Final Technical Report: "Representing Endogenous Technological Change in Climate Policy Models: General Equilibrium Approaches"

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The research supported by this award pursued three lines of inquiry:

(a) The construction of dynamic general equilibrium models to simulate the accumulation and substitution of knowledge, which has resulted in the preparation and submission of several papers:

- A submitted pedagogic paper which clarifies the structure and operation of computable general equilibrium (CGE) models (C.2), and a review article in press which develops a taxonomy for understanding the representation of technical change in economic and engineering models for climate policy analysis (B.3).
- A paper which models knowledge directly as a homogeneous factor, and demonstrates that inter-sectoral reallocation of knowledge is the key margin of adjustment which enables induced technical change to lower the costs of climate policy (C.1).
- An empirical paper which estimates the contribution of embodied knowledge to aggregate energy intensity in the U.S. (C.3),followed by a companion article which embeds these results within a CGE model to understand the degree to which autonomous energy efficiency improvement (AEEI) is attributable to technical change as opposed to sub-sectoral shifts in industrial composition (C.4)
- Finally, ongoing theoretical work to characterize the precursors and implications of the response of innovation to emission limits (E.2).

(b) Data development and simulation modeling to understand how the characteristics of discrete energy supply technologies determine their succession in response to emission limits when they are embedded within a general equilibrium framework. This work has produced two peer-reviewed articles which are currently in press (B.1 and B.2).

(c) Empirical investigation of trade as an avenue for the transmission of technological change to developing countries, and its implications for leakage, which has resulted in an econometric study which is being revised for submission to a journal (E.1). As work commenced on this topic, the U.S. withdrawal from Kyoto and the administration's announcement of a voluntary target based on emission intensity made it apparent that that the degree of emission leakage to developing countries would depend on (i) the form of the emission limit set by developed countries and (ii) the incentives faced by developing nations to accede to an international climate regime. This realization led to synergistic research on the properties of intensity targets under uncertainty, which resulted in two theoretical studies, one which has been published (A.1) and the other which is currently in review (C.5).

This grant also funded a number of masters and PhD students to work on different elements of the analysis. Overall, this research has produced one published peer-reviewed journal article, three articles in press at peer-reviewed journals, five articles currently in review for journals and an edited volume, and two papers in preparation for submission to peer-reviewed journals. Additional results have been disseminated through presentations at a number of conferences and seminars.

A. Published papers:

1. Ellerman, A.D. and I. Sue Wing (2003). Absolute v. Intensity-Based Emission Caps, Climate Policy 3 (Supplement 2): S7-S20.
   Cap-and-trade systems limit emissions to some pre-specified absolute quantity. Intensity-based limits, that restrict emissions to some pre-specified rate relative to input or output, are much more widely used in environmental regulation and have gained attention recently within the context of greenhouse gas (GHG) emissions trading. In this paper we provide a non-technical introduction to the differences between these two forms of emission limits. Our aim is not to advocate either form, but to elucidate the properties of each in a world where future emissions and GDP are not known with certainty. We argue that the two forms have identical effects in a world where future emissions and economic output (i.e., GDP) are known with certainty, and show that outcomes for marginal costs, abatement, emissions and welfare diverge only because of the variance of actual future GDP relative to its forecast expectation.

B. Papers in press:

1. Sue Wing, I. (forthcoming). The Synthesis of Bottom-Up and Top-Down Approaches to Climate Policy Modeling: Electric Power Technology Detail in a Social Accounting Framework, Energy Economics.
   Differences between "bottom-up" engineering and "top-down" macroeconomic representations of the energy system in climate policy simulations generate divergent predictions of carbon-free energy technologies' contributions to future energy supply and climate change mitigation. This paper employs Howitt's (1995) positive mathematical programming approach to integrate bottom-up technology detail into the social accounting framework of top-down CGE models. Using U.S. data, the inputs to the electric power sector are apportioned among discrete generation technologies by minimizing the deviation of the allocation of inputs from that implied by engineering cost shares, subject to the zero-profit and market-clearance constraints of the sector's macroeconomic production structure.

2. Sue Wing, I. (forthcoming). The Synthesis of Bottom-Up and Top-Down Approaches to Climate Policy Modeling: Electric Power Technologies and the Cost of Limiting U.S. CO_2 Emissions, Energy Policy.
   In the U.S., the bulk of CO_2 abatement induced by carbon taxes comes from electric power. This paper incorporates technology detail into the electricity sector of a computable general equilibrium model of the U.S. economy to characterize electric power's technological margins of adjustment to carbon taxes and to elucidate their general equilibrium effects. Compared to the top-down production function representation of the electricity sector, the technology-rich bottom-up specification produces less abatement at a higher welfare cost, suggesting that bottom-up models do not necessarily generate lower costs of abatement than top-down models. This result is shown to be sensitive to the elasticity with which technologies' generating capacities adjust to relative prices.

3. Sue Wing, I. (forthcoming). Representing Induced Technological Change in Models for Climate Policy Analysis, Energy Economics.
   Induced technological change (ITC), whereby the relative price effects of reducing greenhouse gas emissions stimulate innovation that mitigates the cost of abatement, is both tantalizing to decision makers and challenging to represent in the computational economic and engineering models used to analyze climate change policy. This overview reconciles the divergent views of technology and technological change within different types of models, elucidates the theoretical underpinnings of ITC, introduces the reader to the techniques of their practical implementation, and evaluates the implications for models' results.

C. Papers in review:

1. Sue Wing, I. (2003). Induced Technical Change and the Cost of Climate Policy, submitted to Economic Modelling.
   This paper investigates the potential for a carbon tax to induce R&D, and for the consequent induced technical change (ITC) to lower the macroeconomic cost of abating carbon emissions. ITC is modeled within a general equilibrium simulation of the U.S. economy by the effects of emissions restrictions on the level and composition of aggregate R&D, the accumulation of the stock of knowledge, and the industry-level reallocation and substitution of intangible services derived therefrom. Contrary to other authors, I find that ITC's impact is large, positive and dominated by the latter "substitution effect", which mitigates most of the deadweight loss of the tax.

2. Sue Wing, I. (2004). CGE Models for Economy-Wide Policy Analysis: Everything You Ever Wanted to Know (But Were Afraid to Ask), revise and resubmit at Journal of Policy Modeling.
   This paper is a simple, rigorous, practically-oriented exposition of computable general equilibrium (CGE) modeling. The general algebraic framework of a CGE model is developed from microeconomic fundamentals, and employed to illustrate (i) how a model may be calibrated using the economic data in a social accounting matrix, (ii) how the resulting system of numerical equations may be solved for the equilibrium values of economic variables, and (iii) how perturbing this equilibrium by introducing tax or subsidy distortions facilitates analysis of policies' economy-wide impacts.

3. Sue Wing, I. and R.S. Eckaus (2004). Explaining Long-Run Changes in the Energy Intensity of the U.S. Economy, submitted to Resource and Energy Economics.
   Recent events have revived interest in explaining the long-run changes in the energy intensity of the U.S. economy. We use a KLEM dataset for 35 industries over 39 years to decompose changes in the aggregate energy-GDP ratio into shifts in sectoral composition (structural change) and adjustments in the energy demand of individual industries (intensity change). We find that although structural change offsets a rise in sectoral energy intensities from 1960 until the mid- 1970s, after 1980 the change in the industrial mix has little impact and the average sectoral energy intensity experiences decline. Then, we use these data to econometrically estimate the influence on within-industry changes in energy intensity of price-induced substitution of variable inputs, shifts in the composition of capital and embodied and disembodied technical progress. Our results suggest that innovations

embodied in information technology and electrical equipment capital stocks played a key role in energy intensity's long-run decline.

4. Sue Wing, I. and R.S. Eckaus (2005). The Decline in U.S. Energy Intensity: Its Origins and Implications for Long-Run CO_2 Emission Projections, submitted to special issue of Energy Policy in memory of Alan S. Manne.
   This paper analyzes the influence of the long-run decline in energy intensity on projections of U.S. energy use and carbon emissions to the year 2050. We build on our own recent work which decomposes changes in the aggregate U.S. energy-GDP ratio into shifts in sectoral composition (structural change) and adjustments in the energy demand of individual industries (intensity change), and identifies the impact on the latter of price-induced substitution of variable inputs, shifts in the composition of capital and embodied and disembodied technical progress. We employ a recursive-dynamic computable general equilibrium (CGE) model of the U.S. economy to analyze the implications of these findings for future energy use and carbon emissions. Comparison of the simulation results against the historical trends in GDP, energy use and emissions reveals that the range of values for the rate of autonomous energy efficiency improvement (AEEI) conventionally used in CGE models is consistent with the effects of structural changes at the sub-sector level, rather than disembodied technological change. Our results suggest that we may well experience faster growth of emissions than have been observed historically, even when the energy-saving effects of sub-sectoral changes are accounted for.

5. Sue Wing, I., A.D. Ellerman and J.M. Song (2005). Absolute vs. Intensity Limits for CO_2 Emission Control: Performance Under Uncertainty, submitted chapter to an MIT Press monograph on the Design of Climate Policy.
   We elucidate the differences between absolute and intensity-based limits of CO_2 emission when there is uncertainty about the future. We demonstrate that the two limits are identical under certainty, and rigorously establish their relative attractiveness under two criteria: preservation of expectations—the minimization of the difference between the actual level and the initial expectation of abatement associated with a one-shot emission target, and temporal stability—the minimization of the variance of abatement due to fluctuations in emissions and GDP over time. Empirical tests of these theoretical propositions indicate that intensity caps are preferable for a broad range of emission reduction commitments. This finding is robust for developing countries, but is more equivocal for developed economies.

<u>D. Non-refereed conference papers</u>:

1. Sue Wing, I., A.D. Ellerman and J.M. Song (2005). Absolute vs. Intensity Limits for CO_2 Emission Control: Performance Under Uncertainty, presented at the David Bradford Memorial Conference on the Design of Climate Policy, Venice, 22-23 July.
2. Sue Wing, I. and R.S. Eckaus (2003). The Energy Intensity of U.S. Production: Sources of Long-Run Change, Proceedings of the 23rd IAEE North American Conference, Mexico City.

<u>E. Papers in preparation</u>:

1. Sue Wing, I., L.E. Seifert and C. Moreno (2006). North-South Technology Diffusion: The Composition Effect of Trade in Machinery and Equipment on Total Factor Productivity.

2. Sue Wing, I. (2006). Induced Technical Change: Firm Innovatory Responses to Environmental Policy.

F. Masters theses:
L.E. Seifert (2004). North-South Technology Diffusion: The Composition Effect of Trade in Machinery and Equipment on Total Factor Productivity, Dept. of International Relations, Boston University.

G. Presentations:
1. "Energy Intensity Decline: Its Origins and Consequences for Long-Run Carbon Emissions", in "Climate Policy Without Cost? Can Technology Solve the Climate Problem?", conference at the U.S. Environmental Protection Agency, Washington DC, Jul. 18, 2006
2. Induced Technical Change: Firm Innovatory Responses to Environmental Policy, Rensselaer Polytechnic Institute Economics Dept., Apr. 24, 2006; Ohio State University Dept. of Agricultural, Environmental and Development Economics, Apr. 20, 2006; Dartmouth College Workshop on Technical Change and the Environment, Mar. 25, 2006.
3. "Explaining Long-Run Changes in the Energy Intensity of the U.S. Economy", National Bureau of Economic Research Productivity Lunch, Cambridge MA, Feb. 7, 2006.
4. "Absolute vs. Intensity-Based Limits for CO_2 Emission Control, Performance Under Uncertainty", David Bradford Memorial Conference on the Design of Climate Policy, Venice, Italy, Jul. 22-23, 2005.
5. "The Synthesis of Bottom-Up and Top-Down Approaches to Climate Policy Modeling: Electric Power Technologies and the Cost of CO_2 Emission Limits". 11th Annual Conference on Computing in Economics and Finance, Washington DC, 24 June 2005. Environment and Development Workshop, Rockefeller Center, Dartmouth College, Mar. 28, 2005.
6. "The role of technological change in reducing energy intensity", NCCR Climate Symposium 2005: Interfaces between Climate and Economic Dynamics, Interlaken, Switzerland, Mar. 3-5, 2005.
7. "Using CGE Models for Economy-wide Policy Analysis", Laboratory for Energy and the Environment, Massachusetts Institute of Technology, Oct. 11, 2005.
8. Representing Induced Technical Change in Climate Policy Models. Energy Modeling Forum Climate Change Impacts and Integrated Assessment Meeting, Snowmass CO, August 5-8, 2003.
9. "Induced Technical Change and the Cost of Climate Policy", in Representing Technological Change in Models for Climate Policy Analysis: Lessons from Different Approaches, AERE Session of Allied Social Science Associations Meeting, San Diego CA, Jan 3, 2004. University of Colorado Environmental and Resource Economics Workshop, Boulder CO, July 17-18, 2003. Center for the Integrated Study of the Human Dimensions of Global Change, Carnegie Mellon University, Pittsburgh PA, March 7, 2003.
10. "The Energy Intensity of U.S. Production: Sources of Long-Run Change." IAEE Session at the Allied Social Sciences Association Meeting, Washington DC, Jan. 4, 2003.

H. Conference sessions funded:
Representing Technological Change in Models for Climate Policy Analysis: Lessons from Different Approaches, AERE Session of Allied Social Science Associations Meeting, San Diego CA, Jan 3, 2004.