

FINAL REPORT

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The Harvard University Center for the Environment initiated its China Project to foster an interdisciplinary approach to understanding environmental problems and policy in China, and the role of environment in U.S.-Chinese relations. It focuses on energy-related atmospheric pollution issues, with disciplinary strengths in economics, atmospheric chemistry, engineering, health, law, and policy. The component studies of the China Project are conducted in partnership with various universities and research institutions in the People's Republic of China.

Major research components supported by the DOE award included: A) developing a dynamic, multi-sector model of the Chinese economy that can estimate energy use, emissions, and health damages from pollution, and using this model to simulate broad economic effects of market-based pollution control policies; B) developing a regionally disaggregated model of technology and investment choice in the Chinese electric power sector; C) applying an atmospheric chemical tracer transport model to investigate carbon uptake in Eurasia (notably China) and North America, and to inform observational strategies for CO₂ in China and elsewhere. Smaller research streams included: D) interview-based investigation of the drafting and implementation of air pollution control law in China, from grassroots to central government levels; E) supplemental support for epidemiological studies of air pollution and health in Chinese settings. As in prior progress reports, we regard these diverse but related components as separate tasks under the guidelines for reporting to DOE.

Diverse results from across this program, supported both by DOE and other sources, were first integrated and published in McElroy and Nielsen (1997) and Nielsen and McElroy (1998). These made the case for international cooperation with China to link its domestic

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priority of air pollution control and environmental health with the global need for limits on greenhouse gas emissions. They also spotlighted the need to do so in a manner fully conscious and informed about great disparities in policy conditions of China and the west, and hence the inapplicability of some western environmental approaches until political, legal, and economic conditions have developed sufficiently to support them.

Harvard principals and Chinese collaborators have featured results of the studies in a number of policy briefings to key decision-makers on environment. At the national level, the team has established regular briefing relationships to Xie Zhenhua, Administrator of the Chinese State E.P.A (SEPA); Qu Geping, founding director of SEPA and Chair of the Environmental and Resources Protection Committee of the National People's Congress (NPC); and Wen Jiabao, current Vice Premier and the next Premier of China.

A. ECONOMICS

Economist Dale W. Jorgenson has led the leading research stream supported by DOE. It focused on assessment of "co-benefits" of emission control in China. Co-benefits analysis includes how policies to control local air pollution in China may simultaneously limit emissions of greenhouse gases (GHGs) and, conversely, how limits on GHG emissions might yield ancillary benefits in local pollution control and health. Such co-benefits are possible because emissions of both global and local air pollutants share primary causation, combustion of fossil fuels. These assessments serve political objectives by aligning environmental priorities of the global community with the immediate domestic environmental needs of China.

The primary analytical tool for the research has been an economic model developed with explicit recognition of both plan and market elements of the economy (Garbaccio et al. 2001). A first paper made simple projections of Chinese growth and carbon emissions, and discussed how these are related to the institutions and policies then in effect (Ho et al., 1998). Our first full research paper (Garbaccio et al. 1999a) used the model to examine the effects of a carbon tax on fuel use, emissions and GDP growth. We next extended the research to begin including local air pollutants (particulate matter and sulfur dioxide) and the health damage they cause. In Garbaccio et al. (2000), using rough health damage estimates derived in a prominent World Bank study titled *Clear Water Blue Skies* (1997), we estimated how policies to reduce CO₂ emissions will also reduce local health damages, primarily premature deaths. Plans to extend this research were the main subject of China Project briefings for Vice Premier Wen Jiabao, SEPA Administrator Xie Zhenhua, and NPC Committee Chair Qu Geping in 2000.

To put the above policy analysis on a firm empirical ground and to improve the team's understanding of recent Chinese developments, we compiled an *Energy Conservation Data Base for China*. This consists of a time series of economic, energy and pollution data, including inter-industry transactions. The reliability of the official economic and energy data has been prominently discussed recently by both the popular press and China

specialists. In Garbaccio et al. (1999b), we discussed some of these data issues and analyzed the causes of the dramatic fall in the energy-GDP ratio between 1987 and 1992.

In Ho and Jorgenson (2001) we completed the first version of the *Data Base*, consisting of a time series of input output tables and capital and labor inputs. It examined various adjustments to reconcile the discrepancies that has been widely noted, and generated alternative estimates of GDP growth. This was done in collaboration with the Institute of Technical and Quantitative Economics at the Chinese Academy of Social Sciences. The joint team studied the productivity experience of all sectors of the economy, and found that the major contributor was agriculture with a 2.2% total factor productivity (TFP) growth rate. On the other hand, many manufacturing sectors even had negative TFP growth. Overall GDP growth came mainly from capital accumulation (6.1% out of 8.0%), with TFP growth contributing only 0.3%, and labor force growth accounting for the remainder.

To understand the effects of development policies our team also analyzed the major government strategy of market deregulation and reform of state-owned enterprises (Fisher-Vanden and Jorgenson 2000). We found that liberalizing capital markets, or privatizing state enterprises, will reduce the carbon intensity of the economy due to a reallocation of activity to less dirty sectors. These also raise economic growth, however, and total energy use.

In a report for an international environmental advisory body to the Chinese government, we examined policies aimed specifically at local pollution control, rather than as an ancillary benefit of carbon control (Ho et al. 2002). We found that a system of Pigovian-like taxes on fuels (taxes in proportion to the damage caused) will result in a heavy tax on coal but will reduce health damage from air pollution considerably. A Pigovian tax on all commodities will be shared more equally but is inefficient and reduces pollution only modestly. These taxes generate substantial revenue that may be recycled and the effects on GDP may be positive in some cases.

The air pollution estimates in Garbaccio et al. (2000) and Ho et al. (2002) are based on the simple emission classifications and linear assumptions for concentrations in the aforementioned World Bank study (1997). These formulations were based in part on atmospheric models run not on Chinese data, but extrapolating from Eastern Europe. This led to a major China Project collaboration of our DOE-funded economists with separately funded scholars at Tsinghua University and the Harvard School of Public Health to develop China-based estimates of pollution concentration and damages, i.e. using local meteorological, population, and source data. The initial phase of this work is currently nearing completion and spawning new research. Preliminary results were reported in the proceedings of an HUCE China Project research workshop held in September, 2002.

The papers applying these damage results to the economic model are Ho and Jorgenson (2002a, 2002b). The research reported there includes latest estimates for the most damaging sectors—electricity, cement, iron and steel, and chemicals—and covers damage

from sulfur dioxide and primary fine particles. We find that our close examination of these sectors reveal damage estimates that are quite different in some cases from those based on the simplifications of the World Bank (1997). We also made a rough estimate for the transportation sector and found that it is becoming a serious source of pollution damage, separate from the familiar costs of urban traffic congestion. Ten papers from the 2002 workshop (including Ho and Jorgenson 2002a, 2002b) are now being prepared for formal publication in an edited volume, with a summary for policymakers. This volume will be the centerpiece of currently planned separate policy briefings for Xie Zhenhua, Administrator of the Chinese EPA, and Wen Jiabao, soon-to-be Premier of China, in June of 2003.

B. ENERGY SYSTEMS

This component of the first grant term (1995-1998) was led by Peter P. Rogers of the Division of Engineering and Applied Sciences. Its objective was to develop a regional model of technology choice in China's electric power system. It considered a range of traditional fossil fuel technologies along with innovative clean coal, modern gas and oil combined-cycle, nuclear, hydro, and wind technologies. The aim of the model was to help Chinese policymakers decide among policy and technology choices in the power sector across different regions of China, taking advantage of their different energy demands and supplies and the characteristics of the energy transportation system.

This model (Murray 1996) was completed using an optimizing framework written in GAMS. It used twelve power generating regions with coal, oil, and gas supplies, and transport of energy either as fuel commodities in their own right or as electricity via interregional links. Each region had an existing stock of fossil and non-fossil power plants ranging in size and having varying performance characteristics. For each region and in each of five time periods from 1995-2020, the model could calculate the optimal (least-cost) investment strategy for additional capacity to meet the increase in the predicted demand for electricity, while at the same time meeting constraints on local, regional, and global pollutant emissions. The model started with estimates of the capital and operating costs of the potential electric power investment, prices of the fuels, cost of fuel and electricity transport, emission characteristics of the different technologies, and the levels of environmental constraints on particulates, sulfur dioxide, and carbon dioxide. It then output the optimal location of the different technologies in different regions and time periods, thus calculating an optimal investment strategy (Murray and Rogers 1998).

The final version of the model included the following technologies: traditional coal plants in a range of sizes (both domestic and imported), the addition of electrostatic precipitators and scrubbers to these technologies, traditional gas- and oil-fired plants, gas and oil combined-cycle plants, atmospheric fluidized bed combustion, hydropower plants, pressurized light water nuclear reactors, wind generators, coal washing, coal substitution, and advanced clean coal technologies such as integrated combined-cycle coal. All technologies had different cost, performance, and pollutant emission characteristics.

The model was developed at Harvard and was presented in March of 1997 by Rogers and colleagues at a variety of governmental and academic institutions in China to evaluate its applicability and results. It was also presented at DOE headquarters prior to the visit of Vice President Albert Gore to China, and served as the basis for a briefing paper on power sector technology used during the Vice President's subsequent visit. Based on the discussions in Washington and Beijing, we further revised the model during 1997 through visits of experts from Tsinghua University and the Energy Research Institute of the State Planning Commission. We presented a revised version at a DOE workshop in Rockville, Maryland in August, 1997.

Our team designed the model as a decision support system for analysts and policymakers, rather than a strict predictor of the future of China's power sector. Some general implications, however, could be concluded from defensible assumptions. We set as a base case—or Business-as-Usual case—the minimum cost trajectory with no additional environmental constraints. Under this case, conventional coal plants dominated the solutions. When sulfur constraints were added, the solution avoided the addition of scrubbers (FGD) in favor of a switch to hydro and the use of oil and gas combined cycle plants. Large reductions in costs were required to make advanced clean coal technologies competitive with traditional coal and hydro. Based on the bulk of model runs, we expect that over the next 25 years China's electric power sector will remain a major user of coal. Furthermore, there appears to be little incentive to burn coal at high efficiencies that the advanced clean coal technologies offer. Reductions in carbon dioxide emissions will come largely from slightly improved combustion efficiencies, but mainly from a switch to hydro over the base conditions when forced by tightening the sulfur constraints. The model was also used to explore the challenges of setting baselines for Chinese power sector projects under the Clean Development Mechanism of the Kyoto Protocol (Liu et al. 2000).

C. ATMOSPHERIC SCIENCE

The atmospheric CO₂ modeling component led by atmospheric scientist and P.I. Michael B. McElroy investigated the distribution of carbon uptake by the terrestrial biosphere in the Northern Hemisphere, including both North America and Eurasian continent (including China).

A key unresolved issue of the current global carbon budget remains the exact magnitude and geographical distribution of the uptake of anthropogenic CO₂ by the natural reservoirs in the ocean and terrestrial biosphere. Over the past decade, identification of the large-scale distributions of net carbon uptake has increasingly been attempted by analysis of spatial gradients in atmospheric concentrations of CO₂ and other trace substances. More recently, investigators have attempted to use analysis of atmospheric concentration gradients to identify longitudinal variations in the northern hemispheric terrestrial sink; the study of Fan et al. 1998, for example, is directed at extracting the relative contributions of North America and Eurasia. In our work, we employed an

atmospheric tracer transport model developed at Harvard to explore issues of resolution raised by such previous studies. The primary project goals were: (a) the development and validation of the CO₂ tracer transport model; (b) use of the model (i) to explore observational strategies to infer the net source of CO₂ from a large region (e.g., net fossil and biospheric emissions from China) and (ii) to investigate the distribution of net biospheric CO₂ uptake in northern mid-latitudes.

Our analysis is based on methods of synthesis inversion, i.e., to find the linear combination of sources and sinks such that the sum of their modeled concentrations best matches the measured concentrations at CO₂ measurement sites. The atmospheric transport model employed is the 3-D chemical tracer model (CTM) developed at Harvard and based on dynamical fields derived from a general circulation model of the atmosphere (GISS GCM MODEL II, Hansen et al. 1983). A range of modeled CO₂ distribution characteristics was evaluated against observations from the NOAA-CMDL flask network (Conway et al., 1994). In addition, model results were evaluated against simulations from the CO₂ model intercomparison project, TRANSCOM. Details on the CTM, sources and sinks included, and evaluations against observational data were provided in prior progress reports; space constraints prevent their repetition here.

Results of our analyses indicate that estimates of the total northern mid-latitude terrestrial sink appear well constrained by the observations; derived flux values are relatively robust to observation network configuration, differing by less than 0.2 Gt C per year. In contrast, the longitudinal partition in the Northern Hemisphere is not as well constrained; for example, estimates of North American uptake display great sensitivity to configuration of the observation network. Our investigation of suitable measurement locations for determining the longitudinal distribution of the terrestrial carbon sink indicates that this is best achieved by measurements around the continental margins, i.e., upstream and downstream of the continental signal. These results are discussed in Suntharalingam et al. (2003).

The CO₂ simulations outlined above have provided the basis for our ongoing, separately funded investigation into the export of Asian carbon emissions during the spring of 2001. We employ CO₂ and CO measurements from the TRACE-P aircraft campaign in conjunction with the model simulations (now using the GEOS-CHEM transport model) to place constraints on regional sources (e.g., Chinese fossil fuel emissions, Chinese biospheric emissions).

D. AIR POLLUTION LAW AND POLICY

The main focus of the legal research stream led by William P. Alford of East Asian Legal Studies at Harvard Law School has been the limitations of environmental law and policy in a country in which the rule of law is still being established. Ideal pollution control strategies such as those explored in above research components must ultimately be implemented in the actual policy conditions of China. Many western environmental scholars fail to recognize that successful environmental approaches of the west are not

always easily transferred to China, where systems of regulatory oversight and enforcement are highly attenuated.

Our legal research team first conducted a general assessment of the systemic limits to environmental law and its implementation in a review paper (Alford and Shen 1997). A subsequent study focused less on implementation and more on the compromised institutional processes by which environmental laws in China are drafted and promulgated (Alford and Liebman 2001). Our focus in this study was the 1995 revisions to the Chinese Air Pollution Prevention and Control Law, first promulgated in 1987. This law, directly relevant to other components of research described above and below, has had a particularly discouraging history. Its structural weaknesses were such after the 1995 revisions studied by our team that the statute was revised yet again, in 2000.

Another study, with large supplemental funding, involved an interdisciplinary team led by Alford and a cultural anthropologist, Robert Weller (Alford et al. 2002). It also included political scientists, an economist, and—in a linked effort published separately and described below (Venners et al. 2001)—health scientists. This effort considered the way the Chinese government has sought to use bureaucratic, political, legal and educational vehicles to address air pollution and related health problems in rural China. It examined the ways in which those policy measures have been communicated to, understood by, and acted upon by the citizenry, drawing on household and epidemiological surveys conducted in rural Anhui. The study suggested that the central government's message has yet to be absorbed to the degree intended and considered both why this has been the case and how the effectiveness of policy mechanisms might be enhanced. Related research now continues under new funding, assessing similar issues in a more urban context.

E. ENVIRONMENTAL HEALTH

Ongoing research led by Xiping Xu at the Harvard School of Public Health into the epidemiology of air pollution and human health in rural and urban China was supplemented over the first grant term (1995-1998) by modest support from the DOE award. Dose-response functions resulting from these studies have been applied in the estimation of health damages of pollution in the economic and policy model of Part A and in the power sector analysis of Part B above.

Our environmental health team first prepared a review of the air pollution epidemiological literature for China, for reference to researchers in other fields (Xu 1998). A following study indicated that both particles and SO₂ are associated with reduced pulmonary function and increased morbidity of respiratory diseases (Wang et al. 1999). An investigation into air pollution and mortality in Shenyang showed that total suspended particulates and sulfur dioxide were each highly significant predictors of daily mortality (Xu et al. 2000). An indoor air pollution study conducted on the same survey households analyzed for their opinions of environment described above (Alford et al. 2002) found significant relationships of monitored air pollutants with respiratory health in both rural and urban China (Venners 2001). The highest prevalence of respiratory

symptoms occurred in the most urban area, lesser prevalence in a rural area, but the least prevalence in a moderately urban area.

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Publications and manuscripts from research supported entirely or in part by contract DE-FG02-95ER62133 include the following.

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