Department of Energy
Chicago Operations Office
9800 South Cass Avenue
Argonne, Illinois 60439

December 4, 2001

John C. Houghton
SC-74 GTN

SUBJECT: FINANCIAL ASSISTANCE TECHNICAL CLEARNACE, AWARD NO. DE-FG02-97ER62504 WITH DUKE UNIVERSITY

A copy of the final technical report for the subject award is attached. The award cannot be officially closed out until we receive written assurance from you that the final technical report is considered satisfactory. Accordingly, it is requested that you complete and return the information requested below.

Tanisha Edwards

Tanisha R. Edwards, Procurement Technician
Operations Division
Office of Acquisition and Assistance

TO: Tanisha Edwards
U.S. Department of Energy
Chicago Operations Office
Office of Acquisition and Assistance
9800 S. Cass Avenue
Argonne, IL 60439

SUBJECT: AWARD NO. DE-FG02-97ER62504

The final technical report has been received and [✓] is [ ] is not considered to be satisfactory. (If the report is considered satisfactory, please indicate specific deficiencies below.)

John C. Houghton
DOE Project Officer

3/5/02
Date

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Final Report

Title: Carbon Policy and Technical Change: Market Structure, Increasing Returns, and Secondary Benefits

Grant: DE-FG02-97ER62504

Principal Investigators: Dr. Pietro Peretto
Associate Professor of Economics
Department of Economics
205 Social Sciences Building
Duke University
Box 90097
Durham, North Carolina 27708-0097
Telephone: (919) 660-1807
Fax: (919) 684-8974
(E-mail: peretto@econ.duke.edu)

)OE Patent Clearance Granted
Apr 28 2004
Date
Mark P. Dvorscak
(630) 252-2393
E-mail: mark.dvorscak@ch.doe.gov
Office of Intellectual Property Law
DOE Chicago Operations Office

Dr. V. Kerry Smith
University Distinguished Professor
Department of Agricultural and Resource Economics
Campus Box 8109
North Carolina State University
Raleigh, North Carolina 27695-8109
Telephone: (919) 513-3761
Fax: (919) 515-6268
(E-mail: kerry_smith@ncsu.edu)

Date: November 19, 2001

This report summarizes the activities and accomplishments associated with grant # DE-FG02-97ER62504 initially awarded to Duke University on July 23, 1997 to begin September 15, 1997. It is divided into five sections: objectives and general summary; background on activities during the grant period; completed research and findings; continuing activities; and status of the partially completed papers.

I. Objectives and General Summary

An economic evaluation of the impact of policies intended to control emissions of CO_2 and other "greenhouse gases" (GHGS) depends on the *net* costs of these controls and their distribution throughout the production sectors of developed and developing economies. The answers derived from appraisals of these *net* costs, in turn, stem from what is assumed about the timing of the controls, the pace of technological change, and any short-term secondary benefits from their control. Most economic analysis of climate policy has focused on the costs of control. There have only been a few serious attempts to estimate the economic benefits from policies associated with such long run outcomes. All of the approaches to date have made fairly strong assumptions or relied on contingent valuation estimates of hypothetical situations.[1] While each approach offers the potential to provide information to the policymaking process, they have not to date had a marked impact on the framing of climate policy. Equally important and relevant to the design of our research is the recognition in modern economic analysis that the direction and pace of technical change, like other production activities, responds to incentives. Nonetheless, despite extensive research that measures and "accounts-for" the effects of technological change on the relative usage of production inputs and the changing pattern of productivity and costs, we know little about how the process actually proceeds.

Our research was designed recognizing this background and investigated four inter-related aspects of the ways climate policy is evaluated. Three consider how technological change affects and is affected by production activities. One evaluates how we measure the net costs of policy and, in particular, the role of pre-existing tax

distortions and secondary benefits for their measurement. Three of these research dimensions are empirical. One is more fundamental and focused on the interaction in how policy impacts the aggregate growth rate through its effects of technological change and market structure.

The first empirical dimension of the research considers whether controls can ever promote technical changes that are actually superior in terms of lower production costs than would have been realized in the absence of any control on emissions. Using a stylized model of a set of production technologies and innovations to them, the research has demonstrated that it is possible to create the appearance of such larger cost reductions due to innovations adopted because of regulations on emissions. However, improvements of this type, sometimes labeled innovation offsets, are the result of mis-specification in the baseline alternatives and not a mysterious gain that arises when we regulate. Innovations selected without regulations reduce total cost of production more than in the regulated situation. What is important about regulation is the redirection in the effects of innovation on input usage. However, this effect is not new and is well recognized in the literature.

The second empirical analysis considers how policy analysts evaluate the *net* costs of controlling the emissions of greenhouse gases. We argue these net costs require at least two adjustments to conventional cost estimates. First, policies creating incentives to control greenhouse gases have secondary effects and can result in additional control of conventional air pollutants. Second, the policy selected to create incentives for control may offer opportunities to reduce the distortionary effects of a pre-existing tax system.

[1] See Mendelsohn, Nordhaus, and Shaw [1994] for an example of a national hedonic study of agricultural land using a model to gauge long term climate change and see Layton and Brown [2000] and Cameron

This reduction is accomplished when taxes on the emissions contributing to greenhouse gases are used to create the desired incentives. It is possible that the revenues raised through these taxes would allow significant reductions in the rates for pre-existing taxes. There is a well-established literature suggesting that such changes in the tax system may enhance consumer well being. Past theoretical and empirical research has suggested the outcome depends on the specific features of household preferences and sectoral production patterns.

Our research investigated the properties of an existing computable general equilibrium model augmented to allow evaluation of these effects and to provide a basis for estimating CO_2 emissions. The model takes account of domestic taxes and international tariffs. It was initially developed by Harrison, Rutherford, and Wooton [1989] to consider policies for the European Union and its primary trading partners. Espinosa and Smith [1995] added the generation of conventional air pollutants to the model. Our research has added carbon dioxide and focused on developing methods for evaluating the welfare effects of revenue neutral tax changes.

New technologies must be learned and in the process we find ways to further improve on the utilization of resources. This "learning by doing" is one of Nobel Laureate Kenneth Arrow's fundamental insights into the renewing process of technical change -- as an activity that provides for continuous expansion in our possibilities. Here too, economists have accepted the logic but know little of the practice and the factors that create synergisms versus impediments to learning. The third empirical activity was associated with these types of studies. We reviewed the learning curve experience of a wide range of empirical studies.

[2001] as examples of contingent valuation studies.

This has resulted in the development of a data-base describing the findings of these learning curve studies. The evaluations consider a wide range of industrial settings and activities hypothesized to be associated with learning. At this stage, preliminary summary statistics have been developed for the database and the PI (Smith) responsible for this component of the research is developing a plan to augment these data with secondary information from other sources that would describe the features of the technologies.

The last aspect of our research uses the framework of endogenous growth models to integrate our empirical insights within a conceptual setting. These models treat research and development (R&D) as a resource allocation choice that responds to incentives. Moreover, because they incorporate the fixed costs underlying entry and exit, they imply that policies to control emissions affect market structure, the allocation of resources to R&D, and ultimately the rate of endogenous growth.

The initial step in the theoretical part of the project has been the construction of a dynamic general equilibrium (GE) model of endogenous growth that included environmental externalities along with research and development and non-competitive markets. Although there was a literature that had considered the role of externalities in dynamic GE models, the problem that we felt was not solved was the role of market structure in this setting. No model in the literature on growth and the environment allowed for the kind of interactions that we were interested in. As a consequence, we had to develop our own framework. This was not difficult because of Peretto's previous work on growth and market structure (Peretto 1998a, 1998b, 1999). The main challenge, therefore, has been to reinterpret and adapt his framework to the goals of the project.

Several routes have been followed, with results that have allowed us to tackle specific problems. The different analyses, nevertheless, share a basic framework and yield consistent insights. This is important because one of the main objectives of the project is to produce a general perspective on a whole class of problems.

The overall picture that is finally emerging from this work is a quite unified vision of the relevant interactions between R&D decisions, growth and environmental quality. Within this framework, we are able to understand ways new incentives induce re-allocations of the resources devoted to R&D over time. For example, we are able to offer a conceptual approach to Porter's (1991) *innovation offsets* that does not require that firms be inefficient producers that do not take advantage of all available opportunities, and yet allows environmental regulations to trigger innovation efforts that reduce their costs. The key insight here – which is very much Schumpeterian in spirit – is that there is a difference between static and dynamic effects of interventions. We find that the static effects are in line with economists' traditional intuition that interventions entail costs. However, we find benefits associated with the dynamic effects that could swamp the static costs. These effects could lead to outcomes where environmental interventions are desirable because of their effects on growth, regardless of their environmental benefits. Of course, this is not true all the time but our point is that it can occur under very specific conditions. We are able to characterize quite sharply such conditions and offer insights into the opportunities and constraints that environmental policy faces as a result of endogenous technological change.

Our theoretical analysis of the effects of environmental policy with endogenous growth models has been developed through several modeling exercises. One of

particular relevance to the current literature parallels the static evaluation of the welfare consequences of replacing pre-existing taxes with taxes intended to reduce pollution. In this case, we consider steady state effects of introducing a pollution tax and the ability to reduce the labor tax rate as a result. By conducting the analysis within an endogenous growth setting, we are able to incorporate the effects of these policies on the composition of R&D and the growth rate for the economy. Thus we have some new results on the relevance of D^3 -- the dynamic double dividend.

II. Background on Research Activities

This research was initiated when both principal investigators were at Duke University. It has extended substantially beyond the original proposed time span and we feel it is only now beginning to develop as an integrated program of research. Several factors contributed to the slow progress. First, we have been unsuccessful throughout the full course of the project in attracting sustained involvement of at least one graduate student to remain with the project. Three have made partial contributions but were not sufficiently interested in the topic to prepare dissertations in the area.[2] As a result, the activities were at times disjointed and required "educating" new graduate students to the project.

Second, both investigators have had "career-related" changes over the course of the research. At an early stage Peretto spent a year in Washington, D.C. as part of his junior faculty leave. While we originally believed the sabbatical from teaching would

[2] Two of the three were Duke University graduate students – Spencer Banzhaf and Randy Walsh. One was a North Carolina State University graduate student – Dimitrios Dadakas, who left the Ph.D. program after a year and a half and in the middle of his funded (by the project) research assistantship.

contribute to the research, the change in location, separating the PIs at a key stage in the research disrupted the progress and ultimate integration of our activities.

Finally, Smith accepted a new position at North Carolina State University delaying further continued funding of his activities until a subcontract could be arranged. The move has involved greater administrative responsibilities, at least over the time to date, to start a new research center on resource and environmental policy.

It is only within the last year that we have been able to have a sufficient set of completed work to begin a more collaborative set of research activities. The result is a joint paper that links one of the empirical themes (i.e., second best effects of replacing pre-existing taxes with taxes designed to reduce greenhouse gases) to the endogeneous growth models so the steady state effects of revenue neutral policies can be considered. A significant body of research has been completed. The completed papers prepared from it are detailed in section three below. Nonetheless, we feel that at least as much additional research is nearly complete, but not as yet in papers that are ready for submission. With additional effort this partially completed research should add to our understanding of the issues posed in the original proposal. We discuss the status of remaining research papers in the last section.

We returned a significant component of the budget. We believe it would have been possible to bring several aspects of the remaining work to a finished state had we been able to attract sustained interest from graduate students. The resources were clearly available, but the interest from students with the requisite skills was not.

III. Completed Research

The research outputs from this project are summarized into five categories – published papers, articles under review, draft manuscripts ready for submission, partially completed manuscripts, and databases. In the case of manuscripts that are complete but not under review and manuscripts partially complete we describe the current status of the material in the last section.

(a) Published Papers

Smith, V. Kerry, "Should Pollution Reductions Count as Productivity Gains for Agriculture,?" *American Journal of Agricultural Economics*, 80 (August 1998): 591-94.

Smith, V. Kerry and Randy Walsh, "Do Painless Environmental Policies Exist?," *Journal of Risk and Uncertainty*, 21 (July 2000): 73-94.

(b) Articles Under Review

Espinosa, J. Andrés and V. Kerry Smith, "Environmental Levies and Non-Separable Damages," to be submitted to *Journal of Public Economics*.[3]

[3] This paper had been under review at the *American Economic Review*. As we were finalizing this report, the journal's editor notified Smith it was rejected. Both referees were "sympathetic" to the basic results. One provided detailed suggestions for revisions, noting that with those revisions " . . . the paper is potentially interesting but probably not for the *AER*. Its contribution is not of a general enough sort to warrant *AER* publication". The other referee makes the same point, suggesting the *Journal of Public Economics*.

Peretto, P. F., "Effluent taxes, market structure and the rate and direction of endogenous technological change," under review at *Rand Journal of Economics* (submitted 2001).

(c) Description of the Completed Research

The research completed as part of this project is divided into two broad components – empirical and theoretical. We describe each separately.

1. Empirical Research[4]

One of the initial objectives of the proposed research was to review the literature on technical change and evaluate its relevance to the relationship between carbon policy and induced technical change. This first set of activities led to two publications (Smith [1998] and Smith and Walsh [2000]). The first was based on a larger set of research that was presented at several special purpose conferences. The published paper considers, as part of an invited session from the American Agricultural Economics Association, the appropriate treatment of pollution abatement in the measurement of productivity gains. A variety of proposals have been in the literature on this topic, ranging from direct adjustment to the rate of change in marketed outputs for reductions in pollution as "gains" (because of the negative external effects of pollution) to the use of a non-parametric distance function to construct measures of how technically efficient loci change over time. As noted, this paper is a brief summary of commentaries Smith has prepared and presented at the AAEA meetings, special conferences organized by the U.S.

Environmental Protection Agency, the RFF Stanford Energy Modeling Conference on technical change, and the RFF Workshop on the design of a new survey to collect information on pollution abatement control expenditures.

The second published paper (Smith and Walsh [2000]) uses the insights from that review to frame an empirical evaluation of the extent to which environmental regulations could be perceived as "promoting" technical change. This is an implicit assumption of much of the applied research in evaluating climate policies. That is, it is assumed that increased carbon taxes or regulation designed to improve energy efficiency will increase the pace of technical change. This argument stems in part from Porter's [1991] suggestion that *innovation offsets* can make environmental regulations painless. Careful reviews and detailed micro-econometric analyses of the joint effects of these regulations and technological innovations have not supported Porter's arguments. To most neoclassical economists, the conceptual arguments are clear. Environmental regulations do have opportunity costs and require that real resources be diverted for controlling pollution.

The research designed to address this question exploited a model Raymond J. Kopp and Smith worked with a number of years ago. It is a large-scale process analysis model of steel production that incorporates heat and materials balances in the description of the production activities. Developed at Resources for the

[4] When there is a published or draft paper available we limit our discussion to a summary of the findings. When research has been completed but it is not at the stage where a complete draft manuscript has been

Future, (Russell and Vaughan [1976]), it was extended to include six process innovations and this is the framework that was used (Vaughan et al. [1976]). The early Kopp-Smith [1985] work considered how well neoclassical models did in describing the role of prices in measuring the influences to the direction of technical change. At base prices the innovations reduce the costs of producing a constant mix of steel products by 10.35%.

In this new work Smith and Walsh imposed restrictions on the emissions residuals to the air and water and investigated the joint effects of these restrictions along with different factor prices on the adoption of these six innovations. The specific focus was on the measured gains in productivity. The framework is well suited to judging the role of regulations on technical change and the so-called Porter hypothesis because it incorporates residual control activities as non-separable components of production and is consistent with a simple, but admittedly static, neoclassical model of innovation. There are no surprises or internal sources of inertia requiring regulators to prompt the firm to undertake innovations. Finally, the model identifies factor inputs at a highly disaggregated level, allowing one to keep track of intermediate responses to factor price and environmental constraints, yet aggregate these detailed changes in a way that corresponds to the conventional practice uses in neoclassical production analysis.

The selection of steel production is fortunate for other reasons as well. Barbera and McConnell's [1990] aggregate analysis for the seventies suggested that

---

prepared, we provide a more complete summary of the results in the body of the report.

environmental regulations caused the largest decline in total factor productivity for steel – 0.43%. More recently, Morgenstern, et al. [1998] also highlight differences in their results for steel plants. They observed that of the four industries in their sample with the largest abatement expenditures, steel was the only one where their fixed-effects model indicated that a dollar increase in PACE expenditures lead to an increase in total production costs. All the others sectors' models indicated smaller production costs.

Production measures are computed in three ways. The first uses a translog cost function fit to the ex ante cost minimizing solution to the process model for steel production *without innovations* to estimate how the factor cost shares respond to relative factor price changes. Productivity is measured in the first method as the proportionate change in input usage (over levels at base prices) weighted by the predicted cost shares (from the translog fit to the static technology) for solutions *with* the innovations available.

The second measure computes the increment in total costs with innovations in comparison to the base solution for the without innovations version of the model. Both relative factor prices and regulations of the emissions of air and water borne residuals are allowed to vary. This measure requires that the effects relative price and environmental regulations be "sorted out" in comparison to the static standard in a second stage of analysis.

The last approach to productivity measurement matches the relative price changes between the no innovation and innovation versions of the model. As a result, it isolates the cost effect of the regulations and the available technologies through the measured proportionate change in costs.

All three estimates for total factor productivity (TFP) suggest it is possible for existing practices to yield TFP measures where the measured gains with environmental constraints appear to exceed those in the unconstrained case. However, these findings cannot be due to so-called Porter effects because the underlying model does not have them. They arise exclusively because the neoclassical models (and productivity measures) do not adequately control for the distinctions in static substitution innovations that alter substitution, and innovations that impact residuals control.

The second set of empirical research was directed at two aspects of the measurement of the "net" costs of controlling greenhouse gases. These factors include: (a) the effects of pre-existing tax distortions on measures of the added costs of environmental regulations to reduce GHGS emissions; and (b) the secondary benefits derived from reductions in other conventional air pollutants that would accompany efforts to control the GHGS emissions.

The research was undertaken in two phases. A model developed by Espinosa and Smith [1995] was used to investigate how revenue neutral taxes on emissions of

conventional air pollutants (e.g., particulates, sulfur dioxide and nitrogen oxide) would be evaluated in a second best setting. A central feature of this model that is especially important to its use in evaluating controls of GHGS emissions is specification of household preferences. Espinosa and Smith were the first to introduce a non-separable treatment of air pollution into the preference functions used to characterize final demands in computable general equilibrium (CGE) models.

Research findings from the first component of this research have been summarized in a recent paper (under review -- Espinosa and Smith [2001]). Three different versions of the Anderson-Neary [1992] welfare criterion were computed with the Espinosa-Smith model. All consider the same type of policy -- revenue neutral taxes on air pollution emissions designed based on the shares of pollution damages coming from the four largest polluting sectors in each EU country in the model. The welfare measures are distinguished based on whether the models incorporate non-separable environmental effects on preferences; include only morbidity effects; and include both morbidity and mortality.

The results are dramatic – non-separability in preferences appears to be fundamentally important in evaluations of the net effect of environmental levies in tax (and tariff) distorted economics. The exact nature of the impact depends, as one might expect, on the characteristics of the economic structure, its sectoral composition, aggregate demand patterns, and both the internal pollution

generation and effects experienced from transfrontier pollutants. They are also affected by the way revenue neutrality of the pre-existing tax distortion is defined.

These findings appear to be a significant departure from the implicit assumption of the majority of the literature in this area. That is, virtually all of the research on the welfare effects of environmental levies in distorted economics maintains that an assumption of separability in preferences (for the pollution as sources of externalities) is neutral to the overall conclusions of the analysis. This finding was clearly called into question.

The second component of this work involves introducing carbon emissions into the Espinosa-Smith framework and repeating the welfare analysis with taxes based on carbon, no taxes on conventional pollutants. As in the case of the first phase we compare the welfare effects of the charges based on carbon emissions with different assumptions about the effects of conventional pollutants on preferences.

To complete this work, we developed estimates of carbon dioxide emissions in 1985 (to match the benchmark year of the Espinosa-Smith model), modified their model and developed the scenarios. Spencer Banzhaf participated with Smith in these efforts. At least two joint papers are planned summarizing the findings.

As the funding period for the project ended, an initial round of solutions were completed. Carbon dioxide emissions were estimated using the method outlined by international energy agency (IEA) of the OECD using the carbon factors per terajoule of each fuel type and then the fractions of carbon combusted to estimate carbon emitted. Finally, the carbon emitted is scaled by the fraction oxidized (to produce CO_2) and converted from tons of carbon to millions of tons of CO_2 for each sector and each country (or region) in the model. These CO_2 emissions are then introduced into the model (after aggregating to correspond to the HRW sectoral definitions) as emission per unity of output.

We considered two policies to evaluate the welfare effects of carbon taxes. While they parallel the design used in Espinosa and Smith [2001] in that they are distinguished based on the level of aggregation for revenue neutrality (i.e., policy I – country level neutrality; policy II – EU wide revenue neutrality), the tax rates are set differently. All six sectors in each country face the same ad valorem tax rate for carbon dioxide emissions in policy I and all sectors in all EU countries face a constant EU wide tax rate of policy II.[5]

Table 1 reports some of our findings, by country, for each policy maintaining the three alternative definitions for the Anderson and Neary [1992] welfare criterion. The first panel reports the net benefits (adjusting for income changes due to the

[5] We have also developed solutions where the tax rates are on carbon alone, and thus the size of these taxes can be interpreted without considering the effects of the taxes on the relative product prices as in the ad valorem case. A sample of these results are reported in Appendix B. They will be incorporated in the final papers.

effects of policy induced price changes on quasi-rents in a distorted general equilibrium) for each case: (a) no feedback effects on conventional pollutants; (b) feedback effects that reflect only morbidity induced substitutions; and (c) mortality and morbidity induced losses. Imposing carbon taxes with recognition of the secondary benefits (due to any reductions in conventional pollutants) would be judged as leading to net losses in most EU countries. The only exceptions are Italy, Ireland, and Denmark. These losses become smaller (in absolute magnitude) if we consider the reduced morbidity effects due to secondary pollutants. However, if we include mortality effects, the losses actually increase! The explanation for this result is found in Table 2, where the changes in sectoral production arising from the carbon taxes actually increase emissions of particulate matter (the primary source of the mortality effects). Carbon taxes serve to reduce SOX and NOX, which are the primary sources of the morbidity effects.

The energy sector is an important source of CO_2 while durables and non-durables are not. So energy production shifts out of the EU and toward the untaxed economies (to some degree) and production of durables and non-durables toward the EU leading to increased particulates and reduced CO_2. Of course, in an actual situation there would be limits on the physical capacity to shift energy production.

Nonetheless, the generic message from policy I is surprising. The secondary effects of CO_2 policies may not be unambiguously positive. Our scenario demonstrates that it is conceivable that the sectoral substitutions may well

increase some conventional pollutants. Evaluating the net effects requires consideration of as many sources of the benefits and costs accompanying policies as possible.

Policy II offers a quite different picture when we consider the net benefits. Here all the EU countries except Denmark gain when we consider secondary benefits, but the mortality effects due to an increase in the emissions of particulate matter reduce the size of these gains.

On the whole, policy II leads to a larger overall percentage reduction to CO_2 emissions, considering all eleven regions together but a different distribution across EU countries. One reason for this different distribution can be found in the implied tax rates for policies I and II. Table 2 lists in the fifth column the tax rate implicit in revenue neutral carbon changes for each country. In most countries these are dramatically different from what would be required for revenue neutrality of the countries as a whole. Policy I rates range from 0.00582 (Denmark) to 0.1231 (Ireland) while the single tax rate is about 0.055 – ten times the smallest and half the largest of the rates derived with country specific neutrality.

Some of the changes in emissions seem implausible, such as the reduction imposed on Denmark, and require further investigation of the features of production. Nonetheless, the results to date suggest that secondary benefits

together with the treatment of existing distortions are important issues for the evaluation of climate policy.

The third aspect of the empirical research developed as part of our activities involved in the construction of a data-base from reviews of all the available studies of learning curves. This data base was constructed to be used in a meta-analysis.

The original motivation for this effort was the inclusion in policy evaluations of regulations intended to reduce carbon emission of an automatic cost reduction factor (i.e., analogous to the autonomous energy efficiency improvement, AEEI). This exogenous source of a cost reduction was described as reflecting the learning effects associated with adopting the technologies to reduce emissions. This factor was usually treated as separate from progressive technical change in the abatement sector. Common estimates were in the range of 0.3 to 1.8 percent annual reductions in energy used (Nordhaus [1994]). These gains have been described in a variety of ways. Jacoby and Wing [1999] characterize them as exogenous efficiency improvements independent of increases in labor productivity. Others have described them in terms more closely related to learning new abatement technologies adopted in response to regulations. We have not attempted to reconcile the explanations. Instead, our objective was to consider what is known about such learning effects.

Learning or experience curves have a fairly long history in economics (Alchian [1948]) and management science.[6] The usual structure of a learning curve is expressed in terms of the labor requirements for a given "production run," or as Argote and Epple [1990] suggest, the next increment to cumulative output (Q_t). Equation (1) describes one version of the relationship.

$$L_t = aQ_{t-1}^{-b} \tag{1}$$

where L_t = unit labor requirements for the production run, t[7],

which is often assumed to be one unit or output

$Q_{t-1} = \sum_{i=1}^{t-1} q_i$ = cumulative output over $t-1$ production runs

b = the learning coefficient (b>0)

a = labor required to produce the first run of the good (a>0)

The learning coefficient describes the rate at which labor hours required for subsequent production are reduced as "experience" with the process or technology used in making q increases. Thus, learning and cost reduction are assumed to accompany or to be jointly produced as a byproduct of production experience.

A common measure reported in describing these learning effects in many studies is labeled progress ratio. This concept measures the cost impact of doubling cumulative output (i.e., the estimated cost reduction of doubling output is defined as 1-p). The progress ratio is defined in equation (2).

[6] A brief overview of the economic literature is provided by Auerswald, et al. [2000]. Argot and Epple [1990] provide a more general overview considering the role of learning curves in organizational change.

[7] This expression could also be described in terms of energy. What is important is the link to cumulative output up to the amounts actually produced with L_t, namely q_t.

$$p = 2^{-b} \qquad (2)$$

Auerswald, et al. [2000] summarize the "stylized facts" about learning curves as follows:

- progress ratios vary from 55% to 105% with "most" estimates around 80%,
- each production process seems to have different learning curves or progress ratios,
- some studies report differences in learning effects across firms in the same industry, and
- a log-log specification in past studies of learning curves, as implied by equation (1), often fails to capture the slow-fast-slow phenomenon that appears present in much of the micro data (e.g., cost improvement that is at first slow, then fast, and finally slow again as the process of production is more fully appreciated).

To evaluate what we know of learning relationships two graduate students (for short periods over the term of the grant, Randy Walsh and Dimitrios Dadakas) worked with Smith to assemble a database describing as many of the learning curve studies as could be acquired, largely through published sources, over the period 1948 to 2000. Estimates of the progress ratio and the attributes of the product, approach, sample, country, and estimator were also recorded.

Appendix A provides the citations to the papers included in the first round of this review. At the close of the grant period, a total of 35 studies were described in the database with over 500 estimates of the parameters of learning curves. Not all of the studies permitted a complete record of the variables used to characterize how the learning curves were measured. Table 3 summarizes the primary variables we collected and Table 4 provides a few descriptive statistics for the estimates, considered separately from individual studies, for each of the four sectors with the largest numbers of observations. Table 5 groups the sample by the country where the application took place. All of these results offer an indication of the diversity in available estimates and the potential for understanding how either the sector or the method used influenced the findings.

The results in Table 6 summarize a few characteristics of the estimates for the cost reduction associated with learning in our database. They are sub-divided into groups based on the level of aggregation of the original study evaluating how unit labor requirements changed with cumulative output. Estimates of the extent of cost reduction tended to increase with the level of aggregation of the study. A number of other characteristics of each study were also collected.

Our analysis of this database is at a very early stage. Nonetheless, the results are ver encouraging. For example in Table 7 we summarize two regression models relating the learning rate measure to the features of the studies used to estimate it, including qualitative variables for how the timing of the "batches" or time spans

over which learning is assumed to take place are measured (as the temporal unit of analysis), whether the study accounted for knowledge depreciation (0, 1), whether it was an experimental or actual cost study (0, 1), and whether transfers of knowledge were taken into account (0, 1). The second model adds qualitative variables for four of the industries used, selected because each had a large number of estimates.

While these results suggest that there appear to be systematic differences in the learning patterns, depending on the modeling assumptions used in the analysis, it is also important to acknowledge that the remaining industries (products or services) represented in our sample are very diverse and we have not accounted for these other characteristics in our analysis. In model two reported in Table 7 they serve as a quite heterogeneous omitted category. One might expect, for example, that learning would be affected by the capital/labor mix in the production process or would be different depending on whether the activity involved highly skilled manufacturing versus activities primarily associated with delivering services. We have not attempted to take account of these types of distinctions in the studies.

Table 8 reports a simple probit model with the dependent variable coded as a one if the primary study's estimate of the learning parameter (b) would be judged as significantly different from zero and a zero otherwise. Ninety-four percent of the estimates reported would be judged as significant. As a result, there is little

variability in experience to "explain." Nonetheless, it does provide some insight into how study characteristics influenced the ability of the primary research to measure learning. In general, we were not able to distinguish effects for specific sectors. Only the shipbuilding studies seem to provide insight on how the activities studied influence whether we can measure precisely learning effects. Research experience with the model itself, as gauged by the year the primary research study was published, seems to have contributed positively and the lower the level of analysis of production activities the better from the perspective of measuring learning (i.e., process analysis is preferred to higher levels).

Table 9 lists the products represented in our database. As this table suggests, the list of products (and the numbers in each category) is too extensive to consider separate models or the use of fixed effects to account for sectoral distinctions. This is especially clear when we recognize, based on our simple model, that the time unit and methodological assumptions also appear to be important. Thus, it would appear to be important to supplement these data with indexes characterizing the features of each production sector that can reduce the dimensionality of the task of controlling for attributes of the production relationship.

2. Theoretical Research

Generally speaking, the research conducted for this project focused on incorporating environmental issues in the class of models of endogenous growth

and market structure that Peretto and other authors have developed in recent years. There are two reasons why these models are interesting and appropriate for the research undertaken under this grant. First they do not suffer from the so-called *scale effect* – a positive relation between the growth rate of the economy and the size of its population (which measures its resources endowment). Second, by focusing attention on the number of firms that operate in a market, they allow us to study issues that are largely ignored in the literature.

The first property -- the absence of the scale effect -- is very important because models that assume a scale effect are inconsistent with the cross-country and time-series empirical evidence on how economic growth has been driven by technical change. Hence, simulations of the effects of policy intervention based on models that exhibit the scale effect do not conform to what we have observed in practice and probably should be regarded as suspicious. The second property -- the explicit incorporation of market structure dynamics -- is also important because it allows us to study the effects of policy interventions on two dimensions of industrial activity: the number of firms and the volume of output (and its growth rate) that is attributed to the individual firm. Under the assumption that firms producing different products use different technologies and as a consequence would also produce different amounts of pollution, the environmental damage associated with industrial activity should be described by a more general function than it is usually done in the literature. This argument builds on the contributions of Carlton and Loury (1980, 1986). The point is that

firm size and the number of firms play different -- although related -- roles in determining aggregate pollution damage, and this implies that designing policies that target pollution abatement is likely to be a more complex exercise than it seems based on simple one-dimensional models.

The model used in Peretto (2001a) introduces several novel aspects to the analysis. It allows for product differentiation within manufacturing, but does not have another sector (hence, it is truly a one-sector model). As a result of this restriction the model focuses on effects that are *intra-sectoral*. The relevant decision unit is the manufacturing firm. Allocation decisions concerning different types of R&D are internal to the firm. Arguably, however, environmental policies have important *inter-sectoral* components to the decision process.. Moreover, the energy sector is an important source of CO_2 emissions and should be part of the analysis. These issues have been considered in extensions to the basic Perreto structure.

A second aspect of the model used in Peretto (2001a), worth discussing, is that it has transitional dynamics in five dimensions, which implies that we have been unable to study the model's transition to steady state analytically. Instead, our analysis outlined above focuses on the steady-state properties of the model. This is not a significant drawback if we keep in mind that the project's objective is to produce new understanding of the long-run effects of environmental policies.

Nevertheless, it would be desirable in some specific applications to be able to trace analytically the transitional dynamics of the model so to gain some insight on transitory and permanent effects of policies.

The energy sector is discussed in specific detail in Peretto (2001b). The model in this paper incorporates an energy sector into the basic framework and studies the effects of energy taxes. In addition to the obvious relevance of these taxes for policy and for the performance of the economy, a reason for focusing on energy taxes is that they offer alternatives to the types of emission taxes discussed in Peretto (2001a). Indeed emission taxes are rarely observed. Policymakers tend instead to favor taxing traded inputs. This implies that energy taxes are a "natural" institutional approach to the taxation of emissions. There is a direct, analytical relationship, discussed in detail in the paper, between energy taxes and emission taxes. Hence, the results of the paper remain qualitatively unchanged if one casts the analysis in terms of emission taxes motivated by the fact that energy production and use are a main source of emissions.

Peretto (2001a) makes the key assumption that there is only one type of technical change; what traditional analyses refer to as total factor productivity (TFP) growth. Hence, manufacturing firms use labor and energy, and invest in R&D in order to generate neutral technological change that raises the productivity of both factors equally. This formulation simplifies the model significantly because it eliminates the intra-firm decision concerning allocation of R&D resources across alternative types of research projects. In exchange, it allows one to trace

analytically the entire transition path of the economy in response to the introduction of the energy tax. This assumption is crucial for allowing us to uncover some novel and striking results concerning the *innovation offsets* discussed earlier.

Peretto (2001b) demonstrates that steady-state growth does not depend on the energy tax, while the number of firms increases with the tax. To explain these results, it is useful to consider what happens to the allocation of labor to production of energy, production of goods, and production of knowledge (R&D). An energy tax lowers employment in production of energy but raises employment in production of goods. (It has no direct effect on R&D.) Expenditures are increasing in the tax if the former effect dominates. That is, if the ratio of the energy price to the energy tax is larger than the elasticity with respect to the after-tax price of energy of the share of energy in the firm's total cost. This condition is likely satisfied when the tax is small or when the elasticity of substitution between labor and energy in production of goods is small. For example, with a Cobb-Douglas production function the condition is always satisfied because the factor shares are constant. Thus, under plausible conditions concerning factor substitution in manufacturing, the energy tax raises expenditure on manufacturing goods. (Notice that we are referring to the "nominal" expenditures, not the real expenditures.)

With this result in hand, the paper demonstrates that consistent with traditional analysis, the energy tax changes relative input prices and induces manufacturing firms to substitute labor for energy. This substitution reduces demand for energy and thus the conditional demand for labor in the energy sector. In addition to these standard effects, there is the novel, positive effect of the tax on aggregate R&D. Since the energy tax shifts labor from production of energy to production of goods, manufacturing firms increase their R&D activity because their volume of production is larger. Despite this reallocation of resources, however, steady-state growth does not change because the dispersion effect due to entry offsets the increase in aggregate R&D. This result is somewhat surprising. In a model where increasing returns that are internal to the firm apply, the level of R&D depends on the level of production. This outcome, indeed, is the standard scale effect driving first-generation growth models with economy-wide increasing returns. When the number of firms adjusts endogenously, however, and increasing returns are internal to the firm, additional forces come into play. The increase in the size of the manufacturing sector, as measured by aggregate expenditure on consumption goods, raises the returns to entry. The resulting larger number of firms generates dispersion of R&D resources across firms and neutralizes the scale effect. In other words, R& per firm does not rise. It follows that the growth rate is independent of the size of the manufacturing sector, and thus of the energy tax.

A key question that the model allows us to ask is the following: Does the energy tax raise long-run real income? Recall that in steady state the tax raises aggregate

expenditure on manufacturing goods, the number of manufacturing firms, and the after-tax price of energy (this despite the fact that the pre-tax price of energy is lower.). Also, due to faster productivity growth along the transition, long-run TFP is higher with the tax than without. The question then is: Do these positive dynamic, indirect effects dominate the negative static, direct effect of the tax on goods prices?

The striking result that the model delivers, and the source of our comment on a dynamic interpretation for a Porter-like effect is that there is a threshold such that a sufficiently small tax does raise long-run income. This is regardless of the benefits from pollution reduction. In fact, when looking at pollution, there are conflicting effects due to the reduced energy use per firm and the larger number of manufacturing firms. This tension does not arise if one postulates that pollution is due only to generation of energy, where there is no role for product differentiation.

To interpret how this argument works, the paper first shows that absent endogenous technological change the standard intuition that a tax on primary inputs lowers real income applies. Next, it shows that technological change gives rise to long-run benefits that can overturn this standard result.

To illustrate how this modeling approach can inform policy in ways that are different from the existing state of the art we now consider some aspects of the

results in more detail. If one ignores endogenous technological change, real income depends only on the ratio between expenditure and the price level, which in turn is proportional to the price of the typical manufacturing good. This price increases with the tax simply because the tax raises input prices and makes production more costly. The paper shows that when product variety and total factor productivity are held constant, expenditure raises less than linearly with the tax so that the static, negative price effect dominates and the real income falls.

Now consider the role of product variety. (To develop this analysis we hold TFP constant to isolate the role of product variety.) The price index of a basket of manufacturing goods now includes a factor that reflects consumers' love of variety. This factor exhibits a constant, *negative* elasticity with respect to the number of firms. In steady state, the number of firms is proportional to expenditure. Hence, real income features a negative, unitary elasticity with respect to the price of the typical good and a positive, elasticity with respect to expenditure that is *larger than one*. This is the key: it is now possible for the increase in expenditure to dominate the increase in goods prices. The paper shows analytically that there exists a threshold value of the tax such that below this threshold (i.e., for a sufficiently small tax) long-run real income rises with the tax. The intuition is that for a small tax the static, negative price effect is not very large so that the dynamic, positive variety effect dominates.

Consider now the role of total factor productivity. (This is where being able to trace the transitional dynamics of the model pays off.) The analysis shows that when the tax is introduced, the economy experiences a transition wherein productivity growth is faster than in the baseline case of no tax. Although this effect is only temporary, and eventually productivity growth reverts to the long-run mean, the new steady state is characterized by higher total factor productivity. This additional positive effect implies that the relevant threshold value for the energy tax is actually higher than the one discussed above where TFP was held constant. In other words, the result is not predicated on large and hard to measure variety effects, but on the *sum* of the variety effect and the TFP effect. The latter is not hard to quantify using standard data. Hence the insight coming out of this model would seem to be quite operational.

This paper is nearly complete and will be submitted soon to *American Economic Review*.

IV. Continuing Activities

(a) Empirical Research

The primary continuing research activity for the empirical component of the research relates to the Espinosa-Smith CGE model. Banzhaf and Smith are investigating the sensitivity of the results reported in Tables 1 and 2 to the design of the carbon tax, as part of the development of a paper (see below) on secondary benefits of control of

GHGS emissions. In addition, they are working to add waterborne emissions to the model.

The motivation for this addition stems from concern about the factors influencing the size of the secondary effects of policies directed at controlling greenhouse gases. Our results considering CO_2 and conventional air pollutants confirmed that sectoral substitution in response to carbon taxes can lead to surprises with the prospect for unintended increases in the emissions of some conventional air pollutants.

Equally important, the Espinosa-Smith framework is the first to operationalize non-separable damages from conventional air pollutants in the household preferences included in a CGE model. However, these effects are all introduced through one marketed good, services. Thus, the marginal rates of substitution important to other consumption choices (e.g., durable versus non-durable or transportation and construction) remain unaffected by changes in pollution impacting preference related tradeoffs. By introducing waterborne emissions and resulting surface water quality into the model, this issue can be addressed with a partial expansion in the commodities impacted by non-market services.

An initial goal of the empirical research was to include in the Espinosa-Smith framework abatement activities as a direct means to address conventional and GHGS emissions. We searched extensively for some systematic information that could be included. The only information (aside from survey articles on the costs of GHGS

controls) were unit cost factors reported in the Industrial Pollution Projection System (IPPS, Hettige, Martin, Singh, and Wheeler [1994]) database. Smith is currently evaluating the feasibility of using the recent Burtraw-Cannon [2000] methodology along with these data to introduce some type of abatement cost functions into the model. This activity is under a longer time horizon than the amendments planned by Banzhaf and Smith which are expected to yield papers for submission to professional journals by the end of the calendar year.

(b) Theoretical Research

Much of the theoretical research for the project is completed. The challenge remaining is to adapt and interpret the work so that it is consistent with the more familiar models used in the environmental literature. For the most part, the framework used in Peretto's work is familiar to macro-economists working with endogenous growth. It is relatively new to environmental economists and a mix of explanation and adaptation is needed to facilitate the transfer of the new insights provided by the theoretical analysis to the policy context motivating the use of these models to consider environmental issues.

The primary joint paper to emerge from our research collaboration on this project involves a dynamic analysis of the tax interaction effects. In this analysis we considered the effects of replacing a labor tax with a revenue neutral tax on pollution. It was possible to characterize the implications for the steady state solution of the

model. The surprising result to emerge was that steady state growth does not depend on the tax!

Our explanation for this stemmed from the R&D structure. The model has two types of R&D to consider: (a) activities enhancing production of market output; and (b) activities that enhance the effectiveness of pollution abatement. Each was treated as an independent process. There was then no reason to undertake R&D in the abatement activities without the emission tax. While the presence of the tax created incentives to re-allocate R&D these affected transitional dynamics and not the growth rate.

This result was not only surprising but also strange. We initially described it as reflecting two entirely different approaches to production. Without the tax the economy adopts one technology and does not constrain emissions. With emission taxes, the services of the environment receiving the emissions are "priced" and a different technology is adopted. The growth rate was displaced, but the rate was not altered.

With further research Peretto considered other conceptions of the R&D process. When there is a stronger positive interaction between R&D investments in abatement and production related activities our counter intuitive result no longer holds. Steady state growth becomes a smooth differentiable function of the emission tax and there are beneficial effects of abatement R&D. Moreover, there appears to be a threshold

value for the tax such that if tax rates are kept below that rate the growth rate is increasing in the tax. While this result depends on the functions we assumed, it does offer a more favorable interpretation of the Porter hypothesis. It is one that argues we should look for complementarities in research and the information created from abatement rather than their proposed static intuition that firms need periodic proding to recognize cost reducing opportunities.

We were nearly finished with the initial draft of the joint paper when dissatisfaction and questions of colleagues created incentives for the new more informative version of the model. We feel that it should be possible to finish the paper describing these results by the end of the calendar year.

V. Status of Remaining Papers

(a) Empirical Analysis

Research for two additional empirical papers was largely completed by the end of the grant period. Depending on the success in efforts to include waterborne emissions, a third could be completed by the end of the academic year.

1. Smith and Dadakas – learning curves

A brief paper targeted at *Economics Letters* will be developed to summarize the current status of the meta-analysis of learning curves. This paper will summarize the database and report findings such as given in Tables 7 and 8 earlier. A more

detailed evaluation of the sources of differences in estimates of learning would require additional resources. When Dadakas left the project (and resigned from the Ph.D. program) we were in the middle of an effort to develop information to augment the database with characteristics of the production processes that might be associated with how learning by doing would be distinguished across different types of activities. It was clear traditional economic sources would not provide the requisite information. One possibility entails searching relevant trade journals to assemble information on the skill requirements as well as time and experience expectations for operationalizing innovations in different processes. These types of activities were beyond the scope planned for our research.

2. Banzhaf, Espinosa, and Smith – secondary benefits of controlling GHGS emissions

   The research in this paper expands on what is reported in Tables 1 and 2 above. We anticipate preparing a paper for *Resource and Energy Economics* on these findings as well as a series of additional scenarios to evaluate how policy design influences the secondary benefits to controlling GHGS emissions. We do not anticipate difficulties in being able to submit this paper by the end of the calendar year.

3. Smith and Banzhaf – non-separable waterborne and airborne residuals in a CGE framework

The basic information on emission rates and benefits from water quality improvements have been assembled and Smith has initiated research to develop the estimates required to recalibrate the Espinosa-Smith model. Assuming that these tasks can be accomplished without significant problems, it should be possible to have the augmented model available before the end of the calendar year (without additional external funding) and determine the professional interest in further policy analysis with CGE models involving non-separable benefits.[8]

(b) Theoretical Analysis

We are working on several extensions of the modeling approaches outlined above. One of the most important is to investigate in further detail the properties of the environmental damage function that drives the results in our models. Again, the novelty here is that we look at a world where the qualitative differences between pollutants associated with different production processes matter and determine how pollutants interact and thereby determine the overall damage to the environment. Another interesting direction in which to extend the results is to model pollution as a stock. At the moment, the model has pollution as a flow. This is arguably not right in the case of CO_2 emissions. The only reason why we set up the original model with pollution as a flow is that the dynamics are simpler -- nothing crucial in the results depends on this simplification.

[8] As noted in footnote # 3 an initial decision on the Espinosa-Smith [2001] paper that there is professional interest in this area, especially for field journals. It would appear that this type of augmentation of the model is desirable. One referee asked why only one threshold parameter in a Stone Geary preference

Peretto (2001a) is the first complete paper that came out of these efforts. It studies the effect of an effluent charge (e.g., carbon tax) on the growth path of an economy where firms allocate resources to cost-reducing or pollution-reducing R&D. With a tax on emissions, pollution-reducing R&D is a form of cost reduction and firms allocate resources to it. The cost of the tax is that it induces firms to split their R&D budgets over two activities, which means that firms advance at a slower pace than before so that productivity growth is slower. The benefit is that firms improve their abatement technologies and reduce pollution.

To evaluate the welfare effects of this policy, one needs to pay attention to the separate roles played by the number of firms and the volume of activity of each firm. The optimal policy is not a constant flat-rate emission tax similar to the one discussed currently. Because there are two distortions, the optimal policy is an emission tax accompanied by a tax/subsidy on entry. The rate at which emissions are taxed is a function of the ratio between the stock of cost-reducing knowledge and the stock of emission-reducing knowledge. In other words, the optimal tax rate is a function of the state of technology. Whether a tax or subsidy on entry is needed, on the other hand, depends on the properties of the environmental damage function and on preferences. Suppose that product variety is very conducive to pollution because firms that produce with different technologies produce different pollutants, and these pollutants interact in a way that exhibits increasing returns to their number. Suppose furthermore that people do not have a very strong taste for

---

function was affected by pollution. His comments ask implicitly why we consider other pollutants and with them other connections to market goods.

variety. Then, it is optimal to try to reduce the number of firms and this requires a tax on entry. Each of these issues offers another avenue for further research. Our current plan is to complete the work on the Peretto-Smith paper dealing with tax interaction effects in a dynamic setting. Once submitted to a journal, Peretto will complete papers describing the existing theoretical results before considering these new avenues.

Table 1: Anderson Neary Welfare Indexes by Country, Policy, and Treatment of Conventional Pollutants[a]

Country	Policy I			Policy II		
	Without Air Quality Benefits	With Morbidity	With Mortality	Without Air Quality Benefits	With Morbidity	With Mortality
Germany	-3.00	-2.97	-3.56	1.39	1.43	1.06
France	-0.46	-0.46	-0.64	1.06	1.07	0.94
Italy	0.16	0.18	0.24	0.79	0.82	0.80
Netherlands	-0.15	-0.15	-0.20	0.32	0.33	0.28
Belgium	-0.27	-0.29	-0.35	0.07	0.06	-0.00
United Kingdom	-0.08	-0.05	-0.03	2.21	2.26	2.30
Ireland	0.01	0.01	0.01	0.13	0.13	0.13
Denmark	0.02	0.02	0.01	-1.33	-1.32	-1.40
United States	0.66	0.65	0.70	0.51	0.50	0.54
Japan	-0.27	-0.27	-0.27	0.04	0.04	0.04
Rest of World	2.52	2.52	2.96	-3.11	-3.09	-3.38

[a] These measures of welfare change are in billions of 1985 U.S. dollars.

Table 2: Distribution of Percentage Changes in CO2 and Conventional Pollutants: Country and Policy[a]

Country	Policy I					Policy II			
	CO2	PM	NOX	SOX	Tax Rate	CO2	PM	NOX	SOX
Germany	-7.28	+0.51	-4.19	-8.28	0.067	-4.69	0.32	-2.63	-5.48
France	-2.40	+0.68	-1.55	-3.69	0.077	-1.17	0.48	-0.62	-1.78
Italy	-0.31	-0.09	-0.30	-0.20	0.020	-2.86	0.03	-1.77	-3.18
Netherlands	-4.93	+0.28	-2.61	-5.94	0.065	-3.39	0.23	-1.74	-4.26
Belgium	-5.25	+0.27	-2.69	-5.81	0.049	-5.65	0.26	-2.90	-6.28
United Kingdom	-3.33	-0.10	-1.91	-3.90	0.036	-5.10	-0.17	-2.87	-6.02
Ireland	-8.02	+0.06	-2.64	-11.70	0.123	-2.24	0.03	-0.43	-3.65
Denmark	-3.55	+0.13	-1.27	-2.65	0.006	-60.99	1.20	-19.56	-4.87
United States	0.30	-0.03	0.15	0.40	--	0.28	-0.03	0.15	0.39
Japan	0.18	-0.00	0.03	0.13	--	0.21	-0.01	0.04	0.15
Rest of World	0.22	-0.02	0.12	0.28	--	0.23	0.01	0.12	0.31
World	-0.30	0.28	-2.34	-4.31	--	-0.45	0.23	-2.59	-5.96

[a] The tax rate for carbon emission with policy II is constant for all EU countries at 0.0547.

Table 3: Variables Collected in Learning Curve Meta Analysis

Description	Number of Observations
Learning Parameter (b)	521
t-test for Learning Parameter	409
Primary Model Account for Time	529
Primary Model Account for Depreciation of Knowledge	529
Primary Model Account for Knowledge Transfer	511
Sample Size in Primary Study	481
Actual or Experimental Study	529
Country of Inquiry	482
Year of Study	293
Time Unit	454
Level of Production Activity	527
Year Published	519
Statistical Methods	77
Product Type	551

Table 4: Summary Statistics for Selected Industries

Sector	Number of Estimates	Learning Rate		
		Mean	Min.	Max
Steel	43	0.183	0.029	0.390
Electrical	101	0.202	-0.439	0.921
Shipbuilding	25	0.097	0.021	0.354
Aircraft	35	0.252	0.041	0.527

Table 5: Summary Statistics by Location Country of Study

Country Code	Number of Estimates	Learning Rate		
		Mean	Min.	Max
U.S.	251	0.178	-0.439	1.11
Bangladesh	54	.070	0.016	0.217
England	1	0.014	--	--
Brazil	52	0.098	0.021	0.354
Canada	1	0.105	--	--
Japan	54	0.265	0.091	0.507
Korea	11	0.226	0.064	0.360
Singapore	11	0.258	0.090	0.472

Table 6: Studies of Learning Curves by Level of Aggregation

Level of Aggregation	Number of Estimates[a]	Learning Rate[b]		
		Mean	Min.	Max.
Process	219	0.136	0.005	0.492
Plant	100	0.179	-0.440	0.646
Firm	104	0.179	0.012	0.527
Industry	85	0.241	0.013	0.921

[a] Some studies did not permit estimates of the progress ratio to be classified by level. There are 512 entries in the database but 508 estimates of the progress ratio.

[b] The learning rate is defined as (1-p).

Table 7: Determinants of the Estimated Learning Rate

Variable	(1)	(2)
Intercept	0.143	0.143
	(8.54)	(8.53)
Time is measured weekly (=1)[b]	-0.073	-0.061
	(-1.67)	(-1.38)
Time is measured monthly (=1)	-0.030	-0.036
	(-2.51)	(-2.96)
Time is measured quarterly (=1)	0.016	0.022
	(0.75)	(0.60)
Accounts for Knowledge Depreciation (=1)	0.126	0.101
	(3.38)	(2.86)
Accounts for Knowledge Transfer (=1)	-0.004	-0.004
	(-9.38)	(-8.67)
Experimental (=1)	0.049	0.046
	(2.45)	(2.35)
Steel (=1)		0.051
		(1.05)
Electronics (=1)		-0.002
		(-0.08)
Shipbuilding (=1)		-0.056
		(-3.30)
Aircraft (=1)		0.084
		(4.66)
R^2	0.107	0.148
Number of observations	511	511

[a] The numbers in parentheses are t ratios computed using the robust standard errors following the Huber sandwich estimator. They were computed using STATA Version 7.

[b] The omitted category is daily periods distinguishing each measurement for the estimated progress ratio.

Table 8: Determinants of Significant Estimates of Learning Coefficient[a]

Independent Variables	Determinants of Significant Estimate of Learning Coefficient (b)
Intercept	-46.199 (-2.96)
Sample size in study	0.002 (1.81)
Year published	0.024 (3.05)
process (=1)	0.830 (3.52)
form (=1)	-0.131 (-0.55)
shipbuilding (=1)	-1.173 (-2.81)
Number of observations	472
Pseudo R^2	0.125

[a] The numbers in parentheses are the ratios of the estimated coefficients of their asymptotic standard errors.

Table 9: Products Included in Learning Curve Studies

Product	Count of Estimates
A computer peripheral device	10
Aircraft	35
Apparel and Related Products	1
Apparel manufacture	3
Assembly of electronic data processing	27
Assembly of major units card punch	1
Automatic Machine Tool	2
Automobile assembly	4
B-17 bombers production	1
Machine shop	2
Beverages	4
Bindery machines	16
Black and White Television	2
Chemical Products	14
Color Television	2
Computers and Electrical Equipment	34
Consumer electronics	3
Deburring and Cleaning in Machine Shop	2
Dishwasher	2
Electric Clothes Dryers	2
Electric Refrigerator	1
Ethanol Production	1
Fabricated Metals	2
Final assembly and testing of card punch	1
Food	5
Furniture	5
Glass product Industry	2
Grinding in Machine Shop	2
Heavy Yarn productivity per spinner hour	10
Hessian Productivity per weaver hour in	12
Industrial Chemicals and Gas	1
Photographic	2
Insurance	1
Iron and Steel	1
Jute Mill	10
Lathes in Machine shop	2
Leather and leather goods	1
Light Yarn productivity per spinner hour	10
Lumber and wood products	1
Machinery	20

Machine Shop	2
Metal Products	3
Milling in machine shop	2
Munition	1
Musical Instruments	7
New Automatic Machine Tool	5
Non-Ferrous Products	1
Nuclear Power	1
Oil Drilling Tools	3
Paints, Pharmaceuticals and other Chemicals	1
Paper	5
Petroleum and coal products	2
Pizza	5
Plastic Products	1
Power sawing in a machine shop	2
Pressing Machine Labor	8
Primary metal industries	1
Printing	17
Pulp paper and allied products	1
Punch Press operation	3
Radar Equipment	1
Room air conditioners	2
Rubber products	2
Sacking productivity per weaver hour in	12
Semi-Automatic Machine tool	2
Semiconductor Manufacturing	10
Semiconductors	57
Ship yard	25
Steel	43
Stone Clay and Glass products	1
Textiles	5
Transport	11
Wearing Apparel	1
Western Electric Plant (microscopic ass	3
cement-asbestos water reservoirs	1
drilling in Machine shop	2
flihgt simulation	1
manufacturing operation of card punch	6
surgery	1

References

Alchian, Armen, 1963, "Reliability of Progress Curves in Airframe Production," *Econometrica*, **31** (October): 679-693.

Anderson, J.E. and P.J. Neary, 1992, "Trade Reform with Quotas, Partial Rent Retention, and Tariffs," *Econometrica*, **60** (January): 57-76.

Auerswald, Phillip, Stuart Kauffman, José Lobo, and Karl Shell, 2000, "The Production Recipes Approach to Modeling Technological Innovation: An Application to Learning by Doing," *Journal of Economic Dynamics and Control*, **24** ( ): 389-450.

Barbera, Anthony and Virginia McConnell, 1986, "Effects of Pollution Control on Industry Productivity: A Factor Demand Approach," *Journal of Industrial Economics*, **35** (February): 161-172.

Barbera, Anthony and Virginia McConnell, 1990, "The Impact of Environmental Regulations on Industry Productivity: Direct and Indirect Effects," *Journal of Environmental Economics and Management*, **18** (January): 50-65.

Burtraw, Dallas and Matt Cannon, 2000, "Heterogeneity in Costs and Second-Best Policies for Environmental Protection," Discussion Paper, No. 00-20, Resources for the Future, April.

Cameron, Trudy A., forthcoming, "Updated Subjective Distributions for Future Climate and Individual Option Prices for Climate Change Mitigation," *Journal of Public Economics.*

Epple, Dennis, Linda Argote, and Rukmini Devadas, 1991, "Organizational Learning Curves: A Method for Investigating Intra-Plant Transfer of Knowledge Acquired Through Learning by Doing," *Organizational Science*, **2** (February): 58-70.

Espinosa, J. Andrés and V. Kerry Smith, 1995, "Measuring the Environmental Consequences of Trade Policy: A Nonmarket CGE Analysis," *American Journal of Agricultural Economics*, **77** (December): 772-777.

Espinosa, J. Andrés and V. Kerry Smith, "Environmental Levies and Non-Separable Damages," to be submitted to *Journal of Public Economics.*

Goulder, Lawrence H., 1995, "Environmental Taxation and the Double Dividend: A Reader's Guide," *International Tax and Public Finance*, **2** (August): 157-184.

Goulder, Lawrence H., Ian W.H. Parry, Roberton C. Williams III, and Dallas Burtraw,

1999, "The Cost-Effectiveness of Alternative Instruments for Environmental Protection in a Second-Best Setting," *Journal of Public Economics*, **72** (March): 329-360.

Harrison, G.W., T.F. Rutherford, and J. Wooton, 1989, "The Economic Impact of the European Community," *American Economic Review Papers and Proceedings*, **79** (May): 288-294.

Hettige, Hemamala, Paul Martin, Manjula Singh, and David Wheeler, 1994, "The Industrial Pollution Projection System," Policy Research Working Paper, December.

Jacoby, Henry D. and Ian Sue Wang, 1999, "Adjustment Time, Capital Malleability and Policy Cost," *Energy Journal*, Special Issue – *The Costs of the Kyoto Protocol: A Multi-Model Evaluation*, edited by J.P. Weyant and J.N. Hill, January.

Kopp, Raymond J. and V. Kerry Smith, 1985, "The Measurement of Non-Neutral Technological Change," *International Economic Review*, **26** (January): 135-159.

Layton, David F. and Gardner Brown, 2000, "Heterogeneous Preferences Regarding Global Climate Change," *Review of Economics and Statistics*, **82** (November): 616-624.

Mendelsohn, Robert, William D. Nordhaus, and Dargee Shaw, 1994, "The Impact of Global Warming on Agriculture: A Ricardian Analysis," *American Economic Review*, **84** (September): 753-771.

Morgenstern, Richard D., William A. Pizer, and Jhih-shyang Shih, 1998, "The Cost of Environmental Protection," Discussion Paper, No. 98-36, Resources for the Future, May.

Nordhaus, William D., 1994, *Managing the Global Commons* (Cambridge: MIT Press).

Peretto, P.F., 2001a, "Effluent Taxes, Market Structure and the Rate and Direction of Endogenous Technological Change," under review at *Rand Journal of Economics* (submitted 2001).

Peretto, P.F., 2001b, "Energy Taxes and Endogenous Technological Change," Working Paper, Duke University, Durham, N.C.

Porter, Michael E. and Claas van der Linde, 1995, "Toward a New Conception of the Environmental-Competitiveness Relationship," *Journal of Economic Perspectives*, **9** (April): 97-118.

Porter, Michael E., 1991, "America's Green Strategy," *Scientific American*, **264** (April): 168.

Russell, Clifford S. and William J. Vaughan, 1976, *Steel Production: Processes, Products and Residuals* (Baltimore: Johns Hopkins University).

Smith, V. Kerry, 1998, "Should Pollution Reductions Count as Productivity Gains for Agriculture?," *American Journal of Agricultural Economics*, **80** (August): 591-94.

Smith, V. Kerry and Randy Walsh, 2000, "Do Painless Environmental Policies Exist?," *Journal of Risk and Uncertainty*, **21** (July): 73-94.

Thorton, Rachel A. and Peter Thompson, 1999, "Learning from Experience and Learning from Others: A Semi-Parametric Exploration of Learning and Spillovers in Wartime Shipbuilding," unpublished paper, Department of Economics, University of Houston, October.

Vaughan, W.J., C.S. Russell, and H.C. Cochrane, 1976, "Government Policies and the Adoption of Innovations in the Integrated Iron and Steel Industry," Report prepared for the National Science Foundation, National R and D Assessment Program under Grant No. RDA74-18148-A01. Available through NTIS, Springfield, VA, May.

Appendix A

Adler, Paul S. and Kim B. Clark, 1991, "Behind the Learning Curve: Sketch of the Learning Process," *Management Science*, **37** (March): 267-281.

Alchian, Armen, 1963, "Reliability of Progress Curves in Airframe Production," *Econometrica*, **31** (October): 679-693.

Baloff, Nicholas, 1966, "Startups in Machine-Intensive Production Systems," *Journal of Industrial Engineering*, **17** (January): 25-32.

Baloff, Nicholas, 1967, "Estimating the Parameters of the Startup Model – An Empirical Approach," *Journal of Industrial Engineering*, **18** (April): 248-253.

Baloff, Nicholas, 1971, "Extension of the Learning Curve – Some Empirical Results," *Operational Research Quarterly*, **22** (4): 329-340.

Baloff, Nicholas and John W. Kennelly, 1967, "Accounting Implications of Product and Process Start-ups," *Journal of Accounting Research*, **5** (Autumn): 131-143.

Bass, Frank M., 1980, "The Relationship Between Diffusion Rates, Experience Curves, and Demand Elasticities for Consumer Durable Technological Innovations," *Journal of Business*, **53** (March): S51-S67.

Benkard, C. Lanier, 1999, "Learning and Forgetting: The Dynamics of Aircraft Production," NBER Working Paper 7127, May.

Cole, Reno R., 1958, "Increasing Utilization of the Cost-Quantity Relationship in Manufacturing," *Journal of Industrial Engineering*, **9** (May-June): 173-177.

Conway, R.W. and Andrew Schultz, Jr., 1959, "The Manufacturing Progress Function," *Journal of Industrial Engineering*, **10** (January-February): 39-54.

Darr, Eric D., Linda Argote, and Dennis Epple, 1995, "The Acquisition, Transfer, and Depreciation of Knowledge in Service Organizations: Productivity in Franchises," *Management Science*, **41** (November): 1750-1762.

Epple, Dennis, Linda Argote, and Rukmini Devadas, 1991, "Organizational Learning Curves: A Method for Investigating Intra-Plant Transfer of Knowledge Acquired Through Learning by Doing," *Organizational Science*, **2** (February): 58-70.

Flamm, Kenneth, "Forward Pricing versus Fair Value: An Analytic Assessment of 'Dumping' in DRAMs," in "Trade and Protectionism. National Bureau of Economic Research East Asia Seminar on Economics- Vol.2", Ito, Takatoshi, Krueger, Anne eds. University of Chicago Press, 1993, pages 47-93.

Goldemberg, José, 1996, "Communication: The Evolution of Ethanol Costs in Brazil," *Energy Policy*, **24** (December): 1127-1128.

Gruber, Harald, 1992, "The Learning Curve in the Production of Semiconductor Memory Chips," *Applied Economics*, **24** (8): 885-894.

Heng, Toh Mun and Linda Low, 1992, "Estimating and Comparing Learning Curves in Three Asian Economies," *Asia Pacific Journal of Management*, **12** (January): 21-35.

Hirsch, Werner Z., 1952, "Manufacturing Progress Functions," *Review of Economics and Statistics*, **34** (2): 143-155.

Irwin, Douglas A. and Peter J. Klenow, 1993, "Learning-by-Doing Spillovers in the Semiconductor Industry," *Journal of Political Economy*, **101** (April): 1200-1227.

Kibria, M.G. and C.A. Tisdell, 1985, "International Comparisons of Learning Curves and Productivity," *MIR*, **25** (April): 66-72.

Kibria, M.G. and C.A. Tisdell, 1985, "Productivity Progress Parameters for Manufacturing in an LDC: The Startup or Learning Phase in Bangladesh Jute Mills," *Australian Economic Papers*, **24** (December): 370-379.

Lieberman, Marvin B., 1984, "The Learning Curve and Pricing in the Chemical Processing Industries," *Rand Journal of Economics*, **15** (Summer): 213-228.

Lieberman, Marvin B., 1987, "Patents, Learning by Doing, and Market Structure in the Chemical Processing Industries," *International Journal of Industrial Organization*, **5** ( ): 257-276.

Nadler, G. and W.D. Smith, 1963, "Manufacturing Progress Functions for Types of Processes," *International Journal of Production Research*, **2** (March): 115-135.

Pegels, C. Carl, 1969, "On Startup or Learning Curves: An Expanded View," *Industrial Engineering Research and Development*, 1 (September): 216-222.

Preston, Lee E. and E.C. Keachie, 1964, "Cost Functions and Progress Functions: An Integration," *American Economic Review*, **54** (2): 100-106.

Rapping, Leonard, 1965, "Learning and World War II Production Functions," *Review of Economics and Statistics*, **47** (1): 81-86.

Reis, Dayr A., 1991, "Progress Functions: A General Model," *International Journal of Production Research*, **29** (May): 927-946.

Sheshinski, Eytan, 1967, "Tests of the 'Learning by Doing' Hypothesis," *Review of*

Economics and Statistics, **49** (4): 568-578.

Vigil, Dimas P. and Hüseyin Sarper, 1994, "Estimating the Effects of Parameter Variability on Learning Curve Model Predictions," *International Journal of Production Economics*, **34** (2): 187-200.

Womer, Norman Keith, 1984, "Estimating Learning Curves from Aggregate Monthly Data," *Management Science*, **30** (August): 982-992.

Yelle, Louis E., 1976, "Estimating Learning Curves for Potential Products," *Industrial Marketing Management*, **5** (2/3): 147-154.

Appendix B

These results relate to a new round of computations Banzhaf and Smith initiated at the end of the research period. They consider revenue neutral proposals but fix the carbon tax at a constant level per unit and retain the value-added taxes as the means to maintain the initial tax revenue. For the policy reported in the attached table, the carbon tax was set arbitrarily, to illustrate the methodology, at 0.01 per million tons of carbon emissions. Revenue neutrality was maintained in each of the eight countries in the European Union (in this version of the model) individually. Thus, it is analogous to Policy I in its treatment of revenue neutrality on an individual country basis. These results should be regarded as preliminary and are included only to indicate a new formulation for the carbon tax policies that we are considering as part of further work.

Appendix B – Table: Anderson-Neary Welfare Indexes*

	Policy III	
	With Morbidity	With Mortality
Germany	-0.200	-0.276
France	-0.004	-0.025
Italy	0.011	0.032
Netherlands	0.000	-0.008
Belgium	-0.043	-0.057
United Kingdom	-0.0289	-0.023
Ireland	0.022	0.022
Denmark	-0.021	-0.040
United States	0.106	0.114
Japan	-0.045	-0.045
Rest of World	0.422	0.483

*These welfare measures are in billions of 1980 U.S. dollars.