tax policies, focusing on co-benefits result and implied induced technology changes. It then examines several mixed national tax policies with sectoral-level non-price emission cap policies and compares different types of modeling methodologies and simulation results. Finally, section 5 concludes.

2. Methodology Review

This section briefly looks at the current "co-benefits" studies in both developed countries and developing countries. Next is a discussion of two major modeling methodologies applied on "co-benefits" estimation: the top-down approach and the "bottom-up" approach, and a detailed comparison of their pros and cons. The section concludes with a review of the current integrated model or hybrid modeling attempts and their applications.

---

[2] The bottom-up model was constructed by Professor Peter Rogers's modeling group at the School of Engineering and Applied Sciences at Harvard University. The detail modeling on this electricity-sector bottom-up model is explained in length in Murray (1996) and Kokaz, Liu, and Rogers (1999).

2.1 Review of "Co-benefits" Studies

Current empirical case studies show a range of ancillary effects, from US$ 3/tC to $508/tC;[3] even studies for the same country have substantial differences. Most of the early co-benefits studies were conducted in developed countries, especially the United States and Europe (Abt 1999; Burtraw et al. 2000; Boyd, Krutilla, and Viscusi 1995; RIVM et al. 2000; and others), although some case studies were conducted in developing countries (Cifuentes et al. 2000; Dessus and O'Conner 1999; Garbaccio, Ho, and Jorgenson 2000b; Aunan et al. 2000; and others). Caspary and O'Connor (2002) suggested that the co-benefits in developing countries are probably more significant than those in developed countries and emphasized the need to conduct more such studies.

Co-benefits for China, which is the largest carbon dioxide (CO_2)-emitting country in the developing world, have been studied by a number of groups. Garbaccio et al. (2000b) estimated that local health benefits for China would be substantial—about $52/tC, gained by imposing $1/tC and $2/tC carbon taxes on the whole economy. Gielen and Chen (2000) used the MARKAL model[4] to estimate the CO_2 emission-reduction benefits of Chinese energy policies and environmental policies for Shanghai between 1995 and 2020. Their results showed the opposite result: the "no-regret" options were very limited in Shanghai because it has improved its energy efficiency significantly in recent years. It is unreasonable to apply this single-city scale result to the whole country because the case they chose, Shanghai, is one of the most developed cities with the most advanced technologies in China. An earlier EEPSEA (Economy and Environment Program for Southeast Asia) report reported on a case study of ancillary benefits from various carbon reduction technologies in Guiyang (Cao 2004). It found that the ancillary benefits range was $41–$323/tC for the more advanced electricity technologies. These figures almost doubled for boiler renovation and replacement (Cao 2004). It reinforced the importance

[3] $/tC = cost or benefit value per ton of carbon emitted.

[4] "The basic components in a MARKAL model are specific types of energy or emission control technology. Each is represented quantitatively by a set of performance and cost characteristics. A menu of both existing and future technologies is input to the model. Both the supply and demand sides are integrated, so that one side responds automatically to changes in the other. The model selects that combination of technologies that minimizes total energy system cost. Thus, unlike some "bottom-up" technical-economic models, MARKAL does not require—or permit—an a priori ranking of greenhouse gas abatement measures as an input to the model. The model chooses the preferred technologies and provides the ranking as a result. Indeed, the choice of abatement measures often depends upon the degree of future abatement that is required." ETSAP, http://www.etsap.org/markal/main.html.

of extending the scale of a co-benefits study to provide useful policy recommendations at the national level.

Basically, estimating ancillary benefits is straightforward. First, specific climate policies or strategies result in emission changes of pollutants, such as SO_2 and PM_{10}, and subsequently there is a change in ambient pollutant concentrations. Emissions inhaled by humans result in damage to health and its associated costs. Epidemiology exposure functions and health damage valuations are then applied to calculate the overall social costs and benefits. Figure 1 details the methodology flow chart for both direct climate benefit and co-benefit estimations. Direct climate benefits are difficult to estimate due to their uncertainty, global and long-time horizon, and discounting issues in the evaluation. On the other hand, these local ancillary benefits are more identifiable, certain, and easy to measure, and have important policy implications as well.

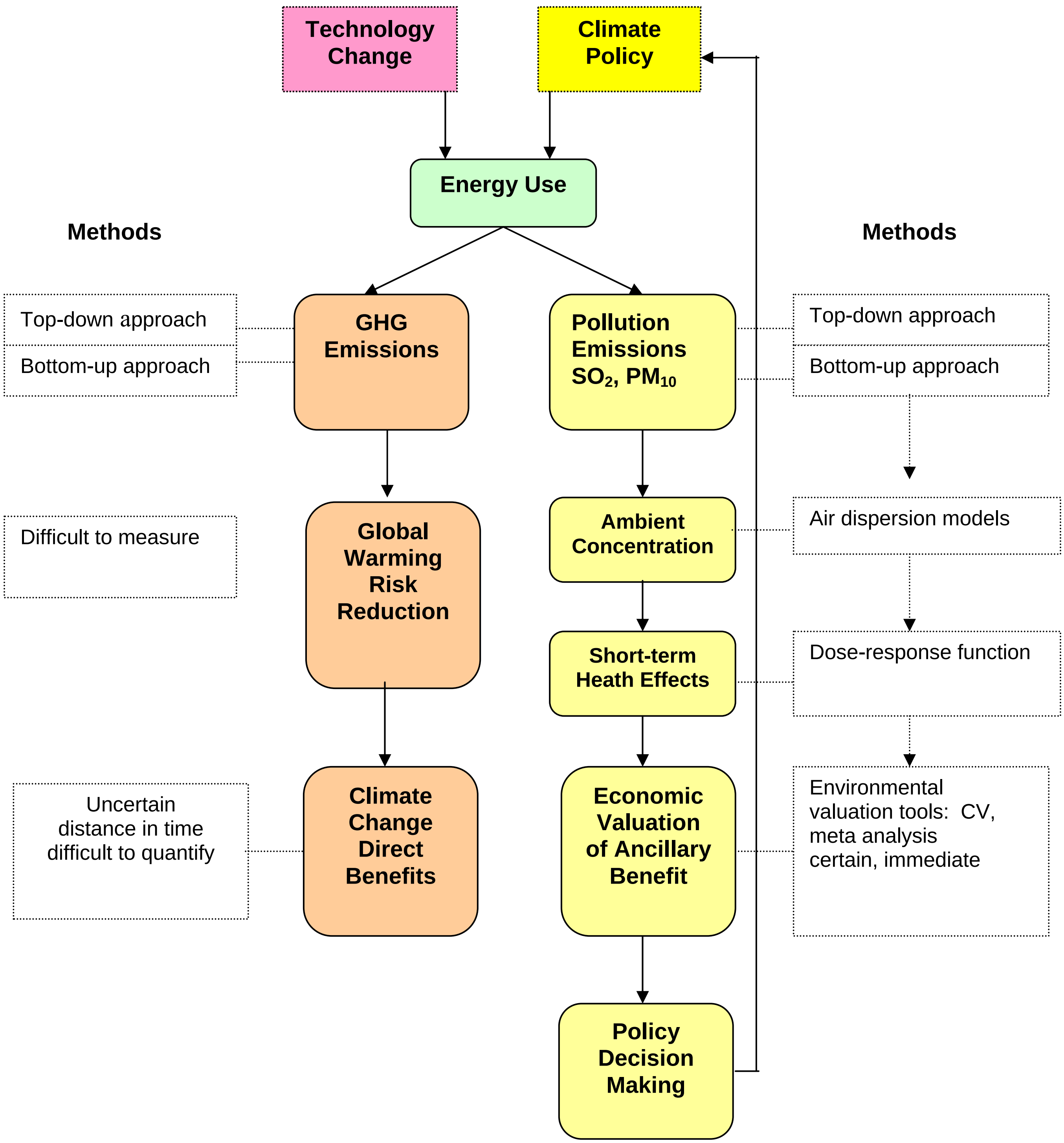
2.2 Review of Modeling Methodologies

Anthropogenic greenhouse gas emissions arise in large part from the extraction, distribution, and combustion of fossil fuels in economic activities. In terms of the modeling approach to greenhouse gas mitigations and impacts on the economy, methodologies differ primarily based on how differently these approaches represent the interactions between the energy system and the economy. Basically, there are two major categories of methodologies: the top-down approach and bottom-up approach.

Although both the top-down and bottom-up approaches of modeling greenhouse gas emissions examine the same relationship between the fossil fuel uses which emit carbon emissions, and economic activities such as manufacturing, construction, mining and etc. The nature of each modeling approach, however, is quite distinct. The terms “top-down” and “bottom-up” themselves are shorthand for aggregated and disaggregated models; i.e., the former emphasizes economic-wide and inter-sector relationships, while the latter focuses on concrete technological details as well as the physical and engineering restrictions. This paper discusses the pros and cons of both models in detail in the following sections.

2.2.1 The top-down approach. Top-down models are generally economy-wide growth or general equilibrium models that examine the broad economy and incorporate feedback effects between different markets triggered by policy-induced changes in relative prices and incomes. The top-down model is useful for estimating co-benefits, since it can be simulated under different national tax policy scenarios involving carbon mitigation, so that the representative consumer utility is maximized subject to economic and policy constraints.

Figure 1. Basic Methodology Flowchart of Ancillary Benefits Estimation



In such analyses, carbon emissions are modeled to be released from the combustion of fossil fuels. The uses of various fossil fuel uses, such as coal, oil and gas, are modeled as energy inputs in a smooth aggregate production function, like capital, labor and other intermediate inputs. Although flexible in terms of incorporating market responses and economy-wide feedbacks and interactions, energy sectors are modeled aggregately by means of smooth production functions, as are other non-energy sectors. However, most energy production (and the electricity sector in particular) deals more with discrete technology options and costs. Smooth production of energy technologies in the top-down model may violate fundamental physical and engineering restrictions (Böhringer and Rutherford 2005). In addition, in the top-down model, technology change is sensitive to calibrated "autonomous" technology improvement or exogenous parameter assumptions (Edmonds 2000). Thus, top-down models rely on flexible-technology production-function assumptions and other exogenous assumptions, such as population growth and total factor productivity, and sacrifice of technological richness and feasibilities. The literature on top-down analyses generally finds that the economic costs or benefits associated with national-wide policies to abate carbon emissions are considerable (Johnstone 1994; Grubb et al. 1993; Wilson and Swisher 1993; IPCC 1995, 2005).

2.2.2 The bottom-up approach. In contrast, bottom-up models focus on either current or prospective technology options in detail, and are frequently used for optimal investment sectoral planning and instigating supply-side efficiency opportunities or demand-side energy conservation measures. In co-benefits estimation, bottom-up sector models are commonly used to simulate the partial equilibrium market (while keeping all prices fixed [Burtraw et al. 2003]), to identify least-cost technology mixes for exogenous demand, or to simulate specific sectoral policies by setting exogenous environmental constraints (McFarland et al. 2002; Kokaz et al. 1999). For example, in many bottom-up models, induced technology changes are represented by how alternative potential technologies enter the technology mix and change the overall energy-use structure.

In most bottom-up models, technology options, life-cycle costs, or geographic allocations have detailed specifications. Environmental constraints, emission caps, or carbon targets can be easily imposed in these models and readily solved using straightforward mathematical programming tools (Barker and Osendahl 2000; Dowlatabadi et al. 1993; Hagler 1995[5]; Palmer et al. 1997[6]; Burtraw et al. 2000[7]; Cifuentes et al. 2000; Wang and Smith 2000; and others).

Although rich in engineering details and important sectoral policy implications, bottom-up models have insurmountable limitations because they lack macroeconomic feedbacks. As McFarland et al. (2000) suggested, under the assumption of exogenous energy demand and market price, these models usually overestimate the potential penetration for advanced technologies. In a sense, these models poorly reflect economic feedback from rising fuel prices or increased costs and concomitant behavioral responses by consumers and producers, especially in a second-best setting.

In addition, the results from the bottom-up model are quite different from the macro-level top-down model. Many bottom-up analyses focusing on costs of carbon mitigation have found that a number of mitigation options are actually available that can be attained at negative, zero, or little cost (Williams 1990; Lovins and Lovins 1991). However, such studies have been criticized for being overly optimistic about low-cost abatement technologies. For example, as Wilson and Swisher (1993) pointed out, they ignore the importance of transaction costs of converting to more energy-efficient systems. In addition, when considering the economy-wide interactions, the shrinking or expanding of different sectors will consequently decrease or increase the overall size of the energy system and may incur higher economic costs in the general equilibrium.

2.3 Review of Current Integrated or Hybrid Modeling Efforts

Some integrated or hybrid models have aimed at integrating the discrete technology choices of bottom-up models with the general equilibrium top-down economic models. First, these models assume that the natures of the two diverse modeling approaches are complementary, rather than being substitutions for each other. (This is discussed thoroughly in both the older literature [Hoffman and Jorgenson 1977] and the more recent literature [Barker et al. 1995; Koopmans and te Velde 2001; Koopmans et al. 1999; Jacobsen 1998; Böhringer and Rutherford 2005].) The so-called “hybrid” models usually have a simplified representation of the energy technologies on the final-demand side or on the energy-supply side, which can be taken

[5] EXMOD model.
[6] PREMIERE model.
[7] HAIKU model.

into the CGE model's equilibrium structures. For example, Pizer et al. (2005) ran a bottom-up model repeatedly by varying technological parameters, and then used econometric methods to calibrate the production function for each technology in the electricity, transportation, and industrial sectors. Next, they took these simplified functions back to the CGE model to simulate both price and non-price policies to mitigate carbon emissions. Wing (2005) drafted a new input-output table by expanding the electricity sector, based on information from the MARKAL model and other electricity cost literatures, and then solved the CGE model with a simplified bottom-up module inside the top-down economic model.

There are other combined integrated models that bridge the engineering and economics models by extracting information from bottom-up models to put into the CGE model and make the two approaches consistent. For example, the Canada Integrated Modeling System (CIMS) model[8] is built to be technologically explicit and to realistically reflect consumer behavior. But, the macroeconomic simulation does not perform as well as the CGE model because of its heavy reliance on trend projections over historical time periods; thus, it is not flexible enough for policy changes. Methodologically, the CIMS model can be modified further by improving the macro- and micro-links, using interaction among sectors through the CGE's input-output and rich interactive feedback frameworks. In contrast, other approaches try to represent energy technology in the CGE model using bottom-up information, such as thermal dynamic coefficients (McFarland et al. 2002). Unfortunately, technical details other than thermal dynamic coefficients are missing in the model, which may also introduce systematic bias as well.

Koopmans et al. (1999) and Koopmans and te Velde (2001) introduced a new type of top-down energy demand model for the Netherlands. In their model, parameters were estimated using bottom-up information and took the energy efficiency gap into account as well. Koopmans' model was the first to bridge the top-down and bottom-up approaches. It made the top-down model consistent with bottom-up information, but this study focused only on energy efficiency change and has not yet been applied to ancillary benefit estimation.

Unlike in previous studies, this study combined two complex models using iteration methodologies to reach convergences of both models, rather than simplifying either model into the other model or extracting bottom-up information into the CGE model in one direction. Linkages of both directions were considered: for example, bottom-up model information is

[8] http://www.emrg.sfu.ca/articles/canadakyoto.pdf

taken into the top-down model, and the time series-price effects from the top-down model are used in the bottom-up model to reflect dynamic price changes and labor-augmenting productivity. Furthermore, none of the above mentioned integrated or hybrid models has been applied to estimate the co-benefits of carbon emissions. This research thus not only contributes to the integrated modeling literature on methodology issues, but also provides useful policy recommendations for Chinese government on future carbon abatements.

3. Integrated Model and Co-benefits Estimation Method

This paper discusses an integrated model that was designed by developing several interfaces between a dynamic recursive CGE model and an engineering bottom-up model in China's electricity sector. In the following sub-sections are an overview of the top-down and bottom-up model, respectively, and presentation of an integrated approach that combined two distinct models for policy analysis. Also described are the damage estimation methods based on the integrated model simulations (particularly the estimation of the environmental health damages, or the co-benefits from the carbon mitigation policies) in this study.

3.1 A Multi-Sector Solow Recursive CGE Model for China

In this paper, the top-down economic module was modified from a prototype of Solow recursive CGE model and a detailed model description which included data sources of the original model (given in Garbaccio, Ho, and Jorgenson 2001). The major characteristics of this integrated model are summarized below.

Production. The production technology is a nested Cobb-Douglas production function:

$$QI_{jt} = g(j,t)KD_{jt}^{\alpha_{Kj}} LD_{jt}^{\alpha_{Lj}} TD_{jt}^{\alpha_{Tj}} E_{jt}^{\alpha_{Ej}} M_{jt}^{\alpha_{Mj}}, \qquad (1)$$

where $g(j,t)$ is the technical progress term that is assumed to have rapid technology progress in the beginning, and then the growth rate decreases and eventually stabilizes at the steady state.

Household. The representative household drives utility from its consumption of commodities, supplies an inelastic supply for labor input in productions, and owns a share of the capital stock. It also receives lump-sum transfers and interests on its public debts. For the recursive property, the representative household makes exogenous savings decisions that are transformed into investments in the subsequent period.

Capital and investment. The Chinese capital stock was modeled in two parts. The first part is a plan share of capital, since some state-owned enterprises might receive favorable investment funds directly from the state budget. The second part is market capital, the rental price of which was equal to the marginal product of capital input. Both types of capital are evolved with investment accumulation and depreciation.

Pre-existing taxation. The model included a variety of pre-existing taxes, such as taxes on production and consumption, subsidies for production and consumption, and tariffs and subsidies for exports. A recent tax reform in 1994 has given the Chinese taxation system a broader tax base, a value-added tax covering all the industrial sectors, a commerce and enterprise profits tax, and a sales tax.[9]

International trade. This model assumed imperfect substitution between goods originating from China and from the rest of the world. Demand for imported of goods was derived from a CES (constant elasticity of substitution) aggregation of domestic and imported goods. The current account and government debts were set as exogenous.

Market clearing. All market prices in the model were endogenous and adjusted to clear the market for goods and factors. In addition, the government's debt balance, trade balance, and savings-investment balance were combined in order to complete the model. The Walras Law was checked to test the market clearing.

Calibration. To improve the robustness of the model, a critical step after setting up the model was to calibrate parameters in the recursive CGE model, so that it could successfully "replicate" the benchmark year 2000 for China.

3.2 A Bottom-Up Model for China's Electricity Sector

The electricity sector model was based on the Harvard Power Sector Electricity Generation Technology Choice Model devised by Peter Rogers' modeling group at the School of Engineering and Applied Sciences (SEAS) of Harvard University (Murray 1996; Kokaz et al. 1999). This model distinguished 15 technologies for electricity generation (see table 1), which

[9] For simplicity in this model, other taxes with small revenues are included in the sales tax on commodities.

included 7 coal-based generators, 3 coil- and gas-based generators, 4 renewable energy generators, and nuclear power.[10]

Table 1. Electricity Generation Technology Description and Abbreviation

Technology Abbreviation	Description
DOM ESP/SCB	Domestic steam-fired combustion, 300MW and above, with ESP or scrubber
DOM BIG	Domestic steam-fired combustion, 200MW to 300MW, with ESP
DOM MED	Domestic steam-fired combustion, 100MW to 200MW
DOM SML	Domestic steam-fired combustion, 100MW and less
AFBC	Foreign atmospheric fluidized bed
PFBC	Pressurized fluidized bed combustion
IGCC	Foreign integrated gasification combined cycle
OILREG	Oil-fired traditional plant
OILCC	Oil-fired combined cycle plant 100MW
GASCC	Gas turbine combined cycle plant 100MW
HYDRO	Hydropower station
NUCL	Nuclear power generation
WIND	Wind power generation
GT	Geo-thermal power
PV	Photovoltaic power generation

Source: Kokaz, Liu, and Rogers (1999), 20, table 2.

The objective of this industrial sector model was to simulate future electricity-capacity expansion path and determine the optimal technology mixes of the above 15 types of technologies by minimizing the total net present costs of electricity generation (shown below):

[10] In the previous version of this model, domestic steam-fired combustion 300MW and above were differentiated with ESP (DOMESP), and the same size with scrubber (DOMSCB). In this version, due to the data limitation for the power generation for the year 2000, the difference was ignored and aggregated into one category only, shown in table 1as DOM ESP/SCB.

$$
\begin{aligned}
Z = \sum_{t=1}^{n} 1/(1+r)^n \times & \\
\sum_i \sum_f QS_{i,f,t} \times UCFUEL_{i,f,t} & \quad \text{fuel mining costs} \\
+ \sum_{k,k1} (CQ_{i,k,k1,t} \times CC_{k,k1} + PQ_{i,k,k1,t} \times PC_{k,k1}) & \quad \text{fuel chemical and physical cleanning costs} \\
+ \sum_{i1,c,m} QTR_{i,i1,c,m,t} \times UCTRPT_{c,m,i,i1,t} & \quad \text{transport and transmission costs} \\
+ \sum_s QSELEC_{i,s,t} \times COSTVAR_{s,t} & \quad \text{variable operating costs} \\
+ \sum_s QCAP_{i,s,t} \times COSTFIX_{s,t} & \quad \text{fixed operating costs} \\
+ \sum_{t1} 1/(1+r)^{t1-t} \sum_s ICOST_{i,s,t} & \quad \text{cost of new generation capacity}
\end{aligned}
\qquad (2)
$$

As shown in equation (2), the net present costs for national-wide electricity generation include the following six components:

- Costs of all types of fuel f (six types of coal, oil, gas, and uranium) mined in all i regions at each period t
- Costs of physical and chemical cleaning of coal at each period t
- Costs of transporting fuel (by rail, road, ship, or pipeline), or transmitting electricity (by wire) to other region $i1$ at each period t
- Variable operating costs of electricity generation at each period t
- Fixed operating costs of electricity generation at each period t
- New investment costs of expanding any new capacity in the optimal technology mix to meet the electricity demand at each period t

As with most bottom-up models and electricity planning studies, in this bottom-up model, a “levelized cost” of electricity generation is used to calculate the new investment flow on increased capacities:

$$ICOST_{i,s,t} = (QCAP_{i,s,t} - QCAP_{i,s,t-1}) \times COSTCAP_s \times \left[\frac{i(1+i)^N}{(1+i)^N - 1} \right], \qquad (3)$$

where the first two terms represent the net present value of the capital costs of expansion of electricity capacity, i is the discount rate in the model (assumed to be 8 percent), and N is its years of operating life.

Table 2 gives the detailed characteristics—capital cost, construction period (year), economic life (year), annual generation hours, efficiency of fuel use (percent), amount of fuel use per kg or m^3 per KWh—as well as cost data, such as fuel price, and fixed and variable operating and maintenance costs of each electricity generation technology option.

In this model, China was divided into six regions: north, northeast, northwest, east, south-central, and southwest. Because this is a sector-specific model, the electricity end-use demand of different regions at each period t was exogenously determined. Also, in order to realistically simulate the future expansion path of the electricity capacity and technology mix in China, a variety of constraints were assumed in the model and categorized into three types.

1. Resource constraints. Fuel production was constrained by the capacity of fuel mining and known mine deposits in each region. In addition, the amount of fuel could not exceed the maximum transport capacity from region i to region $i1$; similarly, electricity transmission was also limited to the existing wire capacity. As a result, the major resource constraints included the fuel supply constraints in each region, transportation capacity constraints, and transmission restrictions.

2. Technological constraints. Each type of technology had conversion efficiencies, representing the efficiency from the raw energy form (fuel) to final energy form (electricity). Each technology also had constraints in terms of capacity factors of technologies. Finally, different types of fuels had different heat contents in electricity generation.

3. Sector-specific environmental constraints. These constraints are not binding if one is simulating only for national level environmental policies. However, if the goal is to examine sector-specific environmental policies as well, these constraints can be used to model the emission cap policies on exogenous SO_2 emissions, sulfur depositions, and CO_2 targets.

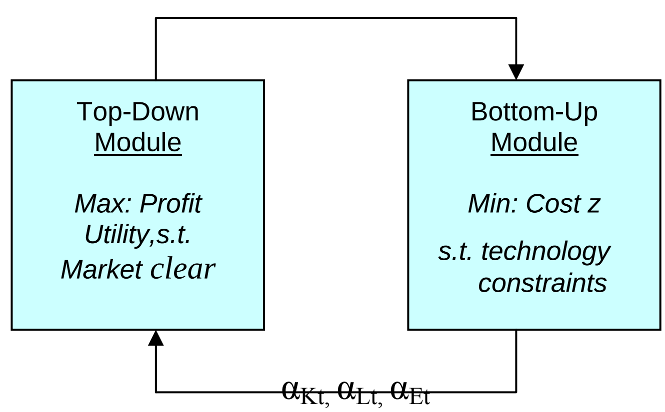
Table 2. Characteristics and Cost Data of Electricity Generation Technologies in the Bottom-Up Model

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	DOM ESP/SCB	DOM BIG	DOM MED	DOM SML	AFBC	PFBC	IGCC	OIL REG	OIL CC	GAS CC	HYDRO	NUCL	WIND	GT	PV
Capital, $/KW	607	625	650	676	850	1125	1150	530	600	800	900	1350	1000	3000	4500
Construction period (years)	3	3	3	2	3	3	3	2	1	1	8	7	1	1	2
Economic life (years)	30	30	30	20	30	30	30	20	20	20	50	30	20	15	30
Annual generation (hours)	6000	6000	6000	6500	6500	6500	6500	6000	6000	6000	4000	7000	3000	5700	2500
Discounted rate (%)	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%	8%
Efficiency (%)	36.5	34.5	33.5	26.0	37.5	39.5	39.5	35.0	40.0	40.0		33.0			
Fuel use (kg or m^3/KWh)	0.478	0.478	0.478	0.649	0.459	0.436	0.436	0.246	0.215	0.231		0.0038			
Fuel price ($/kg or m^3)	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.1084	0.1084	0.09		6.30			
Fuel cost ($/KWh)	0.0086	0.0086	0.0086	0.0117	0.0083	0.0078	0.0078	0.0266	0.0233	0.0208		0.0239			
Variable cost (million $/TWh)	3.5	3.6	4.0	5.0	4.5	4.5	4.5	2.8	2.8	4.0	1.0	4.0	2.0	0.05	0.07
Fixed cost ($/KW)	18.2	18.8	19.5	20.3	25.5	33.8	34.5	15.9	18.0	24.0	13.5	40.5	15.0	45.0	67.5

3.3 *Integrated Modeling Approach*

In fact, considering the logic of the two models, the optimal principles applied in both models are just two sides of the same mirror. In the bottom-up model, the objective was to minimize the total cost of meeting electricity demand. Total electricity generation costs were calculated by adding the net present value of all of the technology options, where the production output must meet demand requirements and environmental, transportation, and transmission capacity constraints; input supply constraints must be met as well. In the CGE model, the objective of private enterprises was to maximize a profit function, which is the total revenue minus the total cost of various inputs (capital, labor, energy aggregate, non-energy aggregate, and land) and various taxes. From the operational research and microeconomic theory, one understands that, in essence, the two objective functions are equivalent, and the optimal solutions for the dual problem calculated by the GAMS software should be consistent as well. Thus, the theoretical basis for the two models was consistent, and the engineering and economic model components could be treated as complementary in simulation, enabling feedbacks between the two models.

Figure 2. Flow Chart of the Integrated Top-Down Bottom-Up Model



To build the linkages between the two models, three integrated principles were assumed in this study.

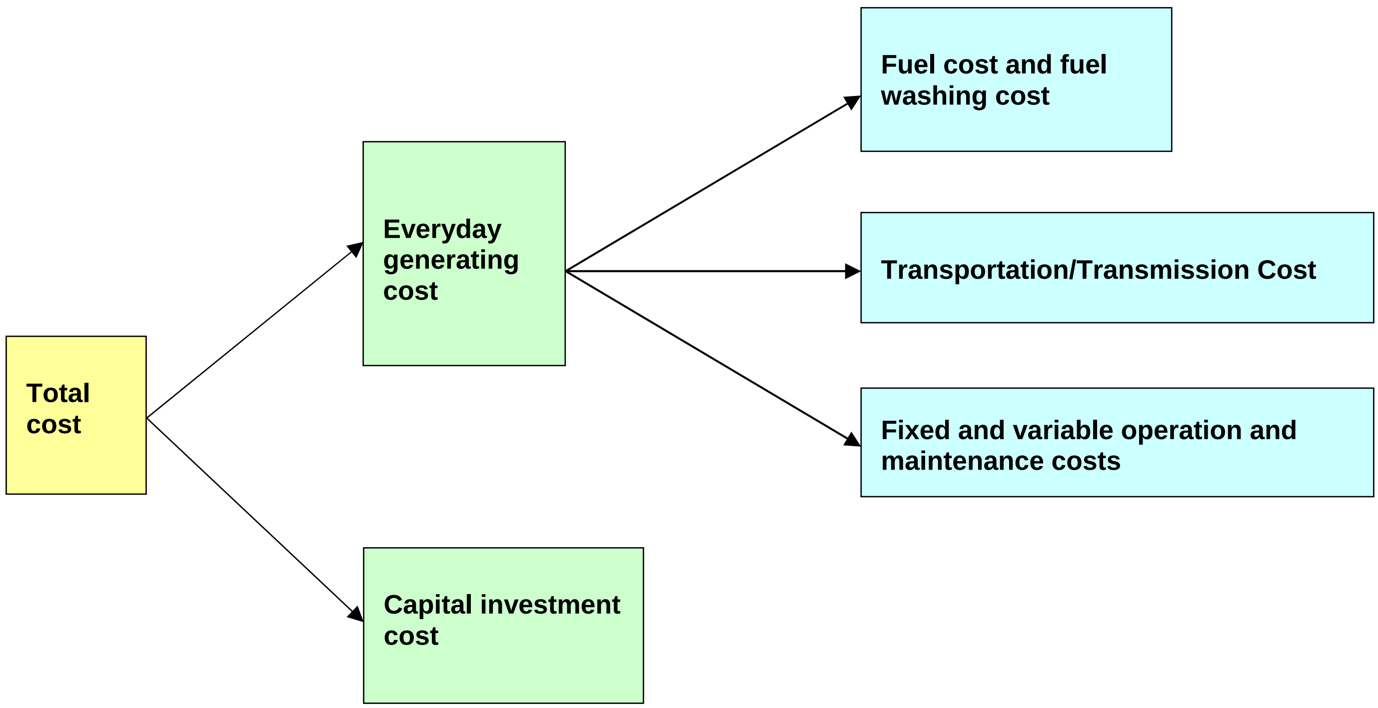
1. The demand for the electricity sector must be consistent in the integrated model. This suggests that exogenously determined electricity demand in future periods should be input by the CGE model's simulated output for the electricity sector. All the six regions were assumed to have the same growth rates from 2000 to 2020. In this way, the simulations from the bottom-up model would reflect the electricity demand from the remaining sectors in the economic system, especially considering the interaction effects within sectors, and changes in consumer and producer behavior after the tax policy is imposed for the entire economy.

2. **All the price variables in two models must be consistent.** For example, if a fuel tax is imposed, the impact on coal prices will be heavy, and the fuel input cost in bottom-up models for all electricity generating technologies should reflect the changes intertemporally. In the base case simulations, all price variables—such as the time-series labor prices, fuel prices, transportation prices, and capital investment costs—are taken into the bottom-up module to reflect behavior changes due to the price signals, and also should be consistent with top-down model assumptions regarding technology progress or augmented labor input. In addition, by comparing the base case and counterfactual case, relative aggregate price changes P(counterfactual)/P(base) can be calculated from the top-down model. Thus, these changes can be captured in the bottom-up model simulations as well to reflect the price shocks in the bottom-up model.

3. **All exogenous parameters in the two models should be consistent.** This requirement was very demanding, especially for the hundreds of parameters in the CGE model. As a result, this study only focused on primary key parameters linking the top-down and bottom-up approaches. It began by looking at the cost structure of two models because, as argued by Jacobsen (1998) in his hybrid model, an important issue for integrating the two modeling approaches was to make the cost concept consistent. For this reason, this study attempted to synthesize the engineering and economic cost structures, and then adjusted the exogenous parameters in the CGE model to achieve consistent optimization solutions for the two models.

By extracting the cost structure for the two models, one can see the huge differences between them, although the basic cost concepts are consistent in actual production activities. In the bottom-up engineering model of China’s electricity sector, total costs to meet electricity demand included everyday generating costs (fuel costs and coal washing costs, transportation and transmission costs, fixed and variable operating and maintenance costs of power plants), and the capital investment cost are shown in figure 3.

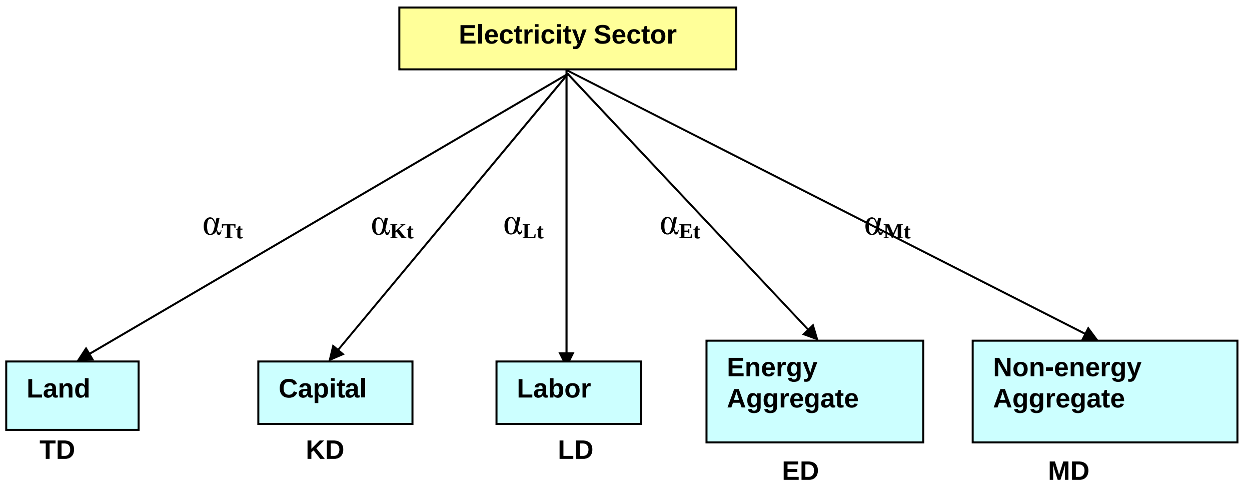
Figure 3. Cost Structure of the Bottom-Up Electricity Sector Model



On the other hand, the total costs in CGE model were divided into capital, labor cost, energy aggregate, non-energy aggregate, and land costs. Although presented in a different terminology, the engineering-detail cost structure actually can be consistent with the cost structure in the CGE model. Here, the bottom-up annual leveled capital investment and fixed operating and maintenance costs can be treated as input of capital; the bottom-up fuel cost and transportation and transmission cost can be treated as energy input cost; and the variable operating costs can be treated as labor input—similar to the approach by McFarland et al. (2002) in a revised MIT EPPA model.

In the integrated model, an optimal technology mix was determined by minimizing the net present-cost function of the total electricity power generation. By structuring the bottom-up costs to be consistent with the top-down cost structures, we could adjust the share parameters of Cobb-Douglas production function for the electricity sector in the CGE model. Therefore, the cost structure (share of these factors) in the top-down model can be represented in the production function with the structure as follows in figure 4.

Figure 4. Production Structure of Power Sector in the Top-Down Model



In figure 4, α_{Kt}, α_{Lt}, α_{Et}, and α_{Mt} were adjusted by the cost share data resulting from the bottom-up model, and α_{Tt} was set as zero, based on China's input output table of 2000. For both models to achieve optimization, iteration techniques were used for convergence. Next, all of the allocations were in general equilibrium, either in the economic or engineering systems. The cost-share parameter-adjusted CGE model now was consistent with the details of the technology cost information for the electricity sector. In the previous CGE model, the cost share parameters were fixed exogenously and were constant for both the base case and the counterfactual cases with tax policies. By incorporating the information from the bottom-up model, one can gain a better idea of how the capital, labor, and energy shares change over time. In addition, in the counterfactual cases when there was a policy change, the technological mix changed, and cost-share parameters with various inputs also changed correspondingly. Thus, these could be endogenously examined in this integrated model as well.

3.4 Co-benefits Estimation Method

The estimation method of the co-benefits was the same as the health damages evaluation method in the environmental economic literature. In this study, due to data limitations, only health related co-benefits were examined, which included benefits from reductions of primary pollutants (such as TSP [total suspended particles] and SO_2) and secondary particles (such as sulfates and nitrates). Here the study followed the same intake-fraction estimation approach discussed in length in Cao, Ho, and Jorgenson (2005) and Ho and Jorgenson (2007). The sectoral intake-fraction coefficients were estimated from the atmospheric pollution dispersion model, which were calculated from the amount of pollutants ingested by someone within a given domain, as well as from concentrations and breathing rates:

$$iF_{xr} = \frac{BR\sum_{d} C_{xd} POP_{d}}{EM_{xr}} \quad (4)$$

Using these estimated coefficients from the atmospheric model and estimated emissions from the CGE environmental module, one can calculate the total dosage (i.e., the total amount of pollutants inhaled by the entire population), which can be directly plugged into the traditional dose-response function framework to derive environmental damages, the reduction of which is a co-benefit of carbon mitigation activities.

$$DOSE_{xj} = iF_{xj}^{N} EM_{xj} = BR\sum_{d} C_{xd,j} POP_{d} \quad (5)$$

$$HE_{hj}^{IF,S} = \sum_{x}\left(DR_{hx} \frac{DOSE_{xj}}{BR} \right) = \sum_{x}\left(DR_{hx} \frac{iF_{xj}^{N} EM_{xj}}{BR} \right) \quad (6)$$

Finally, based on the contingent valuation studies from both China and abroad, the co-benefits of each health endpoint h can be monetized by using the marginal willingness to pay unit value V_{ht}, and then the sum gives the total health related co-benefits:

$$TD_{t} = \sum_{h} V_{ht} HE_{ht} \quad (7)$$

4. Model Simulation Results

The integrated model described above was based on the recent national input-output table of the year 2000, compiled by Li Shantong and He Jianwu of the State Council Development and Research Center and Chinese National Bureau of Statistics. In the top-down model, the general equilibrium effect was simulated for an exogenous tax policy shock for 33 industrial sectors, in which the electricity sector was the largest user of coal and thus the largest carbon emitter. For the electricity sector, although only an aggregate production function was applied in the aggregate CGE model, all the endogenous and exogenous variables and parameters were modeled to be consistent with the lower-level bottom-up model.

4.1 Base Case Simulation

The central goal of this study was to provide estimates for co-benefits from carbon-mitigation environmental tax policies. Thus, it was important to simulate a base-case projection of the future Chinese economy where one can compare all the endogenous variables for consumption, investment, energy use, and environmental damages—and compare the base case where no policy is implemented to the counterfactual simulation case with a hypothetical tax. In the base case model, population growth, technical progress, world price, and government debt and current account deficits were exogenously determined in the model. Although these strong assumptions may deviate in the base case simulation from China's actual economy in the future, it must be noted that since only the changes[11] between the base case and counterfactual cases were examined, the bias from the real world had just a second-order effect in terms of magnitude.

Table 3 briefly summarizes the Solow economic model projections, including population growth, gross domestic product (GDP) growth, and estimates of environmental damages in 2000, 2010, and 2020. The projection of Chinese GDP growth over the next 10 years using this integrated model is about 7.6 percent annually, and the growth rate for the whole simulation period (20 years) is about 6.46 percent. This is similar to the forecast made by the World Bank (1997), but lower than that forecasted by the second generation model (SGM) in Jiang and Hu's study (2001). In addition, this model assumed that, due to rapid technological progress in energy conservation, the projected future energy intensity would gradually decline, so the growth rate of energy use was simulated at 4.65 percent over the next 20 years, slightly slower than the projected GDP growth rate for China. The growth rate of coal use, oil use, and carbon emissions should follow a similar trend of future growth at about 4.59–4.71 percent, and oil use would grow slightly faster, considering the increasing demand for automobiles in China.

In the environmental module, based on the simulated industry output and input requirements, one can also calculate the emissions of primary particulate matters, SO_2, and NOx.[12] First, the model simulation suggested that technological progress on PM_{10} abatements would dominate future particulate matter emissions. This is despite the fact that demand for coal will increase as China's economy grows, so that PM emissions will actually decline for the next 10 years. However, after that, PM_{10} emissions should rise again as the demand for coal increases and eventually dominates, while progress in technology may become quite flat beyond a certain point. The overall decline of PM emissions in 2020, compared to 2000, is about 0.89 percent.

[11] In the CGE modeling literature, percentage changes are commonly used to reflect impacts on key variables between base case and counterfactual cases.
[12] NOx is mainly emitted by the transportation sector only.

Table 3. Selected Variables from Base Case Simulation

Variable	2000	2010	2020	20-year growth rate
Population (million)	1,262	1,351	1,431	0.63%
GDP (billion, in 2000 yuan)	9,180	19,088	32,111	6.46%
Energy use (fossil fuels, million tons of standard coal equivalent)	1,174	2,099	2,912	4.65%
Coal use (million tons)	1,183	2,092	2,904	4.59%
Oil use (million tons)	206	379	517	4.71%
Carbon emissions (million tons)	780	1,392	1,930	4.63%
Primary particulate emissions (million tons)	11.20	8.88	9.36	-0.89%
SO_2 emissions (million tons)	18.57	26.60	34.87	3.20%
NOx (transportation, in million tons)	3.06	6.33	9.50	5.82%
Premature deaths (per 1,000)	89	146	223	4.69%
Value of health damages (billion yuan)	151	459	966	9.70%
Health damage/GDP	1.65%	2.52%	3.29%	

However, for SO_2, a less optimistic estimate of improvements in its emission factors was assumed over the next 20 years. Thus, the simulated SO_2 was expected to double by 2020, and the annual growth rate was projected at 3.2 percent. Currently, because China's transportation sector is expanding very rapidly, simulated NOx emissions from automobile exhaust were expected to increase rapidly as well, at an annual growth rate of about 5.82 percent.

Based on the intake fraction and integrated model, the estimated premature deaths due to environmental pollution was about 89,000 deaths in the first year (2000), and should increase about 2.5 times in 2020 at an average growth rate of 4.69 percent over the 20-year simulation period. When estimating the monetary value of the overall health damages, since the WTP (willingness-to-pay) unit valuation of all health endpoints is adjusted based on the increasing per capital incomes, the value of the health damages should increase faster than the number of premature deaths, at about 9.7 percent over the next 20 years. The ratio of health damage over GDP was also estimated to increase from 1.65 percent in 2000 to 3.29 percent in 2020.

As described in the methodology section, we iterated the top-down CGE model and bottom-up electricity sector model until both models converged. We then checked the interface linkage variables—such as the electricity demand extracted from the CGE model and input into the electricity model, and the cost-share parameters extracted from the bottom-up—and imported them into the CGE model. The iterations terminate when the key linkage variables in any two consecutive simulations satisfy the following condition:

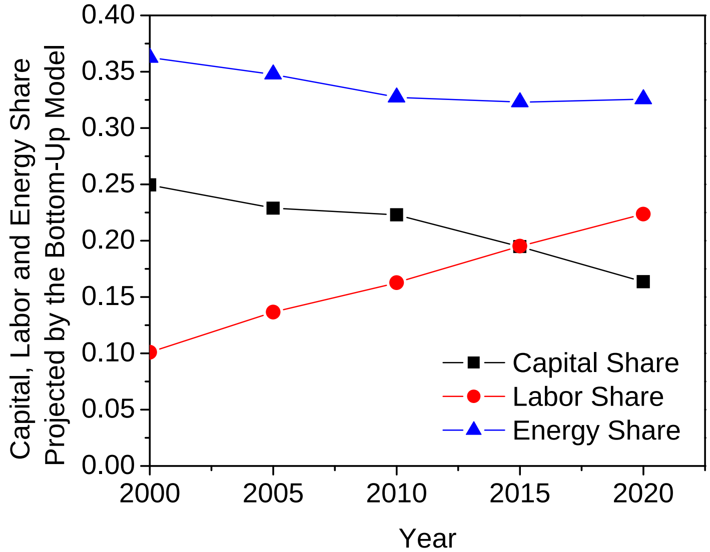
$$\frac{|x_N - x_{N-1}|}{x_{N-1}} \le \zeta \quad , \tag{8}$$

where ξ is the end-iteration tolerance level (such as in the base case, ζ =0.2% for the factor share parameters, and ζ =0.3% for the electricity demand projected in CGE model for each period), and N is the number of simulation times approaching convergence and exiting the loop.

In a previous version of the Solow recursive CGE model used in Ho and Jorgenson (2007) and Cao, Ho, and Jorgenson (2005), the capital, labor, and energy share were calibrated in the first year to match the base-year input-output table of 2000. In the subsequent periods, the capital share was assumed to be fixed for all simulation periods from 2000 to 2020. The China energy share (as in Cao, Ho, and Jorgenson 2005; and Ho and Jorgenson 2007) was assumed to eventually converge with the energy shares in the US input-output table of 1982. Thus, the energy intensity was assumed to decline gradually. In previous versions of CGE model, where the bottom-up module was not added in, the energy share was assumed to be 37 percent in the first year and to gradually decline to 30.4 percent in 2020. To maintain the sum of total share equal to unity, the labor share was correspondingly adjusted to increase from 13.3 percent in the first year and to 29.9 percent in 2020. The problem with this treatment was that all of these assumptions were made exogenously, which might bias the results from the CGE model alone—and particularly in evaluating the policy changes in the medium or long run.

However, based on the detailed technology information and cost data in the bottom-up electricity sector, the capital, labor, and energy shares could be adjusted based on the concrete technology options and their costs. In the base case, when both top-down and bottom-up models converged, the cost-share parameters were extracted from the bottom-up model. The trends are shown in figure 5.

Figure 5. Projections of the Trend of Cost-Share Parameters from the Bottom-Up Model



In the base case, the capital share was projected to decline from 24.9 percent in 2000 to 16.4 percent in 2020. The energy share will not be fixed anymore, but will decline from 36.2 percent in 2000 to 32.6 percent in 2020, and the labor share will increase from 10.1 percent in 2000 to 22.4 percent in 2020. In the bottom-up model, since the model is simulated every five years, only five data points were extracted for input into the CGE model. To solve this problem, we assumed a monotonic linear function for interpolation of factor cost-share parameters for the periods within the simulation gaps.

Thus, using the new input share parameters, the CGE model gave a new projection of future GDP growth; electricity output; coal use; oil use; and particulate, sulfur dioxide, and NOx emissions, as well as total health damage (shown in figure 6).

In addition, the study compared the new results with the bottom-up cost-share parameter adjustments and the single CGE model results by keeping the old assumptions on technology progress and not using bottom-up model adjustments. One can see that, for the nation-wide projections, such as GDP, total coal or oil use, NOx emissions and health damages, the difference between the two base case simulations was very small.[13] For coal use, particulate matter and sulfur dioxide emissions, the integrated model suggests lower estimates before 2010 and higher estimates after 2010. The electricity output for input to the bottom-up model is also lower in the first few periods; but higher for later periods. The simulations also suggest that electricity demand is the key factor determining the overall technology mix in the bottom-up model.

4.2 National Policy-Environmental Tax Simulations

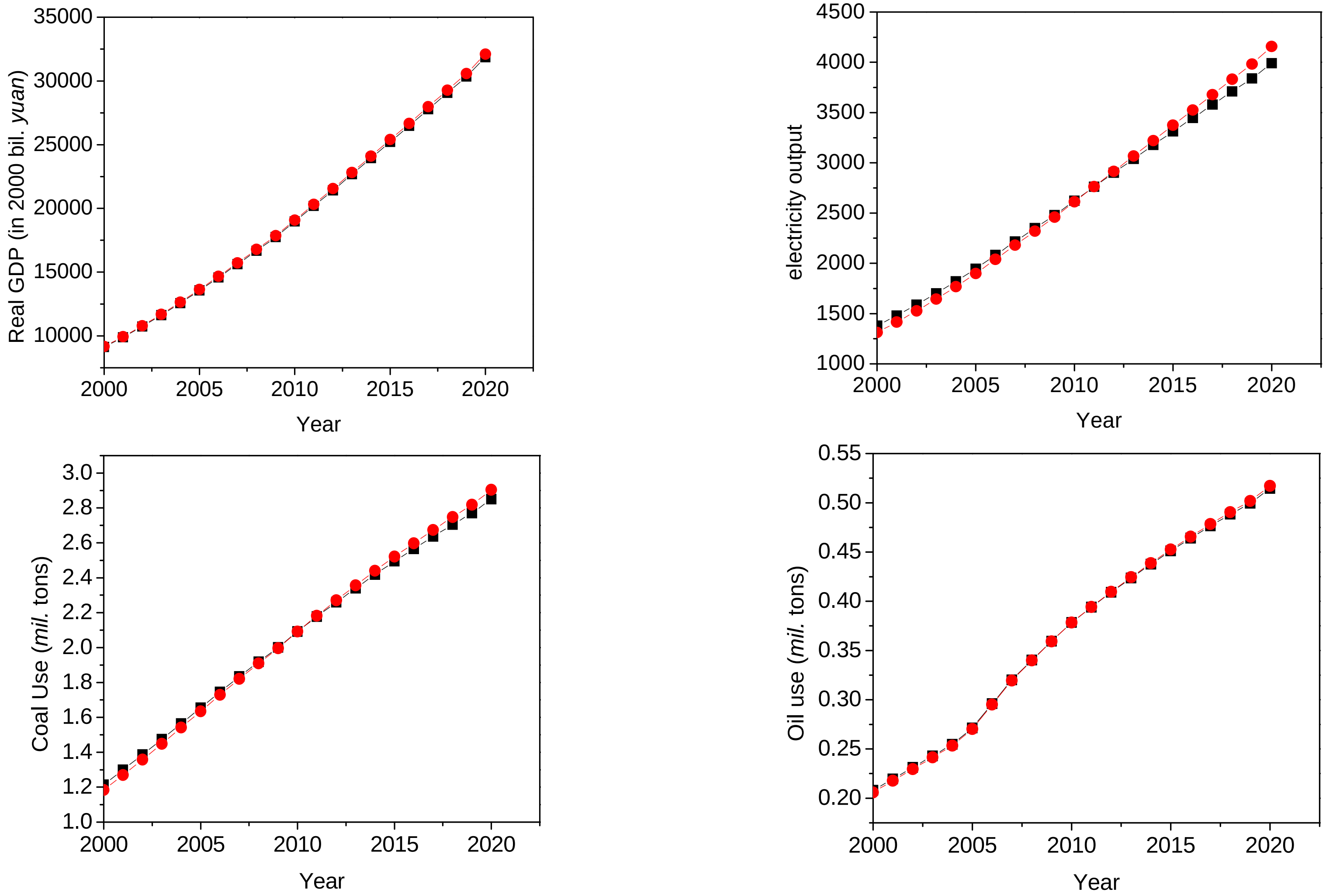
The use of an environmental tax as an incentive-based environmental control instrument has been examined in many studies and is also quite common in the co-benefits literature. This study assumed three hypothetical environmental tax policies for the Chinese government to implement to curb future carbon emissions: a carbon tax, a fuel tax, and an output tax. For the latter two tax regimes, the marginal tax rate was based on the marginal environmental damages by each unit of fuel use or by each sector.

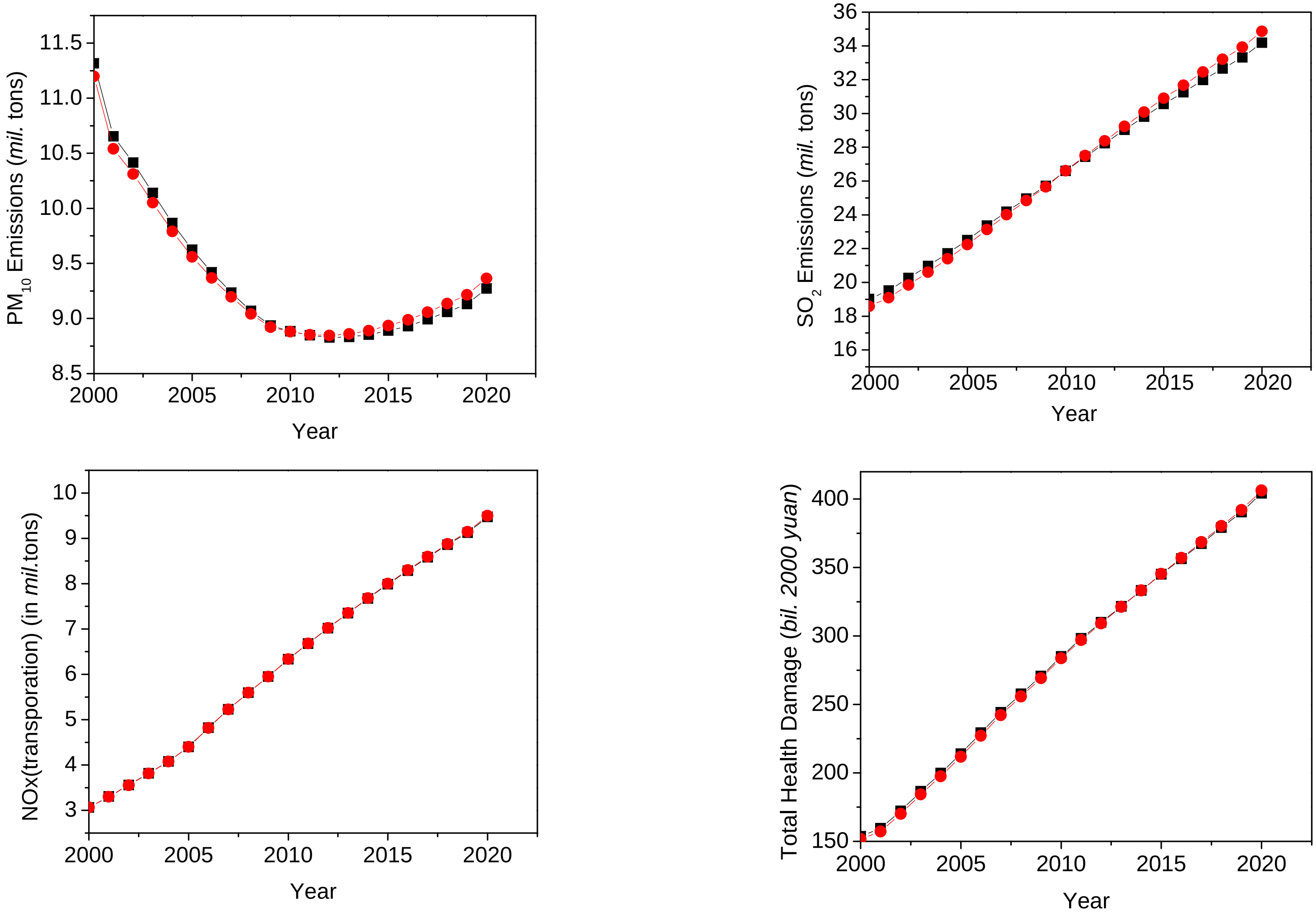
Table 4 shows the marginal health damages from PM, SO_2, and NOx emissions for the 33 industrial sectors examined. One can see that the transportation sector and warehousing sectors had the largest marginal damage, where about one-fourth came directly from NOx emissions. The second largest amount of damage was in the electricity, steam, and hot water sector due to its heavy dependence on coal. The non-metal mineral products sector (primarily the cement industry) was ranked third in terms of marginal damage because the cement industry emits large TSP and SO_2 emissions from low smoke stacks and exposes human-beings to more pollutants.

Other sectors following this ranking were real estate, health, education; social and other services; and the coal mining and processing sectors. Most of them also have low smoke stacks, but their lower-pollution emissions will eventually have a significant concentration in the atmosphere.

[13] In the bottom-up model, the exogenous parameters, such as discount rate, were also calibrated so that the first-year factor cost-shares (capital, labor, energy) in 2000 were close to China's official input-output table of 2000.

Figure 6. Base Case Projections




PM_{10} Emissions (*mil.* tons)
11.5
11.0
10.5
10.0
9.5
9.0
8.5
2000 2005 2010 2015 2020
Year
SO_2 Emissions (*mil.* tons)
36
34
32
30
28
26
24
22
20
18
16
2000 2005 2010 2015 2020
Year
NOx(transporation) (in *mil.*tons)
10
9
8
7
6
5
4
3
2000 2005 2010 2015 2020
Year
Total Health Damage (*bil. 2000 yuan*)
400
350
300
250
200
150
2000 2005 2010 2015 2020
Year

In the counterfactual simulations (following Ho and Jorgenson [2007] and Cao, Ho, and Jorgenson [2005]), the output tax rate was set at 100 percent marginal damage per yuan output, and the fuel tax rate set at 30 percent of average damage per yuan of fuel use.[14] Carbon tax was based on the carbon contents of fuel use. In this model, a value-added carbon tax rate at 50 yuan/yuan of carbon consumption was used, which has similar carbon reductions as the fuel tax case when λ =30%.

Output tax rate: $t_j = \lambda MD_j$, where (j = 1, 2, …33, sector, λ =100%) (9)

Fuel tax rate: $t_i = \lambda AMD_i$, where (i = coal, oil, natural gas, λ =30%) (10)

Table 4. Sector Health Damages from Combustion per Unit Output, and Share of Total Damages, 2000 (Integrated Model)

	Sector	MD_{XJ} x = PM *yuan/yuan*	MD_{XJ} x = SO_2 *yuan/yuan*	MD_{XJ} x = NOx *yuan/yuan*	MD^O *yuan/yuan*	Share of total (%)
1	Agriculture	0.000036	0.000378	0.000000	0.000414	0.21
2	Coal mining and processing	0.003356	0.003548	0.000000	0.006904	3.53
3	Crude petroleum mining	0.000227	0.000390	0.000000	0.000617	0.32
4	Natural gas mining	0.000019	0.000142	0.000000	0.000161	0.08
5	Metal ore mining	0.002269	0.002058	0.000000	0.004327	2.21
6	Non-ferrous mineral mining	0.001050	0.001817	0.000000	0.002867	1.47
7	Food products and tobacco	0.001126	0.001754	0.000000	0.002880	1.47
8	Textile goods	0.000620	0.001465	0.000000	0.002085	1.07
9	Apparel, leather	0.000089	0.000147	0.000000	0.000236	0.12
10	Sawmills and furniture	0.001160	0.001042	0.000000	0.002202	1.13
11	Paper products, printing	0.002392	0.004187	0.000000	0.006579	3.36
12	Petroleum processing and coking	0.000819	0.000432	0.000000	0.001251	0.64
13	Chemical	0.001369	0.002889	0.000000	0.004258	2.18
14	Nonmetal mineral products	0.019922	0.013780	0.000000	0.033702	17.22
15	Metals smelting and pressing	0.002868	0.003185	0.000000	0.006053	3.09
16	Metal products	0.000436	0.000987	0.000000	0.001423	0.73

[14] The same output tax rate and fuel tax rate as Ho and Jorgenson (2004) was used.

	Sector	MD_{XJ} x = PM *yuan/yuan*	MD_{XJ} x = SO_2 *yuan/yuan*	MD_{XJ} x = NOx *yuan/yuan*	MD^O *yuan/yuan*	Share of total (%)
17	Machinery and equipment	0.000430	0.000573	0.000000	0.001003	0.51
18	Transport equipment	0.000145	0.000340	0.000000	0.000485	0.25
19	Electrical machinery	0.000106	0.000215	0.000000	0.000321	0.16
20	Electronic and telecom. equipment	0.000024	0.000091	0.000000	0.000115	0.06
21	Instruments	0.000110	0.000208	0.000000	0.000318	0.16
22	Other manufacturing	0.000143	0.000286	0.000000	0.000429	0.22
23	Electricity, steam, and hot water	0.006036	0.027927	0.000000	0.033963	17.36
24	Gas production and supply	0.001782	0.002691	0.000000	0.004473	2.29
25	Construction	0.002344	0.001473	0.000000	0.003817	1.95
26	Transport and warehousing	0.017393	0.012680	0.008182	0.038255	19.55
27	Post and telecommunication	0.000175	0.000093	0.000000	0.000268	0.14
28	Commerce and restaurants	0.001744	0.000841	0.000000	0.002585	1.32
29	Finance and insurance	0.000490	0.000289	0.000000	0.000779	0.40
30	Real estate	0.007158	0.003769	0.000000	0.010927	5.58
31	Social services	0.004521	0.002723	0.000000	0.007244	3.70
32	Health, education, other services	0.006276	0.003292	0.000000	0.009568	4.89
33	Public administration	0.003273	0.001877	0.000000	0.005150	2.63
	Total				**0.195659**	**100**

For the three types of counterfactual tax simulations, the "revenue neutral" condition was assumed such that the government size was the same as the base case. For this purpose, when a new environmental tax was imposed, other taxes such as the value-added tax, capital income tax, sales tax were reduced proportionally so that the total revenue was the same in both the base case and counterfactual cases.

When a carbon tax at the value-added tax rate of 50 yuan/yuan was imposed, the simulations suggested that the coal industry was dramatically impacted by a -11.5-percent decline in output and 14-percent increase in the price level. Other energy sectors, such as crude oil, natural gas, refined oil, electricity, and gas product sectors were also negatively affected, and correspondingly, their prices incorporated a positive shock from the carbon tax as well. Since the fuel tax was also imposed on fuel use, the distribution effects on the output and price impacts were similar to the carbon tax simulation. In contrast to the carbon tax and fuel tax, which impacted the energy use intensive sectors, the output tax spread the tax distribution effects to most of the sectors—the non-metal mineral products (cement), transportation, building, electricity industries were mainly affected.

Table 5 summarizes the effects of the three kinds of taxes in terms of changes to both economic and environmental quality. The integrated model simulations confirmed the "double dividend" results in China. That is, a corrective environmental tax could achieve both economic efficiency and environmental improvement at the same time. In addition, a revenue-recycling environmental tax regime (cutting the distorted capital and output taxes) was projected to have a more profound effect on the economic system over time.

Based on the simulation, there was a slightly negative impact on consumption with the fuel and carbon taxes, but there was a positive effect for the output tax. Although there were some negative shocks on the consumption side for the first several years, the simulations showed that these would eventually diminish and become a positive shock. All three counterfactual tax simulations suggested that an environmental tax would have significant positive impacts on investment: about 0.03–0.10 percent for the first year, and a quite large 1.02–2.13 percent for the last year, 2020.

These counterfactual simulations also suggested that the fuel tax had the greatest potential to reduce coal use and carbon and other pollutant emissions, and that the impacts would increase faster than for carbon tax and output tax. Correspondingly, the concentrations of PM and SO_2, as well as the premature deaths and value of total health damages, would decline the most with a fuel tax.

Since the fuel tax impacted very few sectors, except for the energy-intensive sectors, the fuel tax revenue accounted for only about 1.7–1.8 percent of the total tax revenue; the carbon tax at a tax rate of 50 yuan/yuan accounted for 2.04–2.41 percent of the total tax revenue. Due to the broader tax base and tax spreading effects, the output tax accounted for 7.15–13.72 percent of the total tax revenue. So, if the government's intent was to mitigate carbon emissions or health damage, the preferred tax instrument might be a carbon tax or fuel tax. But, if the government decided to raise more revenue through an environmental tax, or preferred a broader tax base to prevent a high tax on specific industries, then an output tax policy was preferred.

Considering the dynamic impacts of the environmental tax, the impacts should decline over time for both the carbon and fuel taxes, while the output tax was more complicated, with increasing reductions in non-fossil fuel sectors (such as NOx emissions from the transportation sector), but declining impacts on SO_2 emissions over time.

Table 5. Effects of a Carbon Tax, Fuel Tax, and Output Tax Based on the Integrated Model

Variable	Carbon tax		Fuel tax (average marginal damages of fuel use)		Output tax (sectoral marginal damages)	
	Effect in 1st year	***Effect in 20th year***	***Effect in 1st year***	***Effect in 20th year***	***Effect in 1st year***	***Effect in 20th year***
GDP	+0.11%	+0.56%	+0.08%	+0.55%	+0.23%	+0.91%
Consumption	-0.01%	+0.09%	-0.05%	+0.04%	+0.10%	+0.33%
Investment	+0.10%	+1.02%	+0.03%	+1.02%	+0.10%	+2.13%
Coal use	-11.34%	-2.99%	-10.6%	-5.2%	-2.33%	-0.68%
Carbon emissions	-9.37%	-2.38%	-8.2%	-3.5%	-1.98%	-0.50%
Primary particulate emissions	-5.73%	-2.49%	-5.4%	-3.6%	-2.75%	-3.08%
SO_2 emissions	-8.70%	-0.49%	-7.8%	-1.4%	-2.28%	-0.69%
NOx (transportation)	-1.76%	-1.58%	-0.72%	-0.73%	-2.99%	-6.28%
Value of health damages	-9.55%	-3.27%	-9.0%	-4.9%	-2.04%	-1.13%
Change in other tax rates	-2.63%	-2.63%	1.9%	2.4%	-7.12%	-15.19%
Reduction in damages/GDP	0.16%	0.11%	0.15%	0.15%	0.03%	0.03%
Pollution tax/Total tax revenue	2.41%	2.04%	1.7%	1.8%	7.15%	13.72%
	Note: The entries are % changes between the counterfactual *ad valorem* carbon tax case and the base case. The last two rows are percent shares.		*Note*: The entries are % changes between the counterfactual fuel tax case and the base case. The last two rows are % shares. In the counterfactual simulation, a fuel tax is proportional to the average marginal damage per unit of fuel use.		*Note*: The entries are % changes between the counterfactual output tax case and the base case. The last two rows are % shares. In the counterfactual simu-lation, an output tax is proportional to the marginal damage per yuan of output is applied.	

In the counterfactual case, two alternative modeling regimes were examined and compared, which shed some light on the differences between the CGE model and the integrated model. The first model assumed that the factor cost-shares (capital, labor, and energy) are exogenous, and thus are fixed to the base case scenarios. The second model assumed the factor share parameters are endogenous in the counterfactual cases, and thus the endogenous feedback mechanisms from the bottom-up model could be incorporated into the top-down model. The second model projected very different results from the findings by Cao, Ho, and Jorgenson (2005), where the share parameters were exogenous and were not allowed to change in either the base case or counterfactual cases. Figure 7 shows how these factor cost-share parameters from the bottom-up electricity sector model varied, compared to the base case.

If environmental taxes were imposed on fuel use, the increase in fuel prices would boost the energy value share as well; thus, for the counterfactual cases, the energy share increased, rather than declined as in the base case. The labor share was quite flat in the counterfactual case, and only slightly increased in the base case. The capital share also followed a declining trend, but was slightly flat in the counterfactual scenarios.

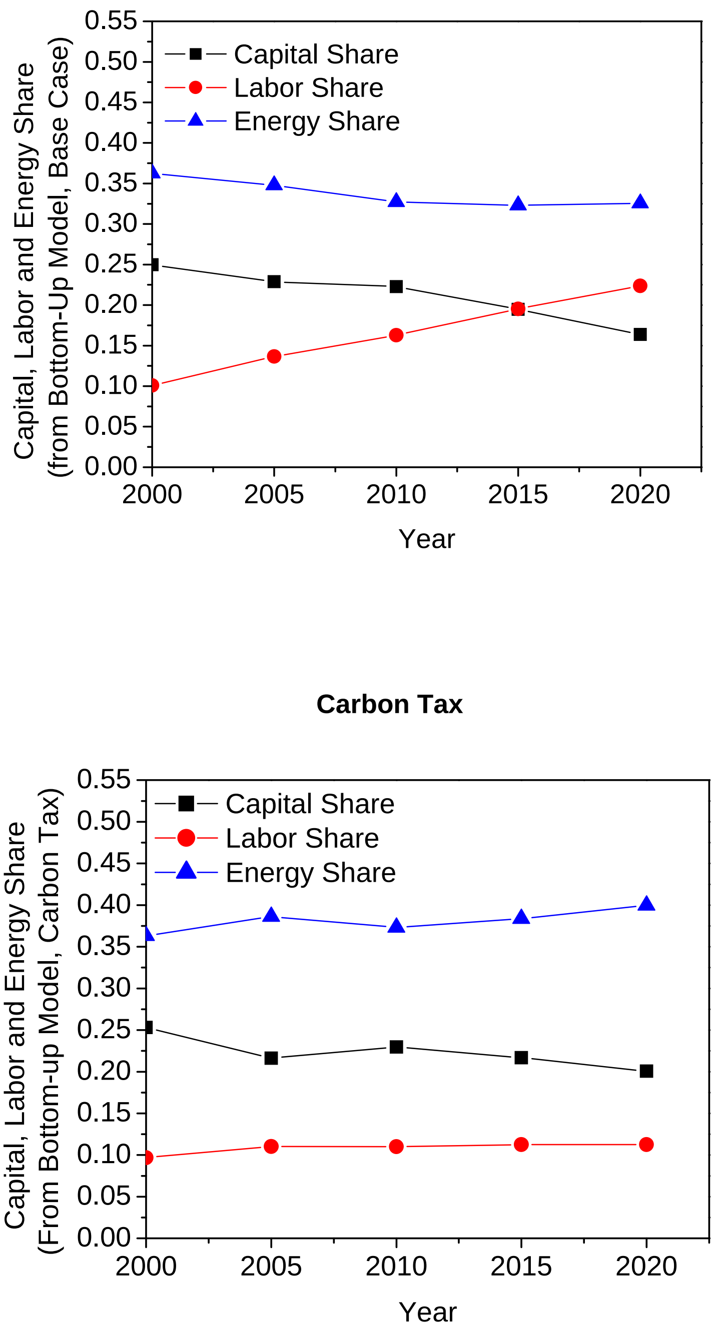
Thus, one could compare these two counterfactual simulations with or without iteration procedures. Figures 8 to 10 show the changes in energy use, carbon dioxide, particulates, sulfur dioxide, and environmental health damage in these two experiments, compared to the same base case. The counterfactual simulation with iterations suggested a lower impact on energy use and pollution, and assumed that fixed cost-share parameters would predict higher impacts. In addition, the dynamic trend was opposite in these two experiments as well. The iterated counterfactual case suggested that the impact would decline for all three environmental taxes, although for the output case particulate emissions slightly increased but had a fairly flat trend overall. These experiments suggested that making share parameters endogenous and allowing feedback into the counterfactual economic model could make the production process more flexible in response to the policy shock, compared with the model with fixed cost-share parameters in the production function.

This result suggested that the economic CGE model itself might overestimate the impact of policy changes, particularly in terms of dynamic impacts over time. Thus, this integrated model, with iteration procedures in both base case and counterfactual simulations, should be preferred when studying the impacts of environmental tax policy shock because it better examines real technology progress in the bottom-up engineering model, and treats capital, labor, and energy share parameters endogenously in the top-down economic model.

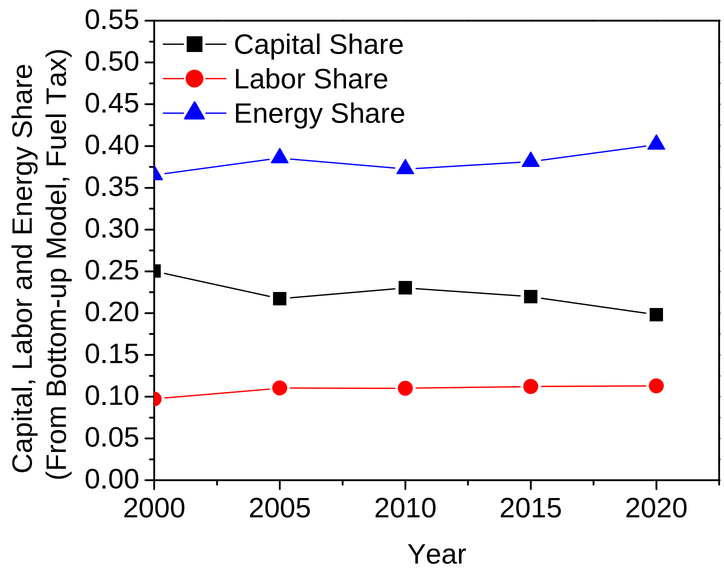
Figure 7. Comparisons of Factor Share Parameters (Capital, Labor, Energy) in the Base Case and Counterfactual Cases

Base Case

Carbon Tax



Fuel Tax



Output Tax

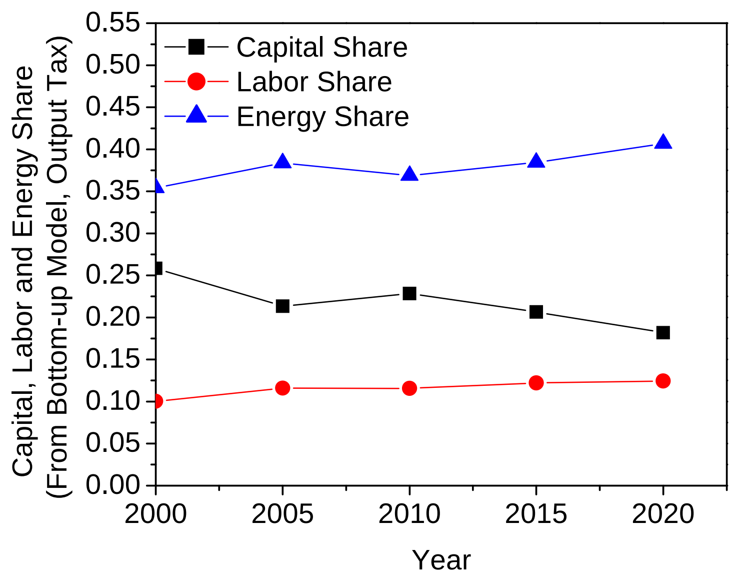
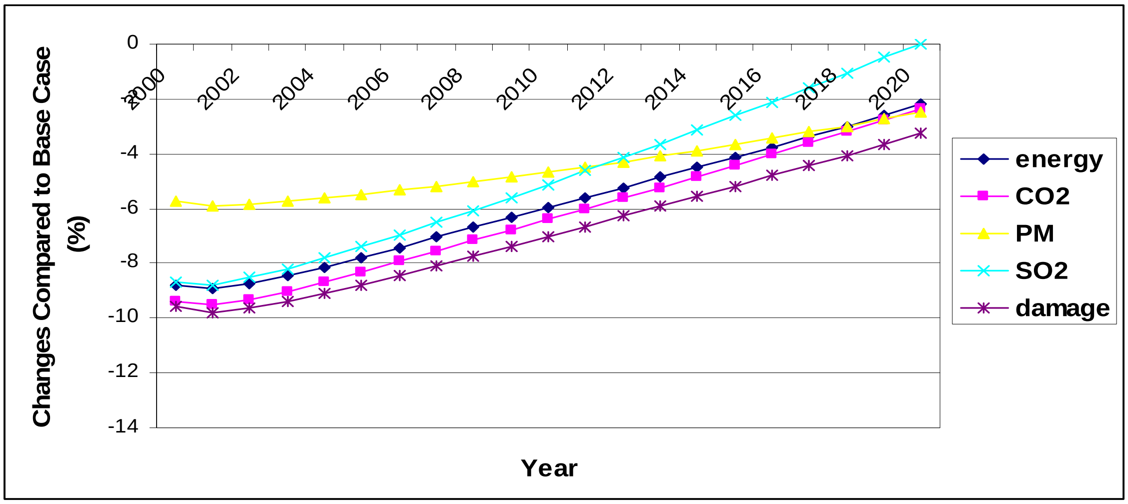


Figure 8. Comparisons on Energy Projection with Iteration and without Iteration in the Counterfactual Cases (Carbon Tax)

Integrated Model with Iteration in the Counterfactual Case



Without Iteration in the Counterfactual Case

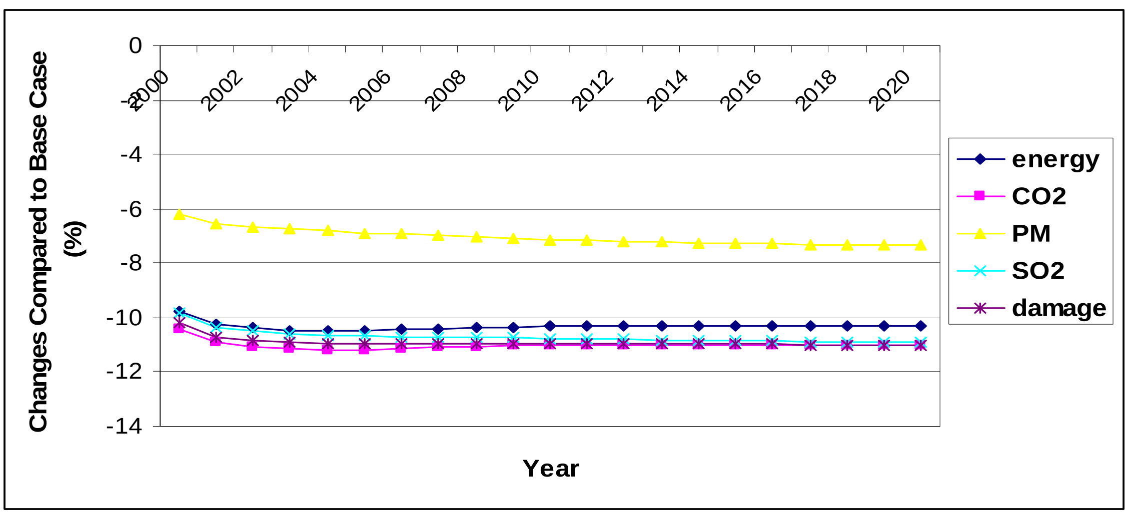
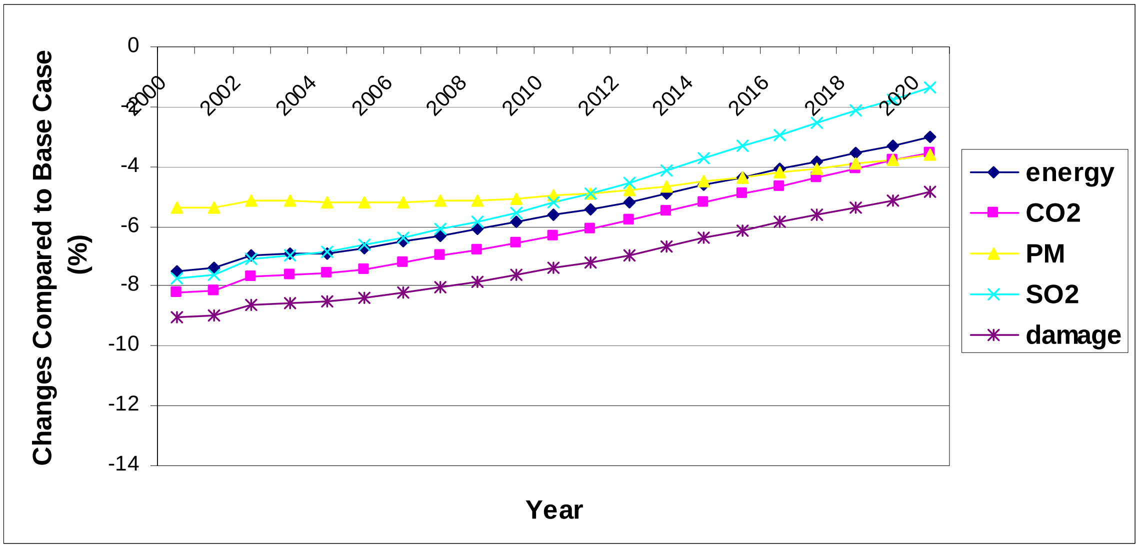


Figure 9. Comparisons on Energy Projection with Iteration and without Iteration in the Counterfactual Cases (Fuel Tax)

Integrated Model with Iteration in the Counterfactual Case



Without Iteration in the Counterfactual Case

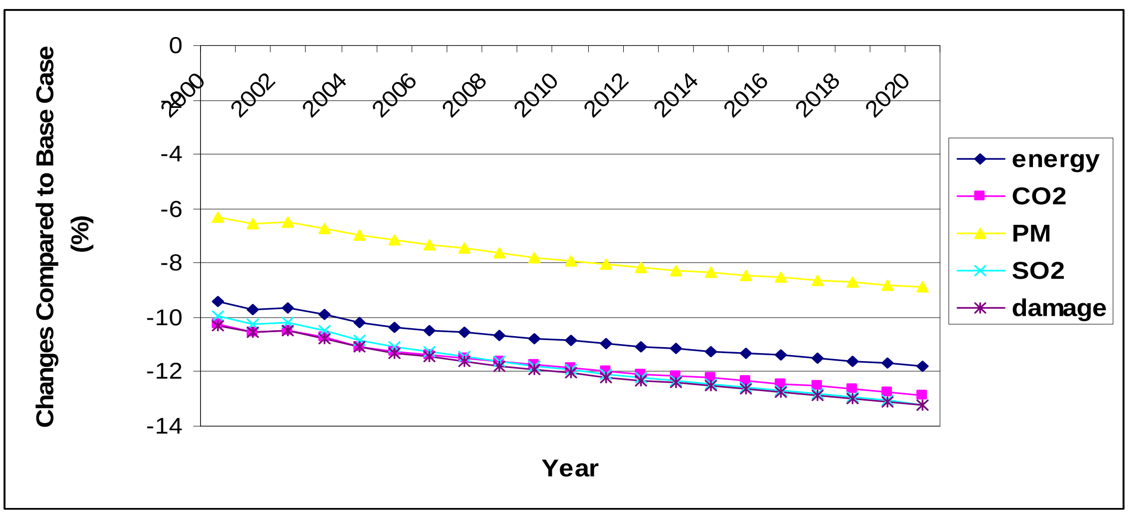
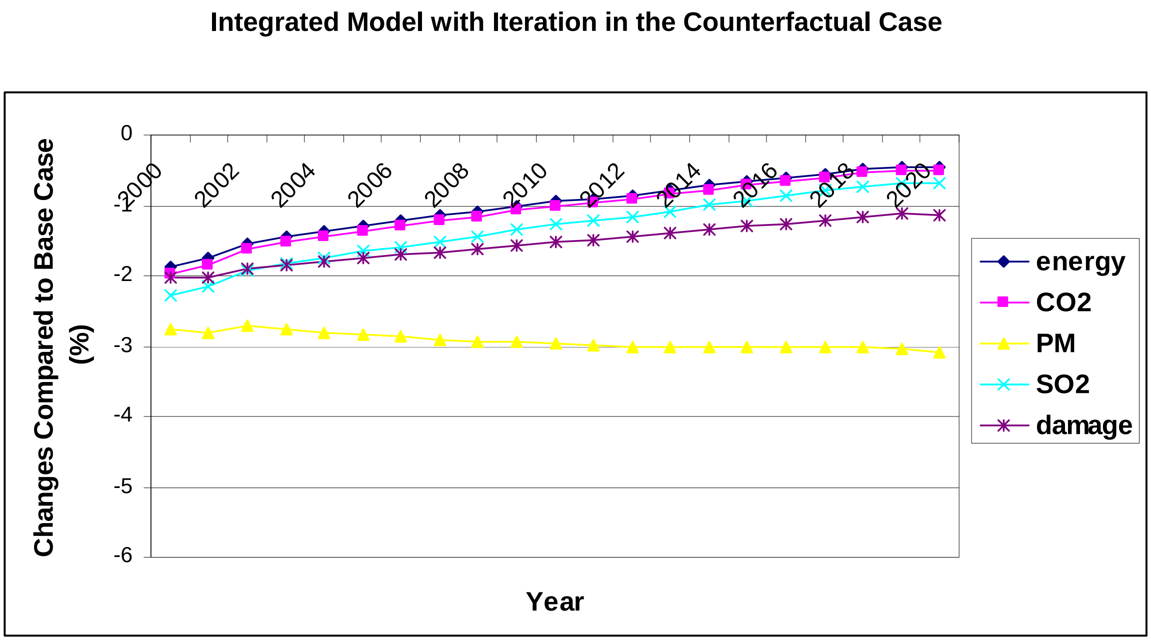
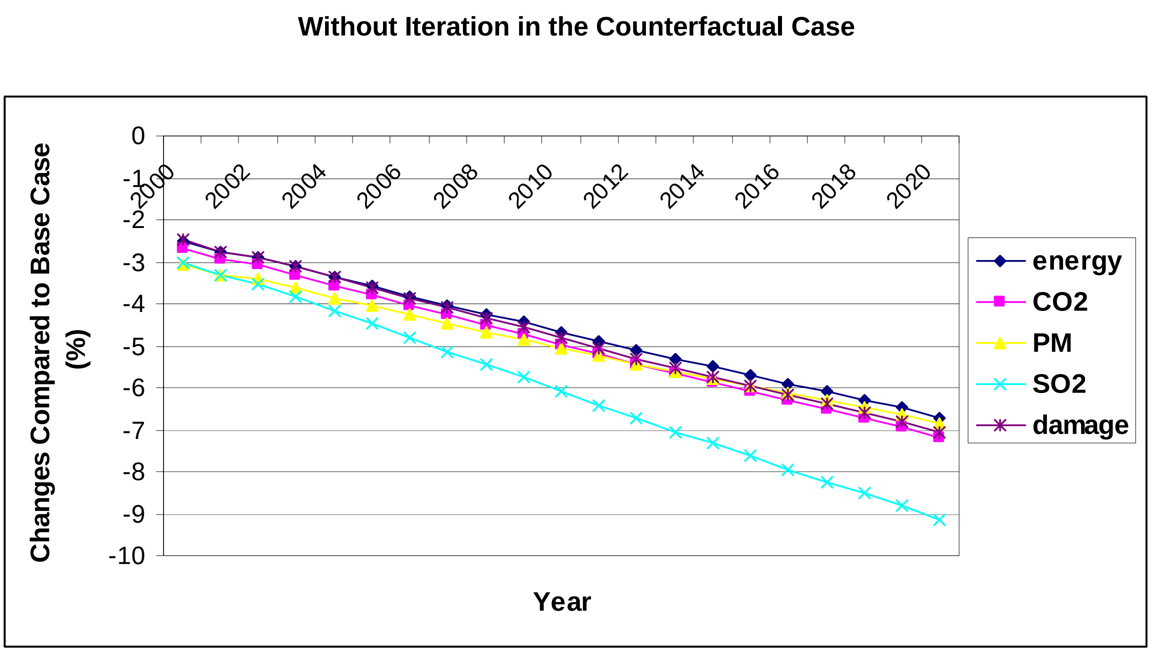


Figure 10. Comparisons on Energy Projection with Iteration and without Iteration in the Counterfactual Cases (Output Tax)





4.2.1 Co-benefits. The co-benefits for the national level environmental tax policies were calculated based on this integrated top-down and bottom-up model. The results are given in table 8. The study found that after imposing an output tax, the health damage would decrease by 3.1 billion yuan in the first year (2000) and by 10.3 billion yuan in the final year, 2020. However, fuel and carbon taxes would be more effective in terms of ancillary health benefits: the fuel tax case would reduce health damage by about 13.7 billion yuan in 2000 and by 49.6 billion yuan in 2020. It would also reap 14.5 billion yuan in co-benefits in the first year; and the carbon tax case, 34 billion yuan in the final year.15

In addition, table 8 also shows that the co-benefits per ton of carbon in the output tax case were comparable to those in the fuel tax and carbon tax cases, and sometimes were even higher although less effective in emission reduction. This was because the output tax reduced a smaller amount of carbon emissions. While the other two tax instruments were more effective in controlling carbon emissions by taxing only on the energy intensive sectors, the distribution effects caused political or competitive concerns. Therefore, one could see that even if an output tax was imposed at a high marginal tax rate (100 percent marginal damage), the fuel tax was taxed at only 30 percent of marginal damage of fuel use and the carbon tax at 50 yuan/yuan of carbon, fuel tax and carbon tax could bring much higher co-benefits than an output tax. In most co-benefits studies, scholars compared the co-benefits per ton of carbon emissions; however, the experiments in this study suggested that this was not an appropriate way to compare policy instruments—unless the target of carbon reduction was the same.

If the goal is to mitigate carbon emissions, this study found that carbon emissions reduction in the short run would be highest with a carbon tax. But, since the carbon tax is fixed at a flat rate and the fuel tax rate is based on the marginal environmental damages, the fuel tax

---

[15] In this paper, sensitivity analyses on environmental exposure and damage valuations were not conducted, but a previous study on the same top-down CGE model (based on 1997 data) included a thorough sensitivity analysis with the upper bound and lower bound estimates of dose-response parameters and unit valuation willingness-to-pay. It suggested that the lower bound estimates of environmental health damages were about one-third of the central base parameter estimates, and upper bound estimates about 2 times (Ho and Jorgenson 2007, 321–23). As for the uncertainty of intake fraction parameters, in the power sector the lower bound *iF* for particulate matter is one order of magnitude lower than the central estimates, and the upper bound is the same order as central estimates; the lower bound and upper bound *iF* for SO_2 are the same as central estimates. For industrial and mobile sources, the lower bound *iF* for particulate matter is one order of magnitude lower than the central estimates, and the upper bound is one order of magnitude higher than the central estimates.

Table 8. Co-benefits for National Level Tax Policy

	Output tax case (taxed at 100% MD)				Fuel tax case (tax rate = 30% MD of fuel)				Carbon tax case			
Year	**Carbon emission reduction (in million tons)**	**Co-benefits (in billion 2000 yuan)**	**Total co-benefits (in *yuan*/ tC carbon)**	**Co-benefits/ real GDP (%)**	**Carbon emission reduction (in million tons)**	**Co-benefits (in billion 2000 yuan)**	**Total co-benefits (in *yuan*/ tC carbon)**	**Co-benefits/ real GDP (%)**	**Carbon emission reduction (in million tons)**	**Co-benefits (in billion 2000 yuan)**	**Total co-benefits (in yuan/ tC carbon)**	**Co-benefits/ real GDP (%)**
2000	15.4	3.1	200.1	0.034	64.2	13.7	213.0	0.149	73.1	14.5	198.2	0.158
2001	15.4	3.4	221.2	0.034	67.8	14.9	219.9	0.150	79.5	16.3	205.1	0.164
2002	14.5	3.6	250.5	0.034	68.4	16.4	239.5	0.152	82.9	18.4	222.1	0.170
2003	14.4	4.1	281.2	0.035	72.1	18.6	258.5	0.159	85.4	20.5	240.1	0.175
2004	14.6	4.5	308.4	0.036	76.2	21.0	275.8	0.166	87.4	22.5	256.9	0.177
2005	14.6	4.9	337.5	0.036	79.2	23.3	294.3	0.171	89.1	24.4	274.5	0.179
2006	14.7	5.4	368.4	0.037	81.8	25.7	314.2	0.175	90.2	26.4	293.1	0.180
2007	14.7	5.9	401.7	0.037	84.0	28.1	334.8	0.178	90.7	28.3	312.2	0.180
2008	14.6	6.3	434.1	0.038	85.7	30.4	354.5	0.181	90.6	30.0	330.7	0.178
2009	14.2	6.7	469.4	0.037	86.7	32.5	374.3	0.181	89.8	31.4	349.4	0.175
2010	14.1	7.2	508.2	0.037	87.7	34.9	397.8	0.182	88.9	33.0	371.6	0.172
2011	14.0	7.7	547.1	0.038	88.0	37.2	422.3	0.182	87.2	34.4	395.1	0.169
2012	13.8	8.1	585.0	0.037	87.7	39.2	446.7	0.181	84.9	35.5	418.6	0.164
2013	13.3	8.4	631.9	0.036	86.4	40.9	473.0	0.178	82.0	36.4	443.6	0.159
2014	12.6	8.6	684.2	0.036	84.7	42.4	501.1	0.175	78.5	36.9	470.7	0.153
2015	12.0	8.9	740.8	0.035	82.7	43.9	531.3	0.172	74.4	37.3	500.6	0.146
2016	11.4	9.1	799.1	0.034	80.3	45.3	563.9	0.169	69.7	37.2	534.1	0.139
2017	10.7	9.3	866.5	0.033	77.6	46.4	597.9	0.165	64.5	36.8	570.9	0.131
2018	9.9	9.4	948.3	0.032	74.4	47.3	636.5	0.161	58.8	36.1	614.7	0.123
2019	9.3	9.5	1029.2	0.031	71.2	48.3	678.3	0.157	52.5	35.0	667.8	0.114
2020	9.6	10.3	1070.2	0.032	67.9	49.6	731.1	0.154	45.8	34.0	740.8	0.105

rate would increase over time. Therefore, the fuel tax would become more effective in terms of reducing carbon in the long run.

If one focused on a short-term carbon target, one could see that a carbon tax might better achieve the carbon reduction goal because the carbon tax is based directly upon the carbon contents of the fuel. Because the fuel tax rate is based on marginal damage only, it is more likely to fulfill the goal of maximizing overall ancillary benefits. Finally table 8 calculates the percentage of co-benefits to China's real gross domestic product: approximately 0.03 percent for the output tax, 0.15 percent for the fuel tax, and 0.16-0.11 percent for the carbon tax.

From a social welfare perspective, these co-benefits are quite significant—about 200 yuan per ton of carbon in the first year—and will increase gradually over time. Therefore, if these ancillary benefits are included in the cost-benefit analysis of climate change, one can conclude that these climate change taxation instruments could be "no regrets" and "win-win" climate policies, since the impacts on the economy would be positive. Therefore, the magnitude of benefits from pollution abatement might exceed the costs of implementing these environmental policies. This implies that the Chinese government should implement an environmental tax policy immediately, simply to mitigate carbon emissions, regardless of the financial support from developed countries or other CDM partners. This integrated-model study suggested that the range of co-benefits in its three national tax policy regimes could raise 200–1070 yuan per ton of carbon. Although this is a crude estimate, it could still provide a quantitative estimate of the magnitude of co-benefits for the China government as well.

4.4.2 Induced technology change. Yet another useful implication of this integrated model lies in its technology richness. In particular, the lower-level bottom-up model could provide a clear view of the dynamic path of induced technology change under a specific economy-wide policy. From the simulation, the study found the projected electricity technology mix to be sensitive to the fuel input price, the counterfactual/base-relative transportation price, the labor and capital factor prices, as well as the projected electricity demand exported from the top-down CGE model.

This study found two major effects linking the top-down CGE model with the bottom-up electricity sector model. One was the scale effect, which came from the shrinking electricity demand due to the economy-wide interaction after imposing the tax policies. The other effect was in sector-induced technology change due to the price signals. In the bottom-up model, fuel prices, transportation costs, and labor and capital costs are linked with the top-down model, and thus would change as well when environmental tax policies are imposed in the economic model.

The two effects had opposite impacts on induced technology changes. For scale effects due to the resulting reduced electricity demand, firms would tend to reduce investments on the expensive generation technology options at the margin. Thus, there was a negative impact on technology progress in the electricity sector as a whole. On the other hand, given the same electricity demand, price signals (such as higher prices on coal use) might induce firms to switch from coal-intensive technologies to cleaner or even renewable technologies. In a partial equilibrium, the first mechanism is typically overlooked, and thus technology progress can be very sensitive to price signals.

Table 9 shows the optimal technology mix for the base case and three counterfactual environmental tax simulations. One can see that the dominant technology in electricity generation is DOM ESP/SCB, which was relatively efficient with a large power generation capacity (>300 MW). The small-scale power plant DOM SML would diminish quickly. OILCC and GASCC increased very quickly in the simulations due to the increasing electricity demand. Hydro power was more than triple in the base case, fuel tax, and carbon tax scenarios.

Comparing the base case and counterfactual simulations showed that the scale effect dominated the induced substitution effects within the electricity sector, which suggested the importance of an economy-wide general equilibrium analysis. For national-level environmental policies, the induced technology changes were very small or even negative. When electricity demand shrinks, the production frontier shrinks from the marginal technologies; thus, firms tend to use less renewable technologies (such as hydro and wind). OILCC and GASCC also declined due to higher costs of electricity production. The scale effects were similar for the carbon and fuel taxes, but were larger for the output tax. In addition, due to lower price signals from increased fuel prices, the output tax tended to shrink more with hydro, wind, OILCC, GASCC, and DOMESP than with the other two taxes. This study also suggested that, although many clean coal studies recommend more advanced technologies (such as PFBC, IGCC, or AFBC), they are still too expensive to be adopted under a national environmental tax regime.

This study also contained a partial equilibrium analysis, which assumed there were no economy-wide impacts on electricity demand and asserted the same price signal on fuel use from the environmental taxes, carbon and fuel taxes in particular. Figures 11 and 12 present the simulation results of this partial equilibrium model, compared to the integrated model when the scale effects were incorporated, and offer a comparison of marginal technologies, such as OILCC and GASCC, and renewable technologies, such as hydro and wind power.

Table 9. Optimal Technology Mix for Base Case and Counterfactual Environmental Tax Cases

	1st year simulation				20th year simulation			
Technology	***Base***	***Output tax***	***Fuel tax***	***Carbon tax***	***Base***	***Output tax***	***Fuel tax***	***Carbon tax***
DOM ESP/SCB	578.1	519.0	544.8	532.3	2661.2	2538.2	2661.2	2661.2
DOM BIG	231.4	231.4	231.4	231.4	231.4	231.4	231.4	231.4
DOM MED	165.1	164.2	164.2	164.2	211.7	211.7	211.7	211.7
DOM SML	65.9	33.1	46.6	38.8	0.0	0.0	0.0	0.0
AFBC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PFBC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
IGCC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OILREG	0.0	0.0	1.1	1.1	0.0	0.0	0.0	0.0
OILCC	8.5	8.4	8.4	8.4	49.9	22.5	35.8	31.5
GASCC	6.7	3.9	3.9	6.0	131.3	65.0	100.7	83.3
HYDRO*	239.9	239.9	239.9	239.9	792.3	498.1	784.0	781.4
NUCL	16.8	16.8	16.8	16.8	16.8	16.8	16.8	16.8
WIND	0.1	0.1	0.1	0.1	63.9	0.1	35.3	34.8
GT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PV	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Total	**1312.5**	**1216.8**	**1257.2**	**1239.0**	**4158.5**	**3583.9**	**4077.1**	**4052.3**

Figure 11. Comparisons of Integrated Model Simulations versus Partial Equilibrium Model Simulations (Carbon Tax)

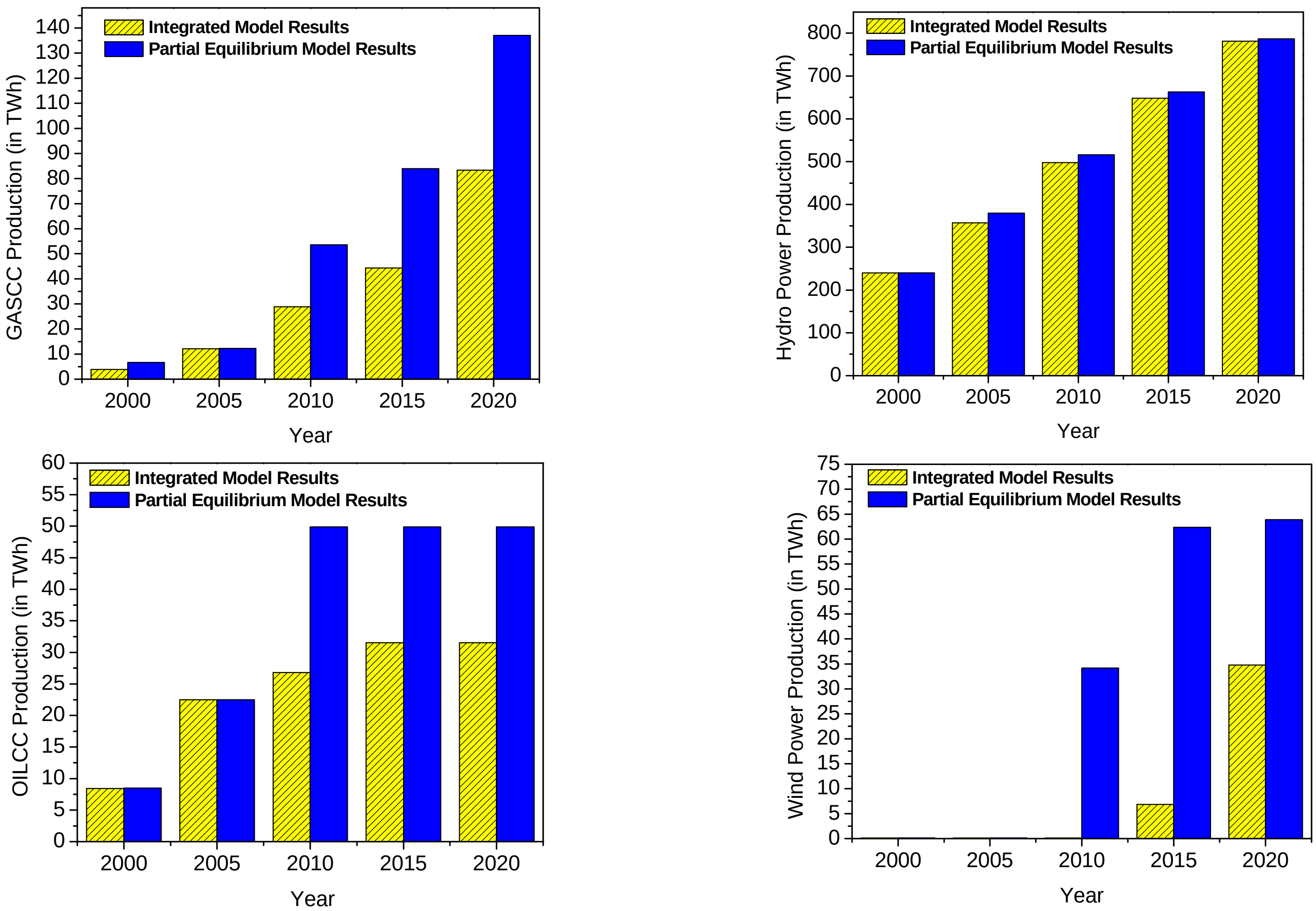
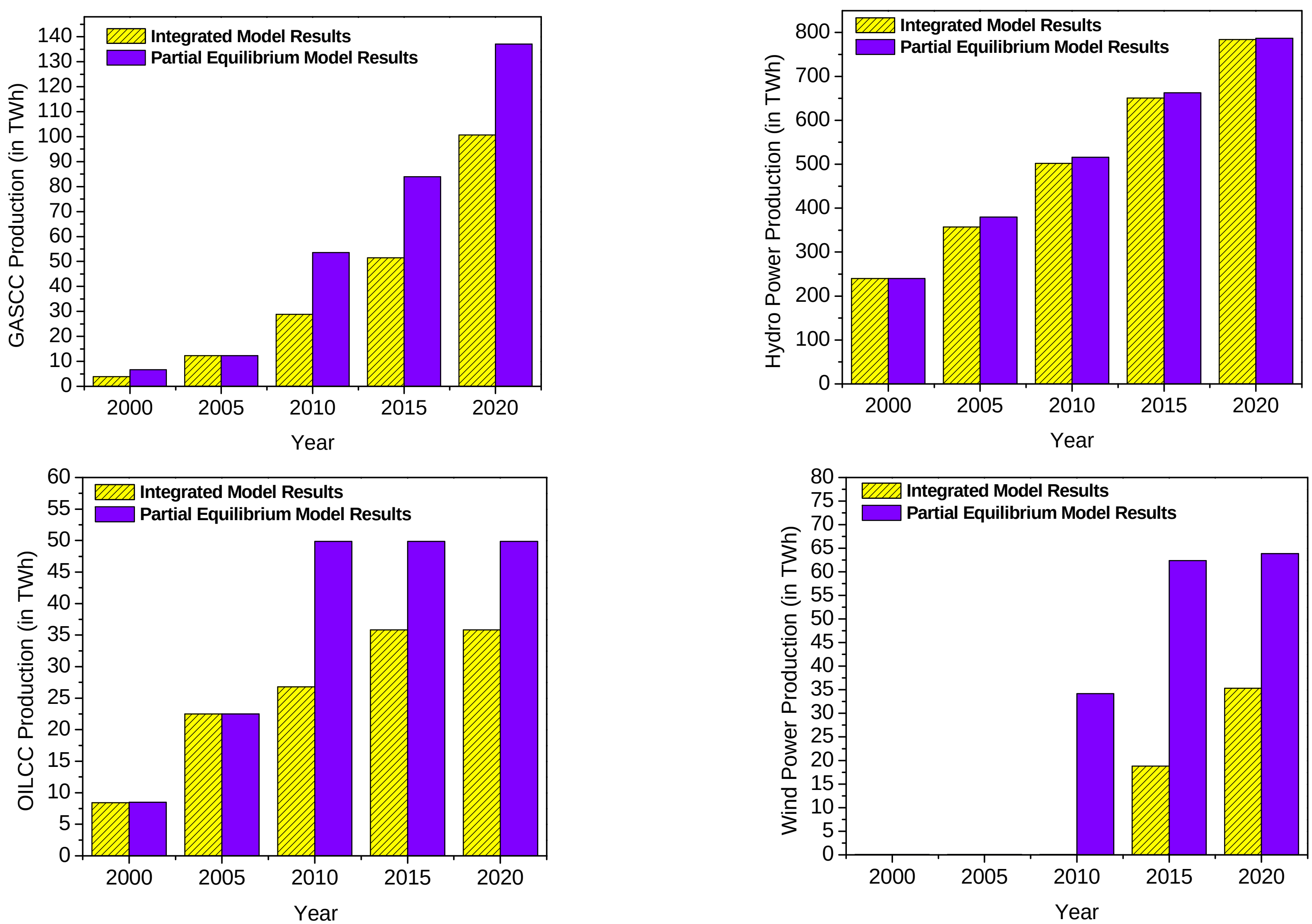


Figure 12. Comparisons of Integrated Model Simulations versus Partial Equilibrium Model Simulations (Fuel Tax)



This study on carbon tax and fuel tax suggested that a partial equilibrium analysis—that is, a bottom-up model only—might overestimate the induced technology change for ignoring the general equilibrium effects, or scale effects. As described earlier, technology options were modeled as discrete choices in the bottom-up model; thus, the more expensive non-coal-fired power plants (OILCC and GASCC) and renewable energy were technology options at the margins of the overall mix. When the total demand for electricity shrinks, these technology options will shrink first. This comparison also confirmed that the scale effects were key in examining induced technology changes, especially technology options at the margin.

4.3 Mixed Policy Simulation

In addition to the national-level tax policy simulation, it was also very useful to look at sectoral-level environmental policies, such as carbon- or sulfur-emission cap policies. Such sectoral cap policies can not be applied in an economy-wide, top-down model, since they are non-price policy instruments. If only a bottom-up model is used, we would get partial equilibrium results.

As previously discussed, without incorporating economy-wide general equilibrium, such partial-equilibrium analyses might be too optimistic about the economic costs of carbon mitigations. Thus, an integrated model approach can help policy makers avoid such pitfalls and help analyze sectoral non-price cap policies. One could also mix these cap policies with national tax policies for more realistic policy implications.

Table 10 shows the optimal technology-mix simulation results for the mixed national and sectoral policies. At the national level, as discussed above, carbon, fuel, and output taxes were imposed. At the sectoral level, we can assume three emission cap policies: 1) a 10-percent cap on carbon emissions; 2) a 10-percent cap on sulfur emissions; and 3) a 10-percent cap on both carbon and sulfur emissions. When they are mixed together, there are nine simulation cases.

Here only the optimal technology mix in year 2020 was compared. For the first year, the technology mix was fixed, based on actual 2000 data. In addition, considering that within-sector policies would have only small effects on non-electricity production, it was assumed for simplicity that the scale effects were the same for the national level policies. Thus, it only focused on within-sector technology substitution effects.

Table 10. Optimal Technology Mix for Mixed Policy (2020)

	Base case	Carbon tax + sectoral policy			Fuel tax (taxed at 30% MD) + sectoral policy			Output tax (taxed at 100% MD) + sectoral policy		
Technology		**+ 10% reduction of carbon cap**	**+ 10% reduction of sulfur cap**	**+ 10% reduction of carbon & sulfur caps**	**+ 10% reduction of carbon cap**	**+ 10% reduction of sulfur cap**	**+ 10% reduction of carbon & sulfur caps**	**+ 10% reduction of carbon cap**	**+ 10% reduction of sulfur cap**	**+ 10% reduction of carbon & sulfur caps**
DOM ESP/SCB	2661.2	758.4	2640.4	758.4	808.0	2640.2	808.0	1826.0	2489.6	1825.1
DOM BIG	231.4	231.4	231.4	231.4	231.4	231.4	231.4	231.4	231.4	231.4
DOM MED	211.7	92.9	211.7	92.9	92.9	211.7	92.9	211.7	211.7	211.7
DOM SML	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AFBC	0.0	0.0	15.3	0.0	0.0	15.3	0.0	0.0	0.0	0.0
PFBC	0.0	1823.1	0.0	1823.1	1777.4	0.0	1777.4	426.2	0.0	427.2
IGCC	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OILREG	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OILCC	49.9	49.9	33.6	49.9	49.9	35.8	49.9	49.9	22.5	49.9
GAS CC	131.3	161.9	86.3	161.9	161.9	106.4	161.9	109.3	82.3	109.2
HYDRO*	792.3	792.5	781.3	792.5	797.5	784.0	797.5	648.0	529.3	648.0
NUCL	16.8	52.5	16.8	52.5	68.5	16.8	68.5	16.8	16.8	16.8
WIND	63.9	66.0	35.3	66.0	66.0	35.3	66.0	64.5	0.1	64.5
GT	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
PV	0.1	23.8	0.1	23.8	23.8	0.1	23.8	0.1	0.1	0.1
Total	**4158.5**	**4052.3**	**4052.3**	**4052.3**	**4077.1**	**4077.1**	**4077.1**	**3583.9**	**3583.9**	**3583.9**
Coal-fired	**3104.4**	**2905.8**	**3098.8**	**2905.8**	**2909.7**	**3098.6**	**2909.7**	**2695.3**	**2932.8**	**2695.4**

Comparing the carbon cap and carbon-plus-sulfur cap policies, the study found that the technology mix was about the same. Therefore, the sulfur cap was not binding, and only the carbon cap determined the optimal technology mix in the simulations. When there is only a sulfur cap, the AFBC may enter the technology mix for the carbon and fuel taxes. Compared to table 9 (without cap policies) in the carbon tax scenario, the DOMESP/SCB declined by 0.78 percent, the GASCC increased by 3.6 percent, the OILCC increased by 6.7 percent, and WIND technology increased by 1.4 percent.

For the fuel tax with a sulfur cap, the DOMESP/SCB declined by 0.79 percent, and the GASCC increased by 5.7 percent. In terms of the output tax, the DOMESP/SCB declined by 2.0 percent, with a significant 26.6-percent increase in GASCC and 6.3-percent in hydro.

One can observe that a dramatic technology change occurred in all three national level taxes plus the carbon emission cap policy within the electricity sector. When the PFBC entered the optimal technology mix, it accounted for about two-thirds of the total coal-fired power generation, corresponding to a sharp decline in DOMESP/SCB. The GASCC also increased by one-fourth. The previous analysis suggested that a national tax policy alone could not drive this dramatic change on advanced coal-fired technologies. In addition, nuclear power increased by more than three times in the carbon tax case, and four times in the fuel tax case. There also was a slight increase in wind technology for all three national level tax plus carbon cap policies as well. Therefore, only the emission cap policies will shift the optimal technology from the traditional coal-fired technology to the more advanced coal-fired power plant, such as PFBC, and renewable energies.

The mixed national-sectoral policy experiments suggested that if the policy goal is to achieve both carbon emissions mitigation and induced technology change in the electricity sector, the most effective policy would be a fuel tax or carbon tax plus carbon emission caps, and that an output tax or sulfur emission cap would not be effective.

5. Conclusion

This study showed that the hidden co-benefits that accompany carbon mitigation tax policies could exceed the mitigation costs and produce a “win-win” solution for China’s future carbon abatement and sustainable development. In this sense, even without an obligation to reduce carbon, under certain national environmental tax reform policies, “no regrets” carbon mitigation is likely to be implemented in China. In addition, by comparing three tax policies, the study found that, although the output tax would raise more revenue, the fuel and carbon taxes would be more effective in achieving carbon mitigation goals and maximizing local ancillary benefits. The model simulations on mixed national-sectoral carbon mitigation policies suggested that a mixed fuel tax or carbon tax plus carbon emission cap would be the best policy in terms of carbon mitigation, co-benefits, and induced technology change.

This study also contributes to key methodological issues as well. The integrated model with iterations in the counterfactual case was compared to the CGE model without iteration procedures on share parameters. These model simulations suggested that a single CGE model with fixed capital, labor, and energy shares tend to overestimate emission reductions, particularly over a long-time horizon. In addition, a partial-equilibrium bottom-up analysis was conducted with electricity demand fixed in the integrated base case, without considering the general equilibrium effects in the counterfactual case. Model simulations showed that without considering the scale effects, the partial-equilibrium bottom-up model tended to overestimate induced technology change, in particular for OILCC, GASCC, and hydro and wind technology options, which were expected to be at the margin of the overall technology mix.

The integrated model analysis illustrates how a top-down approach can be complemented by a bottom-up approach. This model is a valuable tool for evaluating the co-benefits of large-scale national environmental tax policies and within sector emission-cap policies. However, several caveats should be mentioned here. First, due to the limitation of information for projected technology options, this integrated model only simulated 20 years, 2000–2020. However, a longer simulation horizon would be more favorable for climate change policy and co-benefits studies, particularly for evaluating long-term induced technology changes based on the price signals of various environmental tax policies. Second, the study used iteration techniques to combine two distinct top-down and bottom-up models. At the current stage of discovery, it is still difficult to implicitly construct a single model that captures both the general equilibrium effects and interactions with all other sectors, and to simultaneously model complicated physical and engineering characteristics of various technology options. Finally, many key parameters in both models were based on either the one-year input-output table or on the engineering literature for potential technology options. This study can be improved by using time-series input-output tables and econometrically estimated key parameters in the top-down model, and by implicitly modeling back-stop energy technology options in the bottom-up module.

References

Abt Associates and Pechan-Avanti Group. 1999. "Co-control Benefits of Greenhouse Gas Control Policies." Prepared for the Office of Policy, U.S. Environmental Protection Agency, Contract no.68-W4-0029, Washington, D.C.

Aunan, K., H.A. Aaheim, and H.M. Seip. 2000. "Reduced Damage to Health and Environment from Energy Saving in Hungary." Paper presented at the "Ancillary Benefits and Costs of Greenhouse Gas Mitigation Strategies" workshop, Washington, DC, March 27–29.

Aunan, K., J. Fang, G. Li, H.M. Seip, and H. Vennemo. 2000. *Co-benefits from CO_2-Emission Reduction Measures in Shanxi, China: A First Assessment*. Oslo, Norway: Center for International Climate and Environment Research Oslo (CICERO).

Barker, T. 1993. "Secondary Benefits of Greenhouse Gas Abatements: The Effects of a U.K. Carbon Energy Tax on Air Pollution." Nota di Lavoro 32.93. Milan, Italy: Fondazione Eni Enrico Mattei.

Barker, T., and K.E. Rosendahl. 2000. "Ancillary Benefits of GHG Mitigation in Europe: SO_2, NOx, and PM_{10} Reductions from Policies to Meet the Kyoto Targets Using the E3ME Model and EXTERNE Valuations." Paper presented at the "Ancillary Benefits and Costs of Greenhouse Gas Mitigation Strategies" workshop, Washington, DC, March 27–29.

Barker, T., R. Ekins, and N. Johnstone. 1995. *Global Warming and Energy Demand*. London: Routledge.

Böhringer, C., and T. Rutherford. 2005. "Combining Top-Down and Bottom-Up in Energy Policy Analysis: A Decomposition Approach." ZEW Discussion Paper 06-007. Mannheim, Germany: Zentrum fur Europäische Wirtschaftforschung GmbH (Center for European Economic Research). ftp://ftp.zew.de/pub/zew-docs/dp/dp06007.pdf. Accessed December 28, 2007.

Boyd, R., K. Krutilla, and W.K. Viscusi. 1995. "Energy Taxation as a Policy Instrument to Reduce CO_2 Emissions: A Net Benefit Analysis," *Journal of Environmental Economics and Management* 29(1): 1–25.

Bruce, J.P., H. Lee, and E.F. Haites, eds. 1995. *Climate Change 1995: Economic and Social Dimensions of Climate Change*. Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Burtraw, D., A. Krupnick., K. Palmer., A. Paul., M. Toman, and C. Bloyd. 2003. "Ancillary Benefits of Reduced Air Pollution in the United States from Moderate Greenhouse Gas Mitigation Policies in the Electricity Sector," *Journal of Environmental Economics and Management* 45: 650–73.

Cao, J. (2004). "Options for Mitigating Greenhouse Gas Emissions in Guiyang, China: A Cost-Ancillary Benefit Analysis." EEPSEA Research Report, no. 2004-RR2. Ottawa, Canada: International Development Research Centre (IDRC), Economy and Environment Program for Southeast Asia (EEPSEA).

Cao, J., M.S. Ho, and D.W. Jorgenson. 2005. "China Clear Skies: The Impact of Market Instruments for Environmental Policy in China." Research report. Beijing, China: China Council for Cooperation on Environment and Development (CCICED).

Caspary, G., and D. O'Connor. 2002. "Beyond Johannesburg: Policies and Finance for Climate-Friendly Development." Policy Brief , no. 21. Paris: OECD.

Cifuentes, L.A., E. Sauma, H. Jorquera, and F. Soto. 2000. "Preliminary Estimation of the Potential Ancillary Benefits for Chile." Paper presented at the OECD "Ancillary Benefits and Costs of Greenhouse Gas Mitigation" workshop, Washington, DC, March 27–29. http://www.oecd.org/dataoecd/32/12/2052062.pdf. Accessed December 28, 2007.

Cobb, C.W., and P.H. Douglas. 1928. "A Theory of Production," *American Economic Review* (supplement) 18: 139–65.

Dessus, S., and D. O'Connor. 1999. "Climate Policy without Tears: CGE-Based Ancillary Benefits Estimates for Chile." OECD Development Working Paper, no.156. Paris: OECD Development Centre. http://ideas.repec.org/p/oec/devaaa/156-en.html. Accessed December 28, 2007.

Dowlatabadi, H, F.T. Tschang, and S. Siegel. 1993. "Estimating the Ancillary Benefits of Selected Carbon Dioxide Mitigation Strategies: Electricity Sector." Paper prepared for the Climate Change Division, U.S. Environmental Protection Agency, Washington, DC, August 5.

Edmonds, J., J.M. Roop, and M.J. Scott. 2000. "Technology and the Economics of Climate Change Policy." Report prepared for the Pew Center on Global Climate Change by Batelle, Washington, D. C. Arlington, VA: Pew Center on Global Climate Change. http://www.pewclimate.org/docUploads/technology_economics.pdf. Accessed December 28, 2007.

Energy Technology Systems Analysis Program (ETSAP). "Markal." On-line source. http://www.etsap.org/markal/main.html. Accessed December 17, 2007.

Garbaccio, R.F., M.S. Ho, and D.W. Jorgenson. 2000a. "The Health Benefits of Controlling Carbon Emissions in China." Paper presented at the OECD "Ancillary Benefits and Costs of Greenhouse Gas Mitigation" workshop, Washington, DC, March 27–29. http://www.oecd.org/dataoecd/31/60/2053233.pdf. Accessed Dec 28, 2007.

———. 2000b. "A Dynamic Economy-Energy-Environment Model of China: Version 2." Working paper. Cambridge, MA: Harvard University, Kennedy School of Government.

Gielen, D., and C. Chen. 2001. "The CO_2 Emission Reduction Benefits of Chinese Energy Policies and Environmental Policies: A Case Study for Shanghai, Period 1995–2020," *Ecological Economics* 39: 257 –70.

Grubb, M., J. Edmonds, P. ten Brink, and M. Morrison. 1993. "The Costs of Limiting Fossil-Fuel CO_2 Emissions: A Survey and Analysis," *Annual Review of Energy and Environment* 18: 397–478.

Hagler B. 1995. "Human Health Benefits Assessment of the Acid Rain Provision of the 1990 Clean Air Act Amendments." Final report prepared by Hagler Bailly Consulting, Inc., Boulder, CO, under subcontract to ICF Incorporated, Fairfax, Virginia, for U.S. Environmental Protection Agency, Acid Rain Division, Washington, DC.

Ho, M.S., and D.W. Jorgenson. 2007. "Sector Allocation of Emissions and Damage" and "Policies to Control Air Pollution Damages." In *Clearing the Air: The Health and Economic Damages of Air Pollution in China,* edited by M.S. Ho and C.P. Nielsen, 279–372. Cambridge, MA: MIT Press. .

Hoffman, K.C., and D.W. Jorgenson. 1977. "Economic and Technological Models for Evaluation of Energy Policy," *Bell Journal of Economics* 8(2): 444–66.

Metz, B., O. Davidson, R. Swart, and J. Pan, eds. 2001. *Climate Change 2001: Mitigation*. Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Jacobsen, H.K. 1998. "Integrating the Bottom-Up and Top-Down Approach to Energy-Economy Modeling: The Case of Denmark," *Energy Economics* 20(4): 443–61.

Jiang, K., and X. Hu. 2001. *Carbon Tax: An Integrated Analysis for China*. Beijing: Center for Energy, Environment, and Climate Change, Energy Research Institute.

Johnstone, N. 1994. "The Integration of Bottom-Up and Top-Down Modelling of CO_2 Emissions: Description of a Sectoral Analysis." Energy-Environment-Economy Modelling Discussion Paper, no. 10. Cambridge: University of Cambridge, U.K.

Kokaz, K, B. Liu, and P.P. Rogers. 1999. "Modeling Investment Strategies in China's Electricity Power Sector and U.S.-China Carbon Trading." University Committee on Environment Discussion Paper. Cambridge, MA: Harvard University.

Koopmans, C.C., Te Velde, D.W., Groot, W., Hendriks, J.H.A., 1999. "NEMO: Netherlands Energy Demand Model—A Top-down Model Based on Bottom-up Information." CPB Netherlands Bureau for Economic Policy Analysis Research Memorandum. The Hague: CPB.

Koopmans, C.C., and D.W. te Velde. 2001. "Bridging the Energy Efficiency Gap: Using Bottom-up Information in a Top-down Energy Demand Model," *Energy Economics* 23: 57–75.

Lovins, A.B., and L.H. Lovins. 1991. "Least-Cost Climatic Stabilization," *Annual Review of Energy and Environment* 16: 433–531.

McFarland, J.R, J. Reilly, and H.J. Herzog. 2002. "Representing Energy Technologies in Top-down Economic Models Using Bottom-Up Information." MIT Joint Program on the Science and Policy of Global Change, Report No. 89. Cambridge, MA: MIT.

Murray, F.E. 1996. "Environment and Technology in Investment Decision-Making: Power Sector Planning in China." PhD diss., Harvard University, Division of Engineering and Applied Science, Cambridge, MA.

O'Connor, D. 2000. "Ancillary Benefits Estimation in Developing Countries: A Comparative Assessment." Paper presented at the OECD "Ancillary Benefits and Costs of Greenhouse Gas Mitigation Strategies" workshop, Washington, D.C., March 27–29.

———. 2001. "Estimating Ancillary Benefits of Climate Policy Using Economy-Wide Models: Theory and Application in Developing Countries." Paper presented at Economy and Environment Program for Southeast Asia (EEPSEA) "Biannual Researchers' Workshop," Hanoi, Vietnam, November 20–23.

O'Connor, D., F. Zhai, K. Aunan, T. Berntsen, and H. Vennemo. 2003. "Agriculture and Human Health Impacts of Climate Policy in China: A General Equilibrium Analysis with Special Reference to Guang Dong." OECD Development Centre Working Paper, no. 206.

Paris: OECD Development Centre. http://ideas.repec.org/p/oec/devaaa/206-en.html. Accessed December 17, 2007.

Palmer, K.L,. and D. Burtraw. 1997. "Electricity Restructuring and Regional Air Pollution," *Resources and Energy* 19: 139–74.

Pizer, W., D. Burtraw, W. Harrington, R. Newell, and J. Sanchirico. 2005. "Modeling Economy-Wide versus Sectoral Climate Policies Using Combined Aggregate-Sectoral Models." RFF Discussion Paper 05-08. Washington, D.C.: Resources for the Future.

RIVM, EFTEC, NTUA, and IIASA. 2001. "European Environmental Priorities: An Economic and Environmental Assessment." Report 481505010. Prepared for the European Commission, Environment Directorate-General, Environmental Action Programme. Bilthoven, The Netherlands: RIVM. http://www.rivm.nl/bibliotheek/rapporten/481505010.pdf. Accessed December 17, 2007.

Sue Wing, I. 2006a. "Representing Induced Technology Change in Models for Climate Policy Analysis," *Energy Economics* 28: 539–62. http://people.bu.edu/isw/papers/snowmass.pdf. Accessed December 28, 2007.

———. 2006b. "The Synthesis of Bottom-Up and Top-Down Approaches to Climate Policy Modeling: Electric Power Technologies and the Cost of Limiting US CO_2 Emissions," *Energy Policy* 34(18): 3847–69.

Wang, S.C.D., and E.P Smith. 2000. "Adjusting for Mortality Effects in Chronic Toxicity Testing: Mixture Model Approach," *Environmental Toxicology and Chemistry* 19: 204–209.

Williams, R.H. 1990. "Low-Cost Strategies for Coping with CO_2 Emissions," *The Energy Journal* 11(3): 35–68.

Wilson, D., and J. Swisher. 1993. "Exploring the Gap: Top-Down versus Bottom-Up Analyses of the Cost of Mitigating Global Warming," *Energy Policy* 21(3): 249–63.

World Bank. 1997. Clear Water, Blue Skies: China's Environment in the New Century. Washington, D.C.: World Bank.