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Induced Technical Change and the Cost of Climate Policy

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Induced Technical Change and the Cost of Climate Policy*

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Abstract

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 modelled 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.

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1 Introduction

Ever since Hicks's articulation of the induced invention hypothesis (IIH) that price changes affect the rate and direction of technological advance, economists have tried unsuccessfully to put theoretical and empirical flesh on its conceptual skeleton.[1] Nevertheless, despite the

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[1]Hicks (1932, p. 124): 'a change in the relative prices of factors of production is itself a spur to invention, and to invention of a particular kind—directed to economizing the use of a factor which has become relatively expensive'. Attempts by Kennedy (1964), von Weizsacker (1965) and Ahmad (1966) to develop this hypothesis into a theory led to a sizeable literature (for surveys, see Binswanger and Ruttan (1978) and Thirtle and Ruttan (1987)) that after much argument and criticism (e.g. Samuelson (1965); Nordhaus (1973)) faded from view in the 1970s.

fact that the IIH remains more a general principle than a fully articulated theory, induced innovation tends to be cited as a benefit of regulatory intervention, especially in the environmental policy arena (e.g. Ashford et al. (1985) and Ashford (1994); Porter and van der Linde (1995)).

Advocates of environmental regulation claim that forcing polluters to bear the costs of reducing pollution induces the development of new technologies that both improve productivity and mitigate abatement costs.[2] Econometric tests of this claim at the level of individual industries or products have yielded mixed results.[3] Recent findings indicate that environmental policies whose effects are large relative to the scale of the economy can have a strong positive feedback on innovation (Popp, 2002b) and may actually have beneficial economic outcomes (Popp, 2001). This paper explores the macroeconomic implications of these findings by examining the effect of environmental policy constraints on aggregate technological progress and investigating the influence of such induced technological change (ITC) on policy's net welfare impact.

The motivation of the paper is to better understand the welfare implications of the effects of climate change mitigation policies on technological progress. Carbon dioxide (CO_2), emitted in combustion of carbon-rich fossil fuels to provide energy for economic activity, is the chief greenhouse gas (GHG) thought to cause global warming. Fossil fuels currently lack large-scale substitutes, causing concern that CO_2 emission limits will precipitate drastic increases in energy prices and reductions in output and welfare (see, e.g. Weyant, ed, 1999).[4] Climate change is thus the litmus test of ITC, because the costs of mitigation policies and the potential for technology to alleviate them dwarf those of other environmental problems.

Technological change is perhaps the single most important source of uncertainty in forecasting the macroeconomic cost of limiting GHG emissions. Figure 1 illustrates that although the direct effects of abatement on aggregate policy costs are fairly well known (I), there is comparatively weak understanding of both the way in which abatement costs might induce innovation (II) and the potential for the resulting technology to increase the substitution possibilities for carbon-based energy (III). Thus, a prerequisite to understanding ITC's impact on the optimal intertemporal program of reductions (IV), is elucidation of the net welfare impact of the mechanisms that drive the feedback loop (II)-(III).[5] This is the contribution

[2]The strong version of this hypothesis, which is attributed to Porter, claims that environmental regulations have a net *beneficial* effect on firms' competitiveness. For a critique, see Palmer et al. (1995).

[3]See Jaffe et al. (1995) and Jaffe et al. (2000).

[4]On the supply side, a lack of alternative fuels prevents energy producers from mitigating the additional costs of carbon abatement incurred in the process of producing energy. Apart from switching to fossil fuels with a lower carbon content (e.g. from coal and oil to natural gas), carbon sequestration or renewable energy technologies are still too expensive for producers to broadly substitute them for hydrocarbons. On the demand side, the inability to quickly change the energy using characteristics of capital or consumer durables limits the substitution of other inputs to production and consumption as energy prices rise (Jacoby and Sue Wing, 1999).

[5]There is considerable debate over the impact of technological change on the cost-minimizing trajectory of GHG abatement. Some argue for postponing emissions cuts to allow for development of new substitution possibilities that facilitate cheaper and more rapid abatement (e.g. Wigley et al., 1996), while others advocate undertaking aggressive abatement to induce the development and adoption of technologies that mitigate abatement costs (e.g. Grubb, 1997). The former "wait-and-see" approach assumes that new technology development follows an autonomous rate of advance of which emission standards should be cognizant, while the latter "act-now" approach assumes that technological change is both amenable to inducement and has

of the paper.

To investigate the workings of the feedback loop (II)-(III) I capture the effects of relative price changes on innovation, changes in substitution possibilities and welfare using a multi-sector computable general equilibrium (CGE) model of the U.S. economy. The model numerically simulates the effects of a carbon tax on the level and composition of aggregate R&D investment, the rate of accumulation of an aggregate stock of knowledge, and the inter-sectoral reallocation and intra-sectoral substitution of the knowledge services derived therefrom. The results reveal the previously unexplored role of knowledge reallocation in the economy's response to policy constraints.

I find that, contrary to the assumptions of simulation studies (e.g. Goulder and Matthai (2000); Nordhaus (2002)) but consistent with econometric evidence on the pollution-innovation link (e.g. Jaffe and Palmer, 1997), a carbon tax *reduces* aggregate R&D, causing a slowing of knowledge accumulation and the rate of technical progress, and a decline in income and output. However, at the same time the relative price effects of a carbon tax induce substantial intra-sectoral substitution and inter-sectoral reallocation of knowledge inputs, enable the economy to adjust in a more elastic manner. The consequent increase in gross input substitutability on the supply side of the economy ends up mitigating the bulk of the deadweight losses incurred by the tax. When the latter "substitution effect" is taken into account, the impact of ITC is positive and large, implying that its role in economic adjustment may be much more significant than previously thought.

The paper is organized as follows. Section 2 develops a simple conceptual model of the effect of pollution abatement on ITC and welfare, applies it as a framework for understanding key empirical results on the mechanisms and impacts of ITC, and uses it to motivate the analyses in the paper. Sections 3 and 4 outline the CGE model's data base, algebraic structure and parameter values, emphasizing representation of the mechanisms through which technical change occurs. Section 5 presents and discusses the results of the model's numerical simulations. Section 6 concludes.

2 Global Warming and ITC

2.1 Conceptual Framework

Induced technical change is the change in the set of substitution possibilities that is brought about by the inventive response to changes in input prices. Consider the simple case in which output (Y) is generated according to a production function (Q) that is defined over a "clean" input (C) and a "dirty" input (D), whose use generates pollution. In the neoclassical model of production, taxing pollution increases the cost of using D and induces the producer to shift to technological alternatives that use relatively less D and more C. The magnitude of this shift is determined the shares of the two inputs in production, their relative prices, and the elasticity of substitution that defines the shape of Q.

The situation of interest in this paper is more difficult to model. Here, Q does not represent the envelope of all possible technologies. Constraining emissions changes the relative price of D, stimulating innovation that alters the shape of Q itself. Early studies of ITC

a mitigating effect on policy costs.

sought to capture this phenomenon by specifying a production function $Y = Q(\nu_D D, \nu_C C)$ in which dirty and clean inputs are augmented by technological coefficients ν_C and ν_D (respectively) that are themselves functions of relative prices, following Kennedy (1964).[6] I use a different approach, that represents the shift in the production function through the substitution of knowledge for tangible inputs.[7] The intuition is that relative price changes induce the creation of knowledge, not technical change *per se*. Only subsequently does technical change arise, as the consequent increase in the quantity of knowledge shifts the envelope of substitution possibilities among tangible inputs.

To formally summarize this intuition, consider an economy in which C and D are the only commodities, with prices p_C and p_D, respectively. C and D are produced by industries that use both commodities as inputs to production. Each industry also invests in R&D (R) according to the inducement effect of the relative price of the dirty input to production and the resources at its disposal for investment, which can be thought of as function of its output. Thus, in each industry i and time period t,

$$(1) \quad R_i(t) = \rho_i(p_C(t), p_D(t), Y_i(t)) \;\; i \in C, D$$

ρ_i can be thought of as i's "inducement function". It is plausible to assume that $\partial\rho_i/\partial Y_i > 0$, because the larger an industry the more resources it possesses for investment in R&D. The signs of $\partial\rho_i/\partial p_C$ and $\partial\rho_i/\partial p_D$ are more difficult to pin down, because Y_i and the relative prices of the inputs responsible for its supply are not independent. In particular, proponents of technology-forcing environmental regulation claim that $\partial\rho_i/\partial p_D > 0$, so that increasing the price of dirty input is a signal for them to innovate. But while this may be true, it is only half of the story. Ceteris paribus an increase in p_D also raises industries' unit costs of production. For competitive markets to clear, rising costs must be a accompanied by a fall in output and a reduction in the resources available for R&D. A realistic specification of ρ should therefore allow prices to *negatively* affect R&D spending, *slowing* the rate of technical advance.[8] This is an important point that will have a significant impact on the rest of the paper.

Over time, R&D drives the accumulation of an aggregate stock of intangible knowledge assets H according to

$$(2) \quad \dot{H}(t) = \varpi\left(\sum_i R_i(t), H(t)\right),$$

where $\partial\varpi/\partial R > 0$ and $\partial\varpi/\partial H < 0$ (e.g., the standard perpetual inventory formulation). By modeling knowledge as a homogenous factor, equation (2) allows innovations in the clean industry to increase productivity in the dirty industry and vice versa. In doing so it reflects the general-purpose or analogical character of knowledge, whereby intangible assets

[6] See, e.g. (Smith, 1974) and (Magat 1976; 1978).

[7] Other studies that do this are Bovenberg and Smulders (1995) and Goulder and Schneider (1999).

[8] If one assumes that Y_i is a function of prices this proposition is evident from the derivative of (1) with respect to p_D: $\dfrac{\partial R_i}{\partial p_D} = \dfrac{\partial \rho_i}{\partial p_D} + \dfrac{\partial \rho_i}{\partial Y_i}\dfrac{\partial Y_i}{\partial p_D}$. The first right-hand-side term, which presumably is positive, captures the direct effect of inducement. But this may be outweighed by the second term which captures the indirect effect of prices on research resources. Which term dominates is an empirical question.

are capable of being cheaply re-used in different contexts, or combined in different ways so as to be useful in entirely new contexts (Bresnahan and Trajtenberg, 1995; Weitzman, 1998).

In each period a vector of intangible knowledge services (v_i) flows forth from this stock to different industries according to the rate of return, that is determined by prices:

$$(3) \quad v_i(t) = \vartheta(p_i(t), H(t))$$

where $\partial\vartheta/\partial p_i, \partial\vartheta/\partial H > 0$. The key feature of ϑ is that it treats knowledge services as a priced factor (similar to capital input) whose inter-sectoral distribution can be shifted by changing relative prices even if the stock of knowledge remains constant. Such treatment of intangible services—possessing a price that can be competitively bid up in the short run, which serves to allocate the benefits of knowledge so that its marginal product is equalized across industries—captures the tacit, specific character of experience, which is costly to codify or transmit outside of the context of its genesis, is in limited short-run supply, and may be embodied in intersectorally mobile human capital or high-tech goods (Nelson and Winter, 1982; Cohen and Levinthal, 1990).

Lastly, output—to which the vector of relative prices is dual in general equilibrium (denoted by the symbol "$\perp$")—is determined by a production correspondence defined over the prices of clean and dirty intermediate inputs:

$$(4) \quad Y_i(t) = \phi_i[v_i(t); Q_i(p_C(t), p_D(t))] \quad \perp \quad p_i(t).$$

Q_i represents each industry's production function (with a slight abuse of notation), in which the ability to substitute clean inputs for dirty inputs is limited. Technical change is the effect of knowledge services on Q_i, which shift the envelope of possibilities to substitute C for D in accordance with the "meta-production function" ϕ.

For the purposes of climate policy D represents fossil fuels. Technical change is induced by the influence on p_D of taxes or quantitative limits on carbon emissions, which in turn affects R&D in the C and D industries, that has a further impact the future supply of knowledge. Induced technical change therefore results from two separate processes:

- An "accumulation effect" in which ρ_i and ϖ determine how price-induced changes in R&D alter the rate of accumulation of the stock of knowledge and the aggregate endowment of knowledge services, and
- A "substitution effect" in which ϑ and ϕ_i determine how prices alter the distribution of this intangible endowment among producers so as to reduce the costs of abatement.

The framework of equations (1)-(4) is too general to serve as a full analytical model, but its simplicity is nonetheless useful to clarify and put into perspective the contributions of empirical studies of ITC, identify the gaps in our understanding of the operation of the feedback loop in Figure 1, and motivate the construction of a numerical simulation that can highlight the role of knowledge accumulation and substitution in technological adjustment to policy constraints.

2.2 The Framework Applied: A Review of the Literature

There has been a recent spate of empirical work on the inducement of technical change by environmental constraints, which is summarized in Table 1. The results of investigations of

the effect of environmental policy constraints on innovation (Figure 1, link II) are mixed. Jaffe and Palmer (1997) find that the overall rate of innovation is largely insensitive to the cost of pollution abatement.[9] Closely allied to the motivation of this paper, Newell et al. (1999) and Popp (2002b) focus on energy (e) as a dirty input, and estimate that the elasticity of energy-saving knowledge (H_e) with respect to energy prices (p_e) is positive.[10] Newell et al. (1999) also find the rate of technical change to be unaffected by energy prices, echoing Jaffe and Palmer's results. Lastly, Popp (2001) examines the effect of innovation on energy use (Figure 1, link III) and finds that the elasticity of energy demand with respect to the stock of energy-saving knowledge is negative.[11]

It is important to note that although the energy price impacts of carbon abatement may induce energy-saving innovation, that does *not* imply that such technological change is welfare improving. There are two reasons for this. The first is the competition for resources among different types of research implied by Jaffe and Palmer's results. If total inventive effort is inelastic with respect to p_D, then increased pollution-saving innovation will be accommodated through a redistribution of industries' R&D portfolios.[12] Thus, compared to the counterfactual case of no energy price increases, a strong response of energy technology innovation may well result in energy-price-induced *reductions* in other types of innovation, with adverse effects on aggregate knowledge accumulation and future productivity. The second reason is that, with a pollution tax or quota, the more intensive an industry's use of D the higher its unit production cost, the more negative $\partial Y_i/\partial p_D$ becomes, and the greater the likelihood that R_i declines. Thus, not only is the sectoral distribution of R&D likely to change but *aggregate* R&D may actually decline, again lowering future productivity. Thus, although empirical studies point to substantial scope for induced technical change at the the level of individual sectors or technologies, the implications of this finding for the macroeconomic cost of climate policy remains unclear.

Simulation studies of the macroeconomic effects of ITC appear to have overlooked this fact. Goulder and Matthai (2000), Nordhaus (2002) and Popp (2002a) consider only the inducement of energy- or carbon-saving R&D and ignore the effects of carbon constraints on non-energy knowledge.[13] This approach, which is tantamount to writing equations (2) and

[9] Jaffe and Palmer find that pollution abatement expenditures in a panel of manufacturing industries do not significantly influence patenting activity, and exert only a small positive influence on R&D.

[10] Newell et al. find that energy prices and environmental policies positively affect the energy-saving bias of technical change in home heating and cooling technology, but do not influence the pace of such technical advance. Popp (2002b) shows that the flow of patent applications in energy technologies responds rapidly to energy price increases, but that the sensitivity of patenting to such price changes is strongly influenced by the state of technological knowledge, as evinced by the stock of energy technology patents in the U.S. economy.

[11] Popp (2001) estimates that the energy savings due to the knowledge embodied in the cumulated stock of energy technology patents account for one-third of the observed reduction in energy intensity in U.S. manufacturing, and represent an overall positive return on the R&D investment required to generate the relevant patents.

[12] Popp (2002a, p. 6) provides evidence of this for the U.S., finding that each additional dollar of energy R&D crowds out about 40 cents worth of non-energy R&D.

[13] Nordhaus extends the DICE model to include R&D investment as a control variable that causes the emission coefficient on output to decline in the presence of abatement policies. He finds that the welfare impact of ITC is negligible, and concludes that the quantity of R&D investment is too small to make any difference without implausibly high social returns. Similarly, Goulder and Matthai find that under a benefit-cost criterion such as used by Nordhaus ITC does not affect the optimal tax rate but stimulates increased

(3) as:

$$\text{(2a)}\quad \dot{H}_D(t) = \varpi\left(R_D(t), H_D(t)\right)$$

and

$$\text{(3a)}\quad v_i(t) = \begin{cases} \vartheta(p_i(t), H_i(t)) & i = D \\ \vartheta(p_i(t), \overline{H}_i(t)) & i = C \end{cases}$$

is problematic because it ignores the potential tradeoff at the aggregate level between emission-reducing research and other types of R&D.

The only study to address these issues is Goulder and Schneider (1999), who model ITC as an R&D spillover within a multisector general equilibrium framework.[14] They find that ITC's welfare impact is positive but so small as to be overwhelmed by the negative effects of emissions limits, which suggests that the net effect of Y_i and p_D on ρ_i and ϖ is dominated by the reduction in output and the resources for research.[15] They also show that this adverse effect can be mitigated by removing taxes on R&D or by subsidizing research.

But Goulder and Schneider's formulation of ITC suffers from other problems. Knowledge accumulation occurs in all industries, but their "ITC spillover" (χ) is confined to energy industries, which is equivalent to writing equations (2) and (3) as:

$$\text{(2b)}\quad \dot{H}_i(t) = \varpi\left(R_i(t) + \chi_i(t), H_i(t)\right)$$

and

$$\text{(3b)}\quad v_i(t) = \vartheta(p_i(t), H_i(t))$$

with $\chi_D > 0$ and $\chi_C = 0$. ITC spillovers provide an extra impetus to the accumulation of knowledge, but only in the D sector, implying that ITC within polluting industries is somehow isolated from the accumulation and substitution of knowledge elsewhere in the economy. There is an inconsistency here. The fact that in general equilibrium the same relative price changes—and therefore the same signal to innovate in a particular direction in input space—is felt by all sectors argues that χ_C should also be positive for consistency. For this reason, Goulder and Schneider's conclusion that the external benefits of R&D (as opposed to ITC *per se*) justify R&D subsidies is misleading.

Finally, all these simulation studies share the characteristic of focusing on the accumulation effect as the mechanism for ITC's impact, while attenuating or ignoring the role that

abatement of carbon emissions. But they also find that under a cost-effectiveness criterion the reverse is true: ITC has a negligible impact on the path of abatement but significantly reduces abatement costs.

[14] Goulder and Schneider construct a dynamic CGE model in which there are two kinds of intangible assets. The first, "appropriable" knowledge, is the value of the additions to the knowledge stock that are captured by the sector undertaking the research investment, where it plays the role of a fixed factor in each period. The second, "spillover" knowledge, is the social return to the R&D performed by each industry's constituent firms, that increases the productivity of the entire industry by increasing the value of a Hicks-neutral shift parameter in its production function. This productivity increase, which they define as induced technical change, is active only in the carbon-energy and alternative-energy sectors of their model.

[15] This result is consistent with the econometric evidence on the productivity consequences of environmental regulation summarized by Jaffe et al. (1995, pp. 150-153) and Jaffe et al. (2000, pp. 26-30).

may be played by the reallocation of knowledge among sectors, i.e., the substitution effect. This seems to arise from a mental model of the inducement process in which price increases stimulate *additional* R&D, not one in which the patterns of use of existing knowledge change in response to new relative price conditions. The rest of the paper is devoted to redressing this imbalance. In the following sections I construct and simulate a CGE model that is motivated by the framework of equations (1)-(4), in which emissions limits are allowed to affect R&D and technical change broadly (i.e., without being confined to the genesis and effects of energy- or emissions-saving innovation), and knowledge can move among sectors in response to relative prices and differences in knowledge-energy substitution possibilities. This latter structural characteristic, whose influence has not been explored, ends up having a significant impact on the economy's response to an emission tax.

3 Knowledge Accounting: An Input-Output Dataset

The first step in creating a CGE model based on equations (1)-(4) is to gather data on which to numerically calibrate the functions ρ, ϖ, ϑ and ϕ. This information is tabulated in the form of a social accounting matrix (SAM), that is a snapshot of the economy in equilibrium. The primary dataset used in this study is the SAM for the U.S. in 1997. However, these data do not separately record the necessary information on industries' investments in knowledge creation or their inputs of intangible services, or the size of the economy's stock of knowledge.[16] The National Income and Product Accounts treat R&D as a current cost of production along with intermediate input (U.S. Dept. of Commerce: Bureau of Economic Analysis, 1994a), with the result that only a portion of each intermediate transaction reflects the value of physical goods and services. The remainder that reflects the value of the knowledge associated with each activity, that must be estimated.[17]

The intangible components of the SAM are shown conceptually by the shaded portion of the cells in the intermediate transactions matrix ($\mathbf{X}$) in Figure 2(a). These can be thought of as a matrix of knowledge flows $\mathbf{\Omega}$ whose row sums are the value of industries' intangible investments ($g_{iR} = \sum_j \omega_{ij}$) and whose column sums are the value of inputs of intangible knowledge services to industries' production ($v_{Hj} = \sum_i \omega_{ij}$). To estimate the elements of $\mathbf{\Omega}$ I assume the simple limiting case shown in Figure 2(b) in which intermediate knowledge flows are completely concentrated in knowledge-intensive industries identified by the the shaded rows and columns.[18] As shown in Table 2, the industries thus categorized are ones

[16]The 1997 U.S. SAM is composed of an $i \times j$ matrix $\mathbf{X}$ of interindustry transactions, an $f \times j$ matrix of value-added activities $\mathbf{V}$, and an $i \times d$ matrix of final demand activities $\mathbf{G}$. The set indices i and j denote industry sectors, shown in Table 2; f denotes the primary factors labor, capital, and natural resources; d denotes the final demands consumption, investment, government, imports, exports. The SAM is constructed from the BEA's 92-sector "Make of Commodities by Industries" and "Use of Commodities by Industries" tables for 1997 (U.S. Dept. of Commerce: Bureau of Economic Analysis, 2001) using the industry technology assumption (for methodological details see Reinert and Roland-Holst). Its components of value added are disaggregated using data on industries' shares of labor, capital, taxes and subsidies in GDP published by (U.S. Dept. of Commerce: Bureau of Economic Analysis, 2000a).

[17]This section builds on Goulder and Schneider's procedure for generating the necessary estimates.

[18]This is the input-output analogue of methods that have been used to estimate the value of unrecorded intangible components of GDP (see, e.g. Kendrick (1976) and Eisner (1989)). The alternative is to impute values to ω_{ij} based on the shares of the value of measured R&D spending in each industry that are ap-

whose outputs are used directly for articulating, manipulating, transmitting and applying knowledge. By assumption, the full value of their inputs represents aggregate investment in knowledge building, while the full value of their sales represents aggregate knowledge input.[19] Thus $\omega_{ij} = x_{ij}$ if $i, j \in$ target industries, and zero otherwise.

Investment in and returns to knowledge are accounted for by aggregating the elements ω_{ij} into a single row and a single column and transferring them out of $\mathbf{X}$ to create an additional row of $\mathbf{V}$ and an additional column of $\mathbf{G}$. This procedure generates an intermediate transactions matrix $\tilde{\mathbf{X}}$ that contains only physical commodity flows ($\tilde{x}_{ij} = x_{ij} - \omega_{ij} \geq 0$); a vector of intangible investment $\mathbf{g}_R$ that represents $\mathbf{\Omega}$'s row totals (and the components of R in equation 1); and a vector of intangible inputs $\mathbf{v}_H$ that represents $\mathbf{\Omega}$'s column totals. As shown in Figure 3(a), it reduces the number of sectors in the SAM (in this case from 92 to 86), but it also makes primary factors a direct input to final demands in the typically empty southeast quadrant $\mathbf{B}$—a situation for which there is no good economic interpretation. To remedy this accounting problem the value of primary factor inputs in $\mathbf{B}$ are transferred back into $\mathbf{V}$, and corresponding adjustments are made to $\mathbf{G}$ to re-balance the SAM.[20]

The result, shown in Figure 3(b), is aggregated to match the 19 sectoral groupings in Table 2, and is scaled to approximate the U.S. economy in the year 2000 using the 1997-2000 average annual growth rate of real GDP (4.2 percent). Benchmark inputs of natural resources are estimated as a share of capital in agriculture, oil and gas, mining, coal, and electric power, and the inputs of capital to these industries are decremented accordingly.[21] This final SAM provides the initial calibration point for the technical coefficients of the production and demand functions of the CGE model that I describe in the next section.

Table 3 highlights the relevant features of these data. The absolute magnitude of both R&D investments and knowledge inputs are largest in services, but R&D's share of output is largest in metals, paper products and general equipment, while knowledge as a share of inputs is largest in construction, general equipment and transportation equipment. The average return on intangible investment, measured by the ratio of industries' knowledge inputs to their R&D expenditures, is highest in transportation equipment, coal mining and

propriated by other industries through spillovers. This approach distributes individual industries' research expenditures according to the shares of their sales to other industries, on the assumption that R&D is embodied in tangible goods and services (Terleckyj, 1974), or according to counts of the patents developed in each industry that are used in other industries (Kortum and Putnam, 1997; Evenson and Johnson, 1997).

[19] Cf. Goulder and Schneider, who estimate $\mathbf{g}_R$ as the columns of $\mathbf{X}$ that correspond to the industries "legal, engineering, accounting and related services" and "other business and professions services except medical", and $\mathbf{v}_H$ as 20 percent of the value of capital input in each sector. Although the present study takes a liberal view of the activities that constitute investment in and returns to knowledge, it excludes activities such as health services and pharmaceuticals whose benefits may be purely consumed.

[20] The total value of the input of each factor in the southeast quadrant is apportioned according to industries' shares of the total industry use of that factor, implying that the increment to v_{fj} is $\lambda^V_{fj} = (v_{fj} / \sum_j v_{fj}) \sum_d b_{fd}$. To balance the SAM, the total value of the increment to $\mathbf{V}$ in each industry is allocated among the elements of $\mathbf{G}$ according to the shares of each type of demand in the total final demand for that industry, implying that the increment to g_{id} is $\lambda^G_{id} = (g_{id} / \sum_d g_{id}) \sum_f \lambda^V_{fi}$.

[21] Shares are estimated from a range of additional sources: U.S. Dept. of Agriculture: Economic Research Service, Resource Economics Division (1997) for arable land in agriculture; U.S. Dept. of Commerce: Bureau of Economic Analysis (1994b) for mineral deposits in the coal, oil and gas, metal mining, and non-metal mining industries; and U.S. Dept. of Energy: Energy Information Administration (2000) for "fixed-factor" energy resources such as riverine flow, wind, insolation and uranium deposits in the electric power sector. Sue Wing (2001) provides a detailed description of these data.

owner-occupied dwellings and lowest in paper products and metals.[22] Taxes on industries that comprise knowledge constitute a three percent tax rate on knowledge and make up 2.8 percent of total tax revenue, implying that the market for R&D will suffer from distortions in the baseline no-policy case of a model calibrated on this SAM. Inputs of knowledge generally constitute less than ten percent of sectoral output (with the exception of the construction, equipment and machinery sectors), shares that are similar in magnitude to energy inputs (with the exception of the primary energy industries coal, petroleum and natural gas). However, the dissimilar distributions of each of these inputs in the economy imply inter-sectoral heterogeneity in knowledge-energy substitution possibilities, and create incentives for the reallocation of knowledge services in response to carbon constraints.

Underlying the SAM's static equilibrium flows are dynamic processes of accumulation that expand the economy-wide stocks of capital and knowledge from their initial levels ($\overline{K}$ and $\overline{H}$, respectively). To calibrate the function ϖ I assume that the aggregate benchmark quantities of physical and intangible investment $\overline{G}_I$ and $\overline{G}_R$ compensates for the depreciation of these stocks (which occurs at rates δ_K and δ_H), expanding them at initial rates g_K and g_H. The benchmark stocks of capital and knowledge that underlie the SAM are thus estimated using the relations $\overline{K} = \overline{G}_I/(g_K + \delta_K)$ and $\overline{H} = \overline{G}_R/(g_H + \delta_H)$.[23] To calibrate the function ϑ it is necessary to estimate the rates of interest on tangible and intangible assets (r_K and r_H) that generate the payments to capital and knowledge in the SAM ($\overline{V}_K$ and $\overline{V}_H$, respectively). These are computed using the standard rate-of-return formulas $r_K + \delta_K = \overline{V}_K/\overline{K}$ and $r_H + \delta_H = \overline{V}_H/\overline{H}$.[24]

4 ITC in a CGE Model of the U.S. Economy

I implement the system of equations (1)-(4) as a recursive-dynamic simulation of the U.S. economy that solves for a series of static equilibria on a five-year time step from 2000 to 2100. The core of the simulation is a static Arrow-Debreu model in which a representative agent maximizes welfare and producing industries maximize profits subject to the technologies of production and consumption, the economy's endowments of primary factors and natural resources, and existing taxes and distortions. The agent is endowed with the factors of production whose services she leases to the industries to produce commodities, thereby generating rental income that finances her demand for commodities for the purposes of consumption, investment and R&D. In the model there are two kinds of assets: physical capital and intangible knowledge, the accumulation of which is driven by the equilibrium flows of aggregate investment and R&D (respectively) computed by the static model in each period. Accumulation of these assets determines the expansion of the endowments of tangible and intangible services that drives the growth of the economy over the simulation horizon.

[22] The former industries are the recipients of knowledge spillovers, which appropriate the benefits of the R&D performed by the latter industries, which are the sources of spillovers.

[23] Based on data in U.S. Dept. of Commerce: Bureau of Economic Analysis (2000b), δ_K is estimated to be 5 percent. By assumption, $\delta_H = 0$, $g_K = 0.05$ and $g_H = 0.1$. The resulting initial values of the stocks are 18.8 trillion dollars for capital and 5.8 trillion dollars for knowledge.

[24] The calculated values of $\overline{K}$ and $\overline{H}$ imply that $r_K = 0.118$, $r_H = 0.257$, the rate of return to capital is 16.8 percent and the rate of return to knowledge is 25.7 percent. These figures imply a joint rate of return to capital and knowledge of 18.9 percent.

Although a forward-looking equilibrium model is the ideal test-bed for evaluating the effects of ITC, a recursive-dynamic modelling approach was pursued because the more complicated intertemporal equilibrium problem could not be solved.[25] The model adopts a Solow-Swan formulation in which the representative agent exhibits a fixed marginal propensity to save and invest in capital and R&D. Consequently, the allocation of resources between tangible and intangible investment in the simulation is based on the relative costs of these two activities—not their relative rates of return. As a result, the model possesses no mechanism for updating the rates of return on capital and knowledge in response to the accumulation of these assets or the relative price effects of emissions limits.

4.1 Production

Each industry j maximizes profit (π_j) subject to the constraint of its production technology (ϕ_j), by allocating its inputs of intermediate goods and factors ($\mathbf{x}_j$ and $\mathbf{v}_j$) to produce output (Y_j), given their prices ($\tilde{\mathbf{p}}^A$, $\mathbf{w}$ and p_j, respectively, where $\tilde{\mathbf{p}}^A$ is gross of commodity taxes):

$$(5) \quad \max_{\mathbf{x}_j, \mathbf{v}_j} \pi_j[p_j Y_j, \tilde{\mathbf{p}}^A \cdot \mathbf{x}_j, \mathbf{w} \cdot \mathbf{v}_j] \text{ s.t. } Y_j \leq \phi_j(\mathbf{x}_j, \mathbf{v}_j)$$

Following Goulder and Schneider, the ϕ_js are nested constant elasticity of substitution (CES) functions, shown in Figures 4(a)-4(c). The substitution elasticities at each level of the nesting hierarchy differ in value by industry, as shown in Table 5.

Figure 4(a) shows the basic nesting structure, which obtains in manufacturing and service sectors. Knowledge services v_{Hj} substitute for an aggregate of physical inputs G_j made up of a value-added bundle KL_j and an aggregate of intermediate inputs EM_j. KL_j is composed of inputs of labor v_{Lj} and capital services v_{Kj}. EM_j comprises nested bundles of energy intermediate goods E_j and non-energy intermediate goods M_j.

Figure 4(b) shows ϕ's structure in primary industries, which contains an additional second-level nest in which sector-specific resources v_{Fj} enter in fixed proportions with G_j. Although inputs that are reproducible within the economy can be substituted among themselves, they can neither create nor substitute for resources, making the latter a limiting input whose scarcity acts as a fundamental brake on output. However, consistent with equation (4) these constraints can be overcome by the substitution of knowledge for the composite of resources and reproducible inputs GF_j at the top level of the production hierarchy.

Figure 4(c) shows ϕ's structure in a carbon-free electric power technology, which, together with a fossil-fuelled electric power technology, makes up the output of the electricity sector. The former uses all of the electric sector's inputs of "fixed-factor" energy resources, while the latter uses all of the electric sector's fossil fuel inputs according to the production function in

[25] Dynamic optimization models with general production technologies and multiple capital stocks that exhibit different depreciation rates are analytically intractable (see, e.g. Wildasin, 1984). The multisector production correspondence of a CGE model, with its full system of intermediate demands, makes it impossible to analytically specify rates of return to capital and knowledge. To simplify the process of calibrating the economy to a dynamic path numerical simulation studies often invoke the assumption that the economy is on a balanced growth path. But the ratios of investment to asset service flows are different for capital and knowledge in the SAM, implying that even the initial condition for the accumulation process is not saddlepath stable. These factors conspire to obstruct the solution for an economic growth trajectory that equalizes the rates of return to knowledge and capital across industries.

Figure 4(a).[26] The outputs of these technologies are assumed to be perfect substitutes. The electricity sector's inputs of non-energy intermediate goods, labor, capital and knowledge are split between these technologies according to their benchmark shares of net generation.

The model's first key feature is that knowledge services are a homogeneous "super factor" that substitute for all other commodities and factors in the economy. The degree to which knowledge services alleviate the effects of natural resources scarcity or regulatory constraints on fossil fuels is a function of the relative magnitudes of the sectoral coefficients on knowledge and fossil fuels (implied by the SAM), and the top-level elasticity of substitution σ_H.[27]

4.2 Public Provision and International Trade

The government is modelled as a passive entity that uses industries' outputs to produce a public good that is allocated between consumption and investment activities. Trade is modelled equally simply.[28] Domestic production of each commodity is allocated between domestic and export markets through a constant elasticity of transformation (CET) technology. The domestically-produced component of each good is combined with imports of that good into an Armington composite commodity (Armington, 1969) according to a CES technology. The resulting vector of Armington goods **A** fulfills intermediate and final commodity demands. Export demands and import supplies are exogenously specified.

4.3 Aggregate Carbon Accounting and Emissions Limits

The model's activities emit carbon in proportion to their demand for inputs of Armington energy goods A_e and a vector of carbon coefficients θ_e shown in Table 4. Emissions accounting occurs in a "weigh-station" sector through which Armington energy commodities pass en route to intermediate and final demand. This sector possesses a fixed-coefficients transformation technology in which aggregate energy use (production minus exports plus imports) is regulated by A_e's embodied carbon:

$$(6) \quad A_e = \zeta(A_e, \theta_e A_e), \quad \sum_e \theta_e A_e \leq \kappa \perp q$$

The representative agent is endowed with a quantity of permits κ that restricts the economy's emissions to the level set by policy. When the permit endowment is small enough to be a binding constraint on the economy's emissions, the carbon embodied in fossil fuels has a positive shadow price q that is the dual of κ. In the model's tâttonement process, initial excess demand for permits induces substitution that distributes emissions reductions among industries and energy commodities so as to minimize the aggregate cost of abatement. The revenue from these purchases accrues to the representative agent as lump-sum income.

[26] Fixed-factor energy resources are uranium reserves in nuclear electric generation, stream flow in hydroelectricity, arable land area in biomass energy and high-insolation land area in solar power. In 1997 carbon-free technologies accounted for 30.3 percent of net electric generation (U.S. Dept. of Energy: Energy Information Administration, 2000).

[27] The true value of σ_H is unknown. In the simulation it is treated as an uncertain parameter whose value is unity by default, but can range from 0.5 to 2.0.

[28] Because the U.S. is a large closed economy (exports and imports sum to 23 percent of GDP in the SAM) trade is largely inconsequential to the main point of the paper.

4.4 Demand

The representative agent maximizes utility U by allocating vectors of commodity inputs to the final demands consumption, investment and R&D ($\mathbf{g}_d$) subject to their prices ($\tilde{\mathbf{p}}^A$) and the constraint of her income (Z):

$$(7) \quad \max_{\mathbf{g}_d} U(\mathbf{g}_d) \text{ s.t. } \tilde{\mathbf{p}}^A \cdot \sum_d \mathbf{g}_d \leq Z[\mathbf{w} \cdot \mathbf{V}, \tau^A \cdot (\mathbf{p}^A \mathbf{A}), q \cdot \kappa]$$

Income is the measure of welfare in the model. It is composed of factor remuneration ($\mathbf{w} \cdot \mathbf{V}$, where $\mathbf{V}$ is the aggregate factor endowment), commodity tax revenue ($\tau^A \cdot (\mathbf{p}^A \mathbf{A})$, where τ^A net ad-valorem taxes and $\mathbf{p}^A$ is the net-of-tax vector of prices of Armington goods), and the revenue from carbon taxes, or symmetrically, auctioned emissions permits.

The model's second key feature is its demand structure, which is modelled by the nested CES function shown in Figure 4(d). It extends the consumption-savings choice of the final demand system of Ballard et al. (1985) by adding a subsidiary nesting hierarchy that resolves aggregate saving S into tangible (capital) and intangible (R&D) investment. The agent's allocation of income between the components of saving on the basis of their relative costs implicitly defines the function ρ, and provides the mechanism for price-inducement of R&D. The resulting aggregate investment (I) and R&D (R) determine the accumulation of physical and intangible capital stocks. The propensity of the representative agent to invest in R&D is a function of the coefficients on I and R (implied by the SAM) and the elasticity of substitution σ_S between physical investment and R&D.[29] This and other elasticities used in the calibration of U are given in Table 5.

4.5 The Dynamic Process of the Economy

The growth of output, energy use and emissions over time is driven by increases in the supplies of labor, natural resources, physical and intangible capital. The aggregate endowments of labor and natural resources are determined period-by-period by simple supply curves whose price elasticities (η_L and η_F, respectively) are shown in Table 5. In each period the resource thus supplied to each industry acts as a fixed factor, while labor is intersectorally mobile. The accumulation of knowledge assets (i.e., ϖ) is modelled according to the standard perpetual inventory assumption, in a manner identical to capital. In each period, the asset stocks are multiplied by their respective benchmark rates of return to yield the aggregate endowments of capital and knowledge services. The inter-sectoral distributions of both these inputs are determined by the general equilibrium solution in each period, which in the case of intangible services implicitly defines the function ϑ.

[29] The true value of σ_S is unknown. In the simulation it is treated as an uncertain parameter whose value is unity by default, but can range from 0.5 to 2.0.

5 Results and Discussion

5.1 Characteristics of the Business-as-Usual (BaU) Simulation

Over the century of the BaU simulation US GDP grows more than eight times, from 11 to 92 trillion dollars, with the annual rate of growth falling from 4.3 percent to one percent by 2100. At the same time aggregate energy demand and carbon emissions rise much more slowly—by almost five times from 102 to 472 exajoules (EJ), and by a factor of six from 1.5 to 8 gigatons (GT), respectively.[30]

The economy exhibits a declining carbon-intensity that is the net effect of a rising carbon-energy ratio and a falling energy-GDP ratio. The former effect is due to the abundance of coal relative to oil and gas, while the latter is driven by the substitution of capital and knowledge inputs for energy. The fact that the aggregate bias of technical change is energy- and emissions-saving is an important result, demonstrating that modeling technical change through the accumulation and substitution of knowledge can successfully reproduce the observed decline in energy intensity of approximately one percent per year, without heuristic modelling devices such as the autonomous energy efficiency improvement (AEEI).[31]

Nevertheless, in the absence of countervailing forces technological change does not cause a reduction in energy use and carbon emissions. Although the substitution of increasingly abundant inputs of capital and knowledge facilitates reduction in aggregate energy intensity, the expanding endowments of these factors simultaneously make possible a greater-than-proportionate increase of aggregate output, with the result that energy use and emissions rise in absolute terms. Thus, the most effective means of reducing emissions is not to generate new knowledge by increasing R&D, but rather to directly impose limits on the use of fossil fuels.

The capital-output ratio and knowledge-output ratio both rise over the simulation, with knowledge accumulating relative to capital because of the former asset's zero depreciation rate. Even in the absence of policy, the process of accumulation causes relative prices to change, inducing follow-on changes in R&D. However, the magnitude of such changes is limited by the ability of the economy to make use of the expanded endowments that result from accumulation. Figure 5(a) gives an indication of the importance of knowledge in this process, wherein increases in its substitutability in production (larger values of σ_H) result in significantly faster growth of emissions, by as much as 1.8 gigatons in 2100. The sensitivity of emissions to elements of the model that represent ϑ and ϕ shows that the shift in production possibilities as a result of knowledge substitution positively affects output. This effect is even more apparent in the presence of the large relative price movements that result from a tax carbon emissions, to which I now turn.

[30] Over the medium term the model's results exceed official forecasts of GDP, energy use and emissions. In U.S. Dept. of Energy: Energy Information Administration's (2001) reference projection for the year 2020, the economy produces 17 trillion dollars worth of goods and services, uses 131 exajoules of energy and emits 2088 megatons (MT) of carbon. The corresponding figures for the BaU simulation are 23 trillion dollars, 172 EJ and 2754 MT.

[31] The first documented use of the AEEI is Edmonds and Reilly (1985), who cite the historical decline in the energy intensity of GDP with increasing economic development as justification for a declining coefficient on energy input. They create a simulation model with a level of energy-saving technology whose inverse is used to attenuate price-determined demands for fuels. This trick is still applied in state-of-the-art intertemporal CGE models for climate policy analysis (e.g. Bernstein et al., 1999).

5.2 Aggregate Effects of a Carbon Tax in the Presence of ITC

To elucidate the macroeconomic impact of ITC I impose a tax (q_t) of 100 dollars per ton of carbon from the year 2010 onward, and allow the simulation to solve myopically for the cost-minimizing dual emission rate in each period (κ_t). The aggregate impacts of this policy are shown in Figure 5. Figure 5(a) shows that the constant tax generates significant abatement, it only negligibly reduces the slope of the emissions profile over the period 2000-2100. Figure 5(b) shows that the tax incurs an immediate welfare loss of about 0.7 percent of national income, which grows in the near term but quickly saturates to a long-run value of between 1.2 and 1.5 percent. Figure 5(c) shows that the carbon tax reduces R&D, implying that in the aggregate innovation is more sensitive to output than to prices, consistent with prior firm- and industry-level studies. The result is that accumulation and the economy's long-run stock of knowledge decline, as shown in Figure 5(d).

Insight into the effects of ITC can be gleaned from the responses of the aggregate variables in Figure 5 to changes in the elasticities of knowledge creation (σ_S) and substitution (σ_H). The time series of R&D and knowledge in Figures 5(c) and 5(d) are strongly affected by σ_S. The larger the value of this parameter, the more sensitive the balance of investment to the relative prices of I and R, and the more pre-existing taxes on R&D are able to tip this balance against intangibles. Thus, smaller penalties to R&D and knowledge accumulation occur when σ_S is at its lowest value. But these charts show that R and H are also affected by σ_H. The larger the value of this parameter, the more elastic the economy's response to the tax, and the smaller the reduction in both income and the resources for investment. Paradoxically however, if the policy shock causes large reductions in R&D, a high value of σ_H makes producers more vulnerable to the consequent decline in inputs of knowledge. Thus, output, research and knowledge suffer the smallest penalty when σ_H is at its highest value and σ_S is at its lowest value. The consequence of interactions of these accumulation and substitution effects is that over the range of variation in σ_S and σ_H, the welfare losses in Figure 5(b) can change by as much as four percent of their mean value in each period.

These results appear to confirm findings by Goulder and Schneider and Nordhaus that the effect of ITC is small. The influence of σ_H on the time series in Figure 5 indicates that the substitution effect is important, but its welfare implications are not obvious. For clearer insight into the effects of substitution and reallocation of knowledge we must scrutinize the behavior of the economy at the sectoral level.

5.3 Industry-Level Impacts and the Effects of ITC

The cumulative effects of an emissions tax at the industry level can be seen in Figure 6. Figure 6(a) shows that carbon taxes yield abatement of cumulative emissions of 10-15 percent in most industries through reductions in fossil-fuel use. However, much more abatement occurs in oil and gas mining, fossil fuel supply and electricity industries due to the additional effects of reduced output and own-sector purchases. Thus, while most industries experience reductions in cumulative output of less than five percent, the fossil-fuel and electricity supply sectors, especially the carbon-intensive coal industry, suffer precipitous declines (Figure 6(b)).

Industries' changes in cumulative R&D tend to mirror their reductions in output, but the decline in R&D exceeds the fall in output in the more carbon-intensive coal and electricity

sectors and falls short of that in the less carbon-intensive mining and natural gas sectors (Figure 6(c)). In fact, the R&D-output ratio increases slightly across a broad range of industries, including the key construction, machinery and transportation sectors that make up the bulk of aggregate R&D (Figure 6(d)). This result indicates that R&D is being induced, but that prices' indirect negative influence through the reduction in output outweighs their direct positive influence on ρ. Still, the net of these influences produces the positive outcome that both R&D and knowledge services decline by a smaller amount than income at the macro-level.

Industry-level changes in the quantity of knowledge inputs highlight the influence of the substitution effect. Figure 6(e) shows that inputs of knowledge to fall sharply in primary fossil fuel supply sectors and decline slightly in non-energy industries, but *rise* in the electricity sector. The reason is that electric power can be produced using the carbon-free technology, mitigating excess demand for energy without increasing emissions. Thus, in the constrained solution there is reallocation of knowledge to this technology, causing its share of cumulative electric output to expand to 40 percent, from 24 percent in the BaU. Additionally, in Figure 6(f) there is more intensive utilization of knowledge by non-energy sectors that under BaU conditions, indicating that knowledge is substituting for physical inputs. Knowledge is therefore reallocated away from output-constrained fossil-fuel sectors toward input-constrained sectors where its marginal product is greater due to its ability to substitute for limited energy inputs.

5.4 Accumulation, Substitution and Welfare

In light of the substantial inter-sectoral movements of knowledge that occur within the model, it is natural to ask how much of the aggregate welfare change is due to accumulation and how much is due to substitution. To address this question it is useful to think of the change in cumulative income (ΔZ^*) as the sum of three influences: the adverse effect of carbon taxes in the absence of ITC ($\Delta Z^*_{\text{No ITC}}$), the effect of knowledge accumulation ($\Delta Z^*_{\text{Accum}}$) at the aggregate level and the reallocation of knowledge at the sectoral level ($\Delta Z^*_{\text{Alloc}}$). To examine the relative importance of these factors I perform two sets of runs of the model, one in which there is no induced change in knowledge accumulation, and another in which accumulation is turned off and the substitution effect is minimized. In the former, aggregate R&D is constrained to match its BaU trajectory, yielding welfare losses that are equivalent to $\Delta Z^*_{\text{No Accum}} = \Delta Z^*_{\text{No ITC}} + \Delta Z^*_{\text{Alloc}}$. In the latter R&D is fixed as before, and in the presence of carbon taxes σ_H is set to its lowest computationally-feasible value ($\sigma_H = 0.5$, irrespective of its value in the BaU scenario), yielding welfare losses that are equivalent to $\Delta Z^*_{\text{No ITC}}$. These simulations permit the components of ITC to be isolated as follows: $\Delta Z^*_{\text{Accum}} = \Delta Z^* - \Delta Z^*_{\text{No Accum}}$, and $\Delta Z^*_{\text{Alloc}} = \Delta Z^*_{\text{No Accum}} - \Delta Z^*_{\text{No ITC}}$.

The results, shown in Figure 7, illustrate the important role of the knowledge substitution and reallocation in determining the welfare impact of ITC. Figure 7(a) shows that in the absence of ITC the carbon tax inflicts large reductions in welfare, over 80 percent of which are mitigated by the substitution effect, and which are also slightly *exacerbated* by the accumulation effect. Decomposing this result into the changes in cumulative income in the first and second 50-year periods of the simulation horizon, Figure 7(b) shows that during the first 50 years the negative effects of the tax are small, but still outweigh the positive effects

of the substitution effect. During this initial period the stock of knowledge has not had time to accumulate, leading to relatively small endowments of malleable knowledge services that do not facilitate sufficient reallocation to mitigate the deadweight loss of the carbon tax. However, during the later 50 years the tax inflicts much larger deadweight losses, that are balanced by greatly enhanced substitution (Figure 7(c)). This occurs because the onset of stringent abatement (and large shifts in relative prices) coincides with the accumulation of knowledge relative to the early part of the simulation, yielding much larger endowments of intangible services that facilitate more knowledge substitution.

5.5 The Welfare Impacts of R&D Taxes and Subsidies

The final issue that I tackle is the effect of distortions in the market for R&D. Thus far, all of the results reflect the presence of taxes on the components of R&D in the model ($\tau_R = 0.03$), which remain at their benchmark levels throughout the simulations. Goulder and Schneider's finding that ITC's ability to mitigate the cost of a carbon tax is enhanced by phasing out taxes on R&D or instituting modest R&D subsidies raises the question of the welfare impact of such measures in the present setting, where there are no external benefits to R&D.[32] To address this question I perform additional simulations in which pre-existing R&D taxes are first phased out ($\tau_R = 0$) and then replaced by subsidies in which the flow of carbon tax revenue in each period is recycled to R&D ($\tau_R < 0$).

The results, shown in Figure 8, while generally confirming Goulder and Schneider's findings, provide fresh insight into the mechanisms through which they arise. Figures 8(a) and 8(b) show that R&D subsidies lower the cost of performing research, causing both the total quantity of R&D and the rate of knowledge accumulation to increase. These act to reverse the sign of the accumulation effect's contribution to aggregate welfare, enabling it to compensate for carbon tax-induced deadweight losses, as shown in Figure 8(c).

Figure 8(d) shows that the tax revenue streams and their corresponding rates of subsidy are so large that cutting emissions creates a substantial net welfare *gain*. This result, which seems implausible, is an artifact of the model's myopic saving rule.[33] But notwithstanding this caveat, the uniformly positive effect of reducing τ_R emphasizes that the real justification for subsidizing R&D is not the external benefits of research. On the contrary, the rationale for an R&D subsidy is simple and fundamental: to mitigate the effects on research of the fall in output, and thereby sustain the rate of accumulation of a factor whose substitutability lowers the aggregate cost of abatement.[34] Spillovers, by dint of the fact that they multiplica-

[32]This result is an example of the "double dividend" of environmental taxation, the revenue from which is ordinarily recycled to consumers as lump-sum income, but whose diversion to other more productive uses may be welfare-improving. An early survey on the double dividend hypothesis is Goulder (1995), more up-to-date analyses in an environmental context are reviewed by Bovenberg and Goulder (2001). Much of this literature focuses on the use of carbon tax revenue to reduce factor taxes, but the issue here is the long-run effect of channelling it into subsidies for R&D.

[33]Over the period 2010-2100 the revenue generated by carbon taxes results in an R&D subsidy that varies between 12 and 17 percent. An intertemporally optimizing agent, sensitive to the effect of current R&D on future abatement costs, would likely allocate a greater portion of her income (and therefore recycled tax revenue) to research, without requiring the additional stimulus of an R&D subsidy.

[34]Goulder and Schneider (pp. 238-239) recognize this fundamental principle: "In sum, whenever parameters are changed to make stocks of knowledge more important as a productive input, cheaper to acquire, or more easily substitutable with other factors, the GDP costs of attaining a given carbon tax rise and the costs

tively augment each unit of R&D, accentuate the benefit of the subsidy, but are nonetheless ancillary to the main effect of accumulation itself.

6 Conclusion

I conclude by returning to the big picture in Figure 1. The results of the paper elucidate both the mechanisms that drive the feedback loop (II)-(III) and the way in which they are affected by distortions in the market for R&D. The accumulation of knowledge responds negatively to the income effects of a tax on carbon emissions, slightly exacerbating its deadweight loss, while the substitution of knowledge in production responds positively to the relative price effects of the tax, strongly mitigating its deadweight loss. Removing pre-existing taxes on R&D or recycling carbon tax revenues to R&D subsidies reverses the sign of the carbon tax's effect on R&D, augmenting accumulation. However, altering the substitutability of physical and intangible investment or the substitutability of knowledge in production only slightly affect the cumulative aggregate welfare losses of a carbon tax.

The implications of these findings for the design of GHG abatement policies are unclear. Whether to make cuts in emissions now or postpone them to future periods is an intertemporal optimization problem that the present recursive-dynamic model is not designed to solve. Nonetheless, the results raise the possibility that a policy of vigorous abatement in the near-term, by generating substantial additional tax revenue that can be recycled to R&D subsidies, can hasten knowledge accumulation over the entire simulation, resulting in an increase in the endowments of knowledge available for substitution. By contrast, a "wait-and-see" policy only allows recycling of tax or auctioned permit revenue toward the end of the policy horizon, with less of a head-start for rapid accumulation and (perhaps) smaller endowments of knowledge. The critical question is what difference the timing of recycled tax revenues makes for cumulative welfare losses of under the two policy approaches. When abatement is imposed and its associated distortions and tax revenue streams are taken as given, the welfare impact of R&D subsidies depends on the balance between their positive effect on output and the opportunity cost of the revenue itself. Given the preeminent role of knowledge demonstrated here, the relevant tradeoff is between the cumulative discounted benefits of investing the revenue in R&D versus consuming it outright. This is an important issue that deserves further scrutiny.

Abstracting from the specifics of climate change mitigation, these findings indicate that induced technical change plays an important mitigating role in the adjustment of the economy to large-scale policy constraints, but not in the way traditionally thought. Implicit in many descriptions of the process of induced innovation is that constraints somehow induce more research, faster intangible accumulation, and substitution of knowledge for polluting inputs to production. The results of the paper argue that this picture is not generally accurate. Accumulation depends less on the mechanism of price-inducement that on the income effects of the policy, whereas the substitutability of knowledge itself—both for constrained inputs and among production activities—is the most important channel through which induced innovation lowers the costs of adjustment.

of reaching a given abatement target fall." However, their association of ITC with R&D spillovers clouds its deeper implications for their results.

This point impinges not only on the way in which ITC is represented in simulation models for policy evaluation and optimization, but also on the way in which the aggregate behavior of knowledge and the impact of its accumulation are modeled more generally. The treatment of knowledge as industry-specific in character reflects its tacitness. By contrast, the treatment of knowledge as both highly fungible for physical inputs and mobile among producers reflects its general-purpose or analogical character. At the aggregate level, which of these formulations best captures the true behavior of knowledge is an open question with implications that stretch far beyond the present environmental policy focus.

The tension between these views lies in their differing predictions of the allocation of knowledge in response to relative price changes, which is the crux of the induced innovation hypothesis. If knowledge is resistant to codification or transmission outside of the context of its genesis, or is embodied in tangible factors whose short-run supply is limited, then its allocation will be governed by the price system in a manner that is identical to other tangible commodities. Alternatively, if knowledge can be costlessly re-used in different contexts, or combined in different ways so as to be useful in entirely new contexts, then it will not behave according to conventional conceptions of scarcity, and will require something other than price changes to stimulate its movement among producers. The central question raised by this paper, then, is where within these extrema is the allocative mechanism that governs the economy's inventive response to policy shocks. This is an important topic for future research.

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Table 1: Papers on Inducement of Technical Change by Environmental Constraints

Jaffe and Palmer (1997)	$\frac{\partial \log \rho_i}{\partial \log p_D} \approx 0$
Newell et al. (1999); Popp (2002b)	$\frac{\partial \log \varpi_e}{\partial \log R_e} \times \frac{\partial \log \rho_e}{\partial \log p_e} > 0$
Newell et al. (1999)	$\frac{\partial \log \rho}{\partial \log p_e} \approx 0$
Popp (2001)	$\frac{\partial \log p_D}{\partial \log v_D} \times \frac{\partial \log \vartheta}{\partial \log H_e} < 0$

Table 2: Industries in the SAM

1. Agriculture
- Livestock & livestock prod.
- Other agricultural prod.
- Forestry & fishery prod.

2. Mining
- Metallic ores mining
- Nonmetallic minerals mining

3. Crude petroleum & natural gas

4. Construction
- New construction
- Maintenance & repair construction

5. Coal mining

6. Petroleum refining & related prod.

7. Gas prod. & distrib. (utilities)

8. Electric serv. (utilities)

9. Paper & allied prod., ex. containers

10. Chemicals
- Industrial & other chemicals
- Agricultural fertilizers & chemicals
- Plastics & synthetic materials
- Cleaning & toilet preparations
- Paints & allied prod.
- Rubber & misc. plastics prod.

11. Stone, Clay and Glass
- Glass & glass prod.
- Stone & clay prod.

12. Metals
- Primary iron & steel mfg.
- Primary nonferrous metals mfg.
- Metal containers
- Heating, plumbing, & fab. struct. metal prod.
- Screw machine prod. & stampings
- Other fabricated metal prod.

13. Machinery
- Engines & turbines
- Farm, construction, & mining machinery
- Materials handling machinery & equip.
- Metalworking machinery & equip.
- Special industry machinery & equip.
- General industrial machinery & equip.
- Misc. machinery, ex. electrical

14. Equipment
- Service industry machinery
- Electrical industrial equip. & apparatus
- Household appliances
- Electric lighting & wiring equip.
- Audio, video, & communication equip.
- Misc. electrical machinery & supplies
- Ophthalmic & photographic equip.

15. Transportation Equipment
- Motor vehicles (passenger cars & trucks)
- Truck & bus bodies, trailers, & vehic. parts
- Aircraft & parts
- Other transportation equip.

16. Transportation
- Rail & rel. serv., passenger ground transp.
- Motor freight transport & warehousing
- Water transportation
- Air transportation
- Pipelines, freight forwarders, & rel. serv.

17. Manufacturing
- Ordnance & accessories
- Food & kindred prod.
- Tobacco prod.
- Broad & narrow fabrics, yarn & thread mills
- Misc. textile goods & floor coverings
- Apparel
- Misc. fabricated textile prod.
- Lumber & wood prod.
- Furniture & fixtures
- Paperboard containers & boxes
- Newspapers & periodicals
- Other printing & publishing
- Pharmaceuticals
- Footwear, leather, & leather prod.
- Misc. manufacturing

18. Services
- Agricultural, forestry, & fishery serv.
- Communications, ex. radio & TV
- Radio & TV broadcasting
- Water & sanitary serv.
- Wholesale trade
- Retail trade
- Finance
- Insurance
- Real estate & royalties
- Hotels & lodging places
- Personal & repair serv. (ex. auto)
- Other business & prof. serv., ex. medical
- Advertising
- Eating & drinking places
- Automotive repair & service
- Amusements
- Health services
- Federal gov't. indus.; State & local gov't. indus
- General gov't. industry; Household industry

19. Owner-occupied dwellings

Knowledge-intensive industries
- Computer & office equip.
- Electronic components & accessories
- Scientific & controlling instruments
- Comp. & data proc. serv., incl. own-acct. serv.
- Legal, engineering, accounting, & related serv.
- Educ. & social serv., & membership orgs.

Table 3: Investment In and Returns to Knowledge in the SAM

Input-output estimates	$\overline{g}_{iR}{}^{a}$	$\overline{v}_{Hj}{}^{a}$	$\overline{v}_{Hj}/\overline{g}_{jR}{}^{b}$	$\overline{g}_{iR}/\overline{Y}_{i}{}^{b}$	$\overline{v}_{Hj}/\overline{Y}_{j}{}^{b}$	$\sum_{e}\overline{x}_{ej}/\overline{Y}_{j}{}^{b}$
Agriculture	2.1	4.6	218	0.6	1.3	2.6
Mining	0.1	1.7	1180	0.4	4.9	8.5
Oil & gas	0.0	7.5	–	0.0	5.5	5.9
Construction	23.6	211.6	898	1.9	16.8	1.3
Coal	0.5	1.9	408	1.6	6.7	14.3
Petroleum refining	2.6	7.1	273	1.3	3.4	11.4
Natural gas distrib.	1.8	10.6	581	1.4	7.9	20.7
Electric utilities	11.2	22.5	202	3.8	7.8	9.0
Paper products	7.2	3.6	50	5.3	2.6	3.6
Chemicals	21.5	38.5	179	3.7	6.7	3.3
Stone clay & glass	4.5	3.1	69	4.4	3.0	4.7
Metals	40.2	17.2	43	8.3	3.5	3.0
Manufacturing	1.2	9.6	771	0.5	3.8	1.1
Machinery	22.2	137.8	622	4.7	29.4	0.9
Equipment	1.0	102.7	10253	0.2	15.9	0.7
Transportation equip.	16.7	60.1	361	2.6	9.5	4.7
Transportation	33.9	42.3	125	2.4	3.0	1.3
Services	369.7	789.9	214	4.1	8.7	1.2
Dwellings	0.0	9.7	–	0.0	1.3	0.0
Distortions in R&D	$\tau_{R}{}^{a}$			τ_{R}/τ^{b}		
Taxes	17.6	–	–	2.8	–	

[a]Billion 1997 dollars

[b]Percent

Table 4: US Carbon Emissions and Energy Use, 2000[a]

	Carbon Emissions[b]	Primary Energy Demand[c]	Output + Imports - Exports[d]	Carbon Coefficient on Energy $(\theta_e^C)^e$	Energy Coefficient on Output $(\theta_e^E)^f$	Carbon Coefficient on Output $(\theta_e = \theta_e^C \theta_e^E)^g$
Coal	566.3	23.4	23.7	24.2	0.99	23.9
Petroleum	646.3	40.2	233.7	16.1	0.19	3.0
Natural Gas	322.7	23.8	133.6	13.6	0.18	2.4
Electricity	–	15.6	292.3	–	0.05	–
Nuclear	–	8.4	–	–	–	–
Renewables	–	6.8	–	–	–	–
Total	1535.3	118.2	633.1	–	–	–

[a]Emissions are attributed to the sectors whose products are combusted, as opposed to those that transform natural resources into fuels. Carbon released to the atmosphere from fossil fuel mining operations is assumed to be negligible.

[b]Megatons

[c]Exajoules

[d]Billion 1997 dollars

[e]Gigatons per exajoule

[f]Exajoules per billion dollars

[g]Gigatons per billion dollars

Source: U.S. Dept. of Energy: Energy Information Administration (2000) and author's calculations.

Table 5: Supply and Substitution Elasticities

	σ_{KL}	σ_E	σ_A	η_F		σ_{KL}	σ_E	σ_A
Agriculture	0.68	1.45	2.31	0.5	Stone, clay & glass	0.94	1.08	2.74
Mining	0.68	1.45	2.31	1.0	Metals	0.91	1.21	2.74
Oil & gas	0.68	1.45	5.00	1.0	Machinery	0.91	1.21	2.74
Construction	0.95	1.04	1.00	–	Equipment	0.91	1.21	2.74
Coal	0.8	1.08	1.14	2.0	Transportation Equip.	0.8	1.04	1.14
Petroleum	0.74	1.04	2.21	–	Transportation	0.8	1.04	1.00
Natural gas	0.96	1.04	1.00	–	Misc. manufacturing	0.94	1.08	2.74
Electricity	0.81	0.97	1.00	0.5	Services	0.8	1.81	1.00
Paper	0.94	1.08	2.74	–	Dwellings	0.98	1.07	–
Chemicals	0.94	1.08	2.74	–				

$\sigma_{Hj} = 1.0$, $\sigma_{Qj} = 0.7$, $\sigma_{Fj} = 0$, $\sigma_{EMj} = 0.7$, $\sigma_{Mj} = 0.6$, $\sigma_{Tj} = 1.0$, $\sigma_{Aj} = 1.0$ $\forall j$
$\sigma_C = 1.0$, $\sigma_I = 1.0$, $\sigma_R = 1.0$, $\sigma_G = 1.0$, $\sigma_S = 1.0$
$\eta_L = 2.0$
Source: Bovenberg and Goulder (1996), Goulder and Schneider (1999), Dahl and Duggan (1996) and author's assumptions. See Sue Wing (2001).

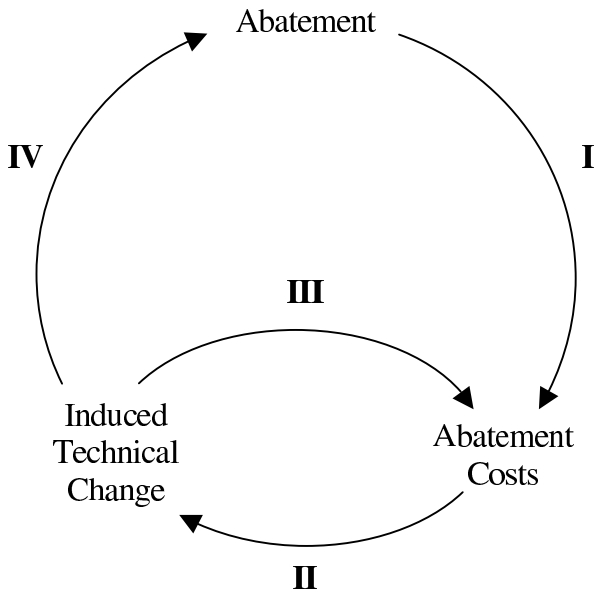
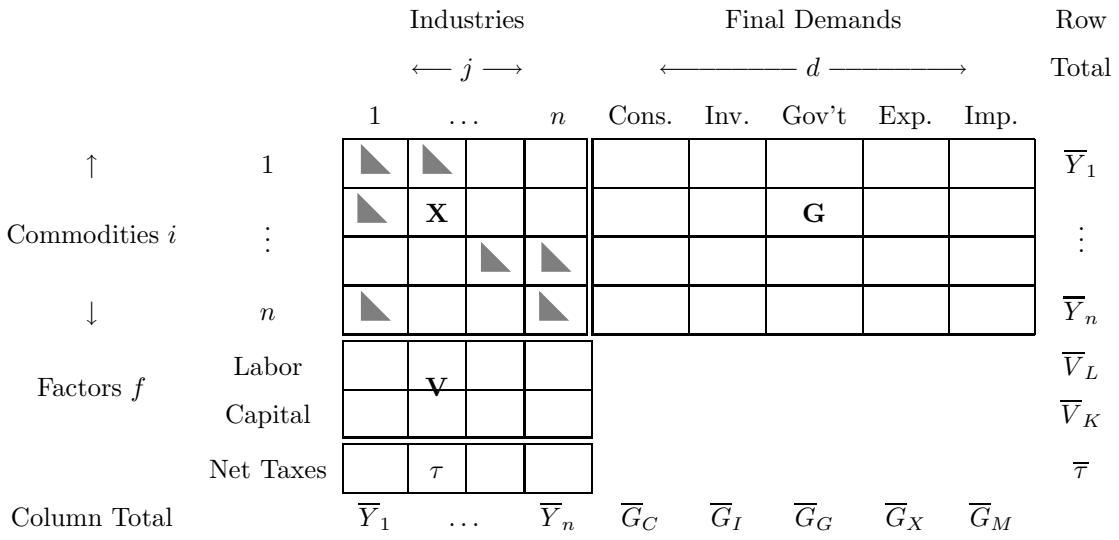


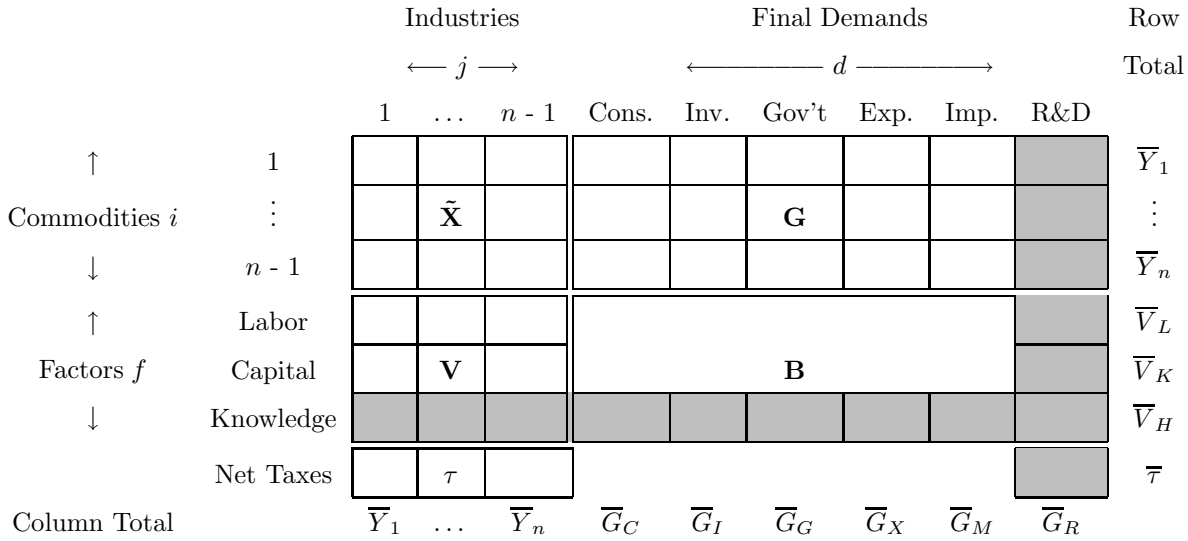
Figure 1: Global Warming and Induced Technical Change



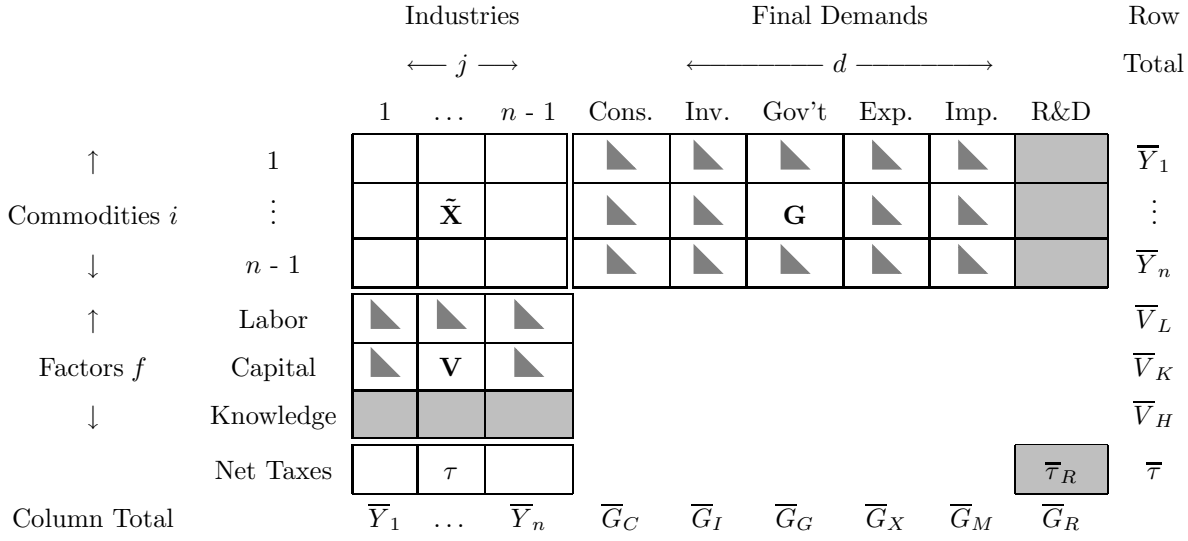
(a) A SAM with embodied knowledge

(b) Concentration of knowledge in a particular industry

Figure 2: Embodiment of Knowledge Within the SAM

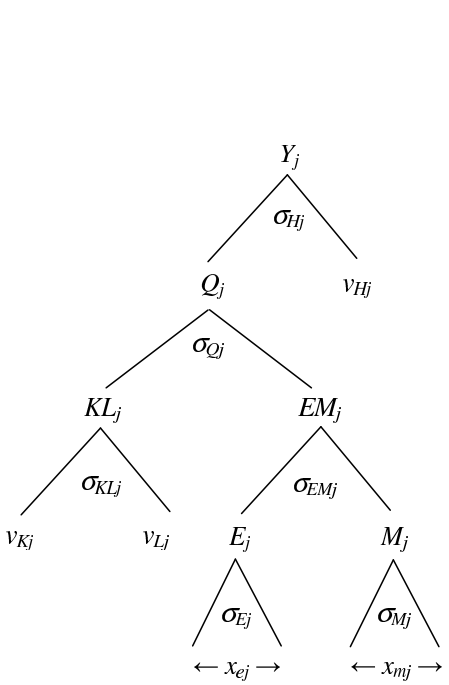


(a) Aggregation of knowledge-intensive industries

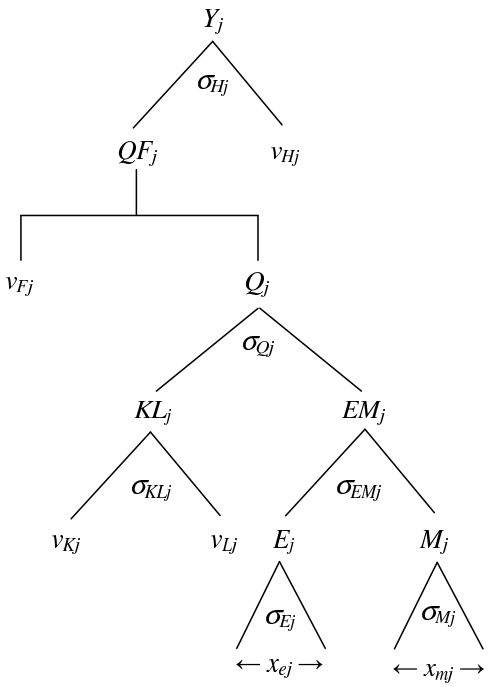


(b) The SAM with explicit knowledge accounting

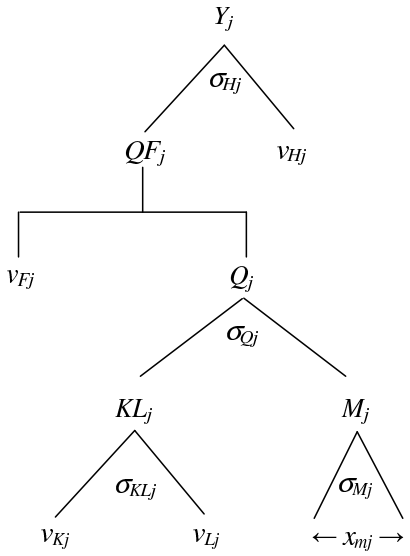
Figure 3: Accounting for Knowledge Within the SAM



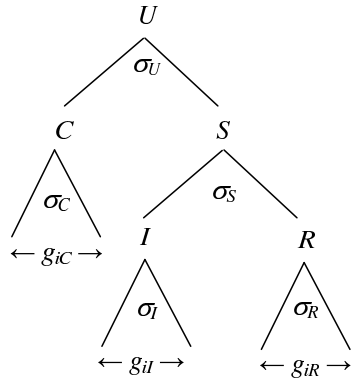
(a) Manufacturing, Services and Carbon-Based Electricity



(b) Natural Resource, Mining and Agriculture Sectors



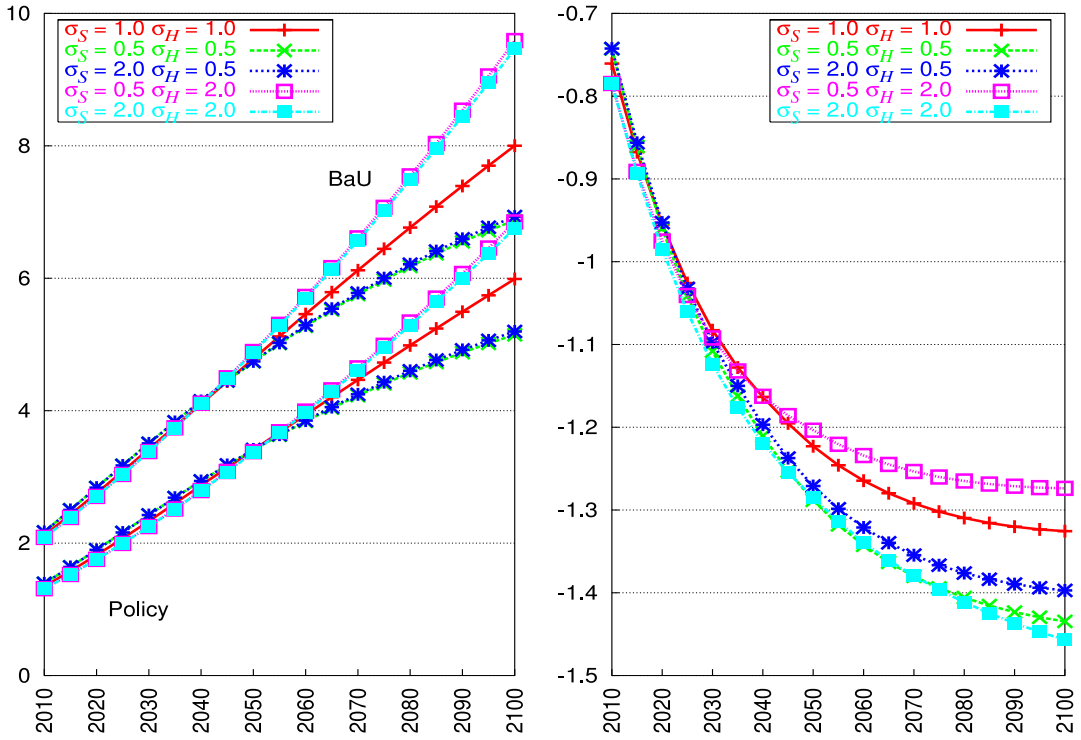
(c) Carbon-Free Electricity



(d) Demand

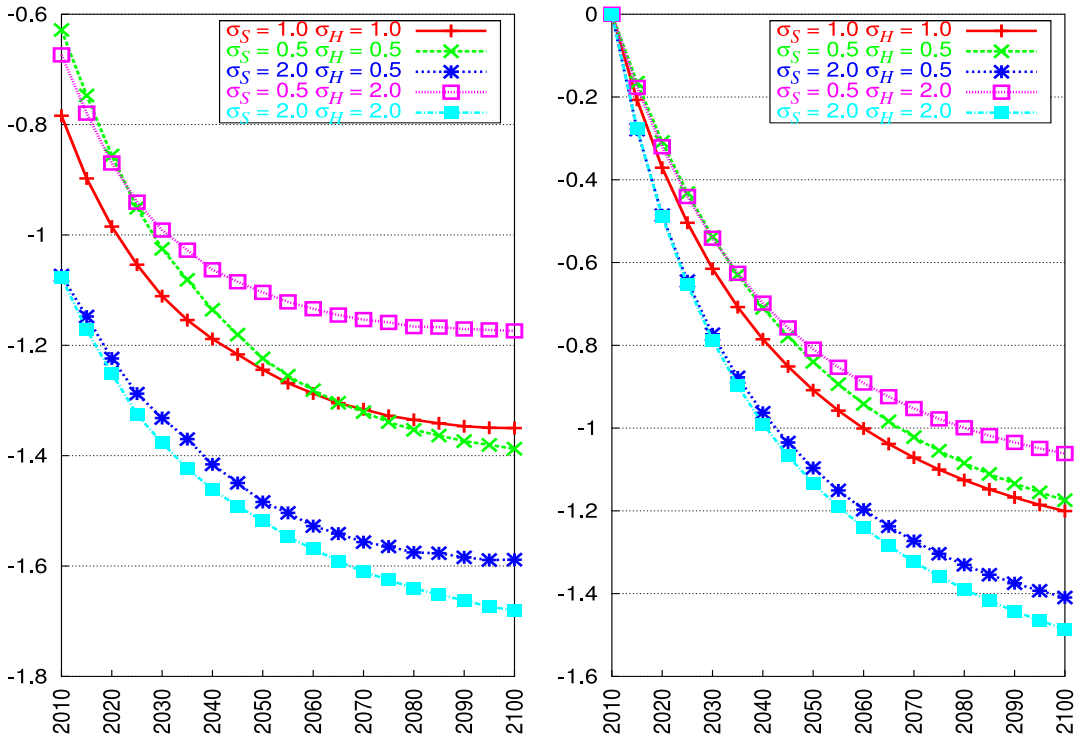
Figure 4: Technologies of Production and Demand[a]

[a]Diagonal connectors represent the relationship between output and the inputs of nested production functions that exhibit positive elasticities of substitution ($\sigma > 0$). Horizontal and vertical connectors (e.g. in (b) and (c)) represent the relationship between output and the inputs in a fixed coefficient (Leontief) production function in which there is no substitution ($\sigma = 0$).



(a) Carbon Emissions (gigatons)

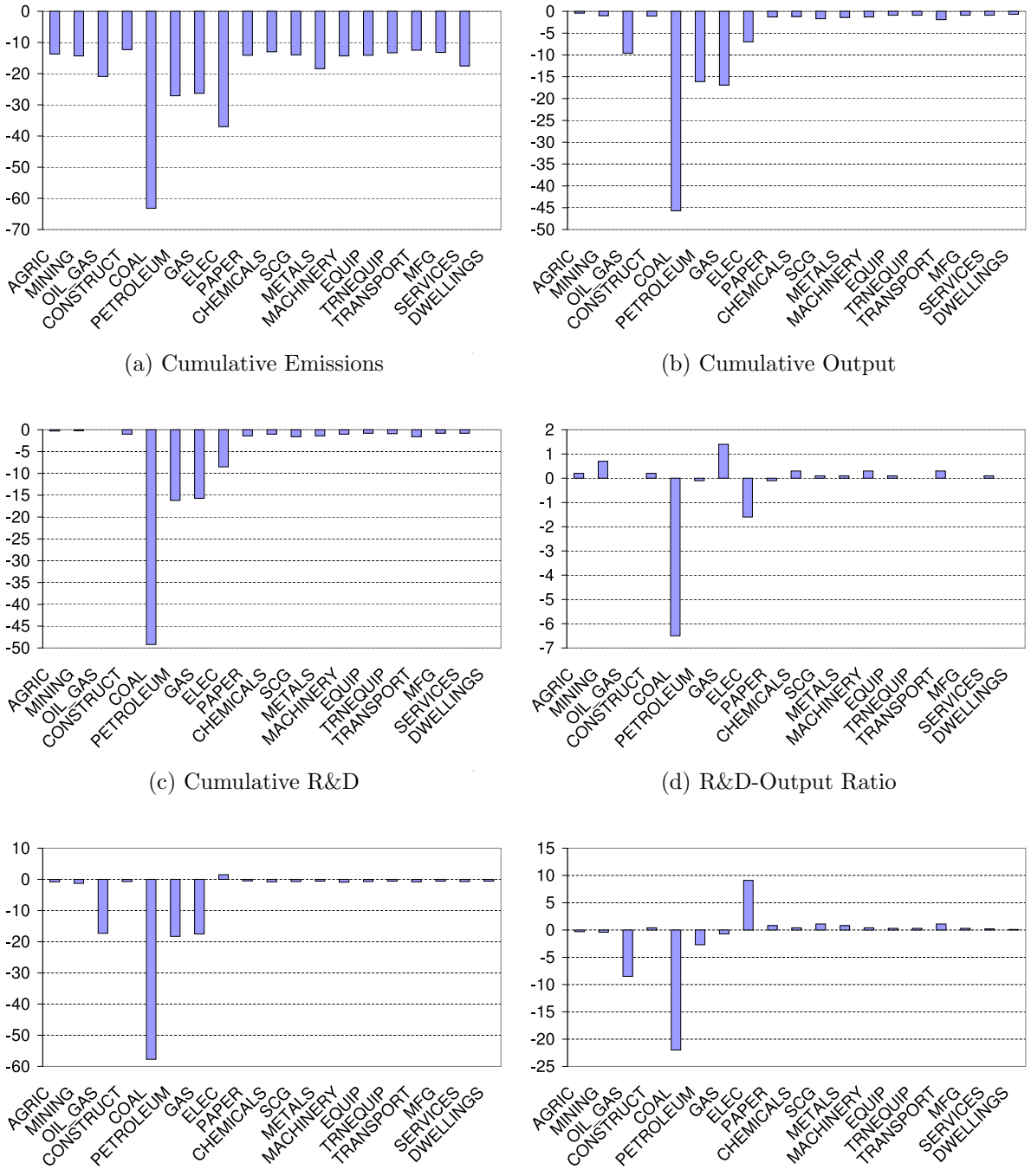
(b) Change in Z from BaU (percent)



(c) Change in R from BaU (percent)

(d) Change in H from BaU (percent)

Figure 5: Aggregate Impacts of a Carbon Tax



(a) Cumulative Emissions

(b) Cumulative Output

(c) Cumulative R&D

(d) R&D-Output Ratio

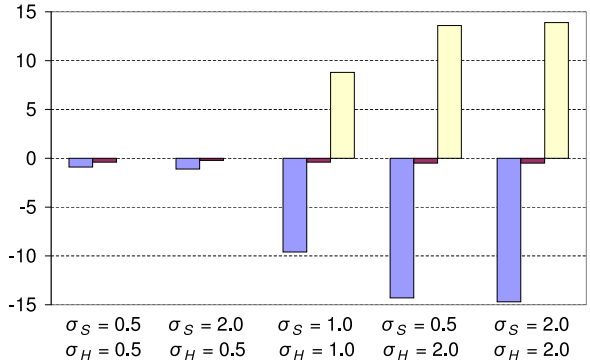
(e) Cumulative Knowledge Input

(f) Knowledge-Output Ratio

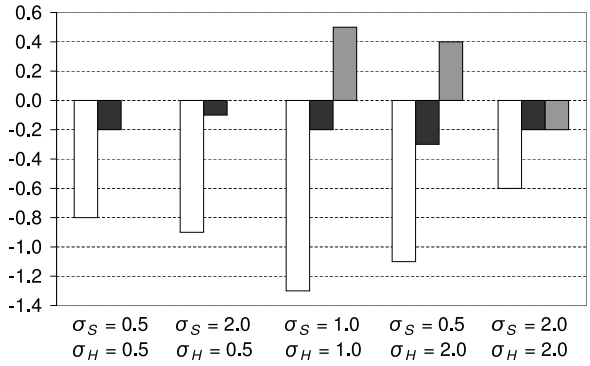
Figure 6: Industry Impacts of a Carbon Tax[a]

[a]Percent change from BaU scenario. Industries are numbered as in Table 2. Impacts shown are for the base case of $\sigma_S = \sigma_H = 1$. The patterns of effects are similar in simulations that use other values of these elasticities.

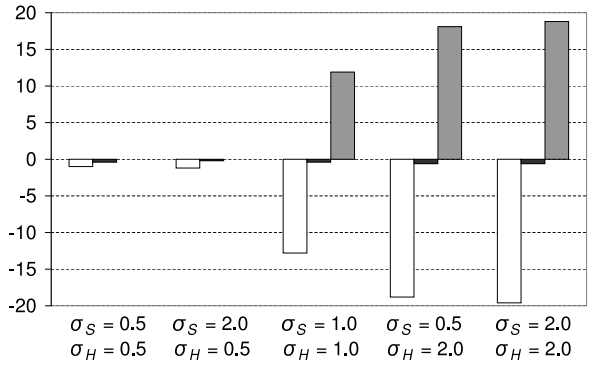
Percent Change from BaU Scenario: □ No ITC ■ Accumulation ▩ Substitution



(a) Change in Cumulative Income

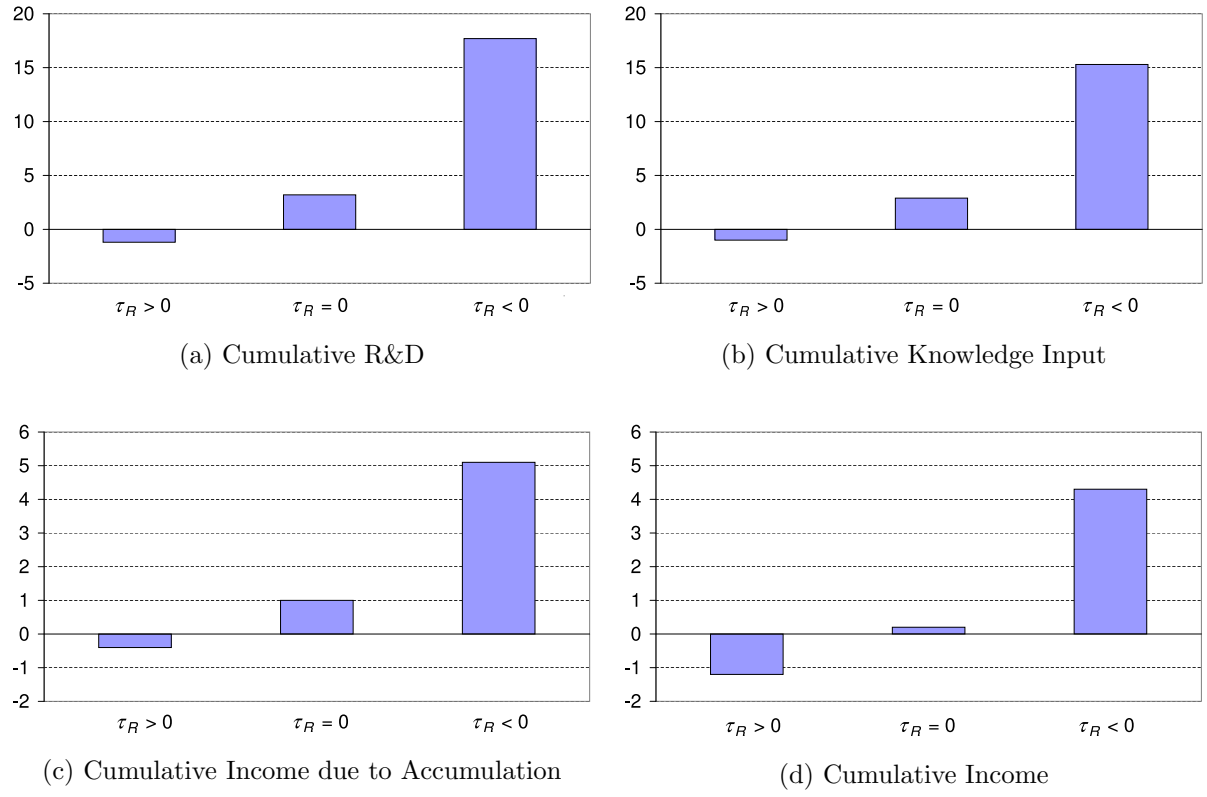


(b) Change in Cumulative Income, 2000-2050



(c) Change in Cumulative Income, 2050-2100

Figure 7: Decomposition of ITC's Welfare Impact



(a) Cumulative R&D

(b) Cumulative Knowledge Input

(c) Cumulative Income due to Accumulation

(d) Cumulative Income

Figure 8: Impacts of R&D Taxes and Subsidies on Accumulation and Welfare[a]

[a]Percent change from BaU scenario. Impacts shown are for the base case of $\sigma_S = \sigma_H = 1$. The patterns of effects are similar in simulations that use other values of these elasticities.

Appendix: The Structure of the Numerical Model

A.1 Nomenclature

Subscripts:

i, j	the set of goods or industries
mfg $(\subset j)$	the set of manufacturing industries
svc $(\subset j)$	the set of service industries
res $(\subset j)$	the set of natural resource industries (agriculture and mining)
cel $(\subset j)$	carbon-based electric power
$ncel$ $(\subset j)$	carbon-free electric power
e $(\subset i)$	the set of energy intermediate goods
m $(\subset i)$	the set of non-energy intermediate goods
f	the set of primary factors (labor, capital, knowledge)

Superscripts:

D	domestic
W	world
A	Armington domestic-import composite

Elasticities of substitution:

σ_{Hj}	between knowledge and physical inputs in sector j
σ_{KLj}	between capital and labor in sector j
σ_{EMj}	between intermediate energy and non-energy goods in sector j
σ_{Ej}	among intermediate energy goods in sector j
σ_{Mj}	among intermediate non-energy goods in sector j
σ_{Ai}	(Armington) between imported and domestically-produced varieties of good i
σ_{Ti}	(transformation) between domestically-produced and exported varieties of good i
σ_U	between consumption and saving (unity)
σ_S	between investment and R&D
σ_C	among sectoral inputs to consumption
σ_I	among sectoral inputs to investment
σ_R	among sectoral inputs to R&D

Supply Elasticities:

η_L	aggregate labor supply
η_{Fj}	natural resources in sector j

Prices:

w_H	price of knowledge services
w_K	price of capital services
w_L	wage
w_{Fj}	price of natural resource in sector j
p_i	producer price in sector i
p_i^D	domestic price of good i
p_i^W	world price of good i
p_i^A	net-of-tax Armington price of good i
$\tilde{p}_i^A$	gross-of-tax Armington price of good i
p_{QFj}	price of intermediate-primary factor-natural resource composite in sector j

p_{Qj} price of intermediate-primary factor composite in sector j
p_{KLj} price of capital-labor composite in sector j
p_{EMj} price of energy-material composite in sector j
p_{Ej} price of energy composite in sector j
p_{Mj} price of material composite in sector j
p_U price of utility
p_C price of aggregate consumption
p_S price of aggregate savings
p_I price of aggregate investment
p_R price of aggregate R&D

Taxes:

τ_i^A net tax rate on supply Armington good i
τ_R net tax rate on aggregate R&D
q tax rate on carbon

Share Parameters:

a_{Hj} knowledge share of output in sector j
a_{Rj} resource share of intermediate-primary factor-natural resource composite in sector j
a_{KLj} capital-labor share of intermediate-primary factor composite in sector j
a_{EMj} energy-materials share of intermediate-primary factor composite in sector j
a_{Kj} capital share of capital-labor composite in sector j
a_{Ej} energy share of energy-materials composite in sector j
a_{ej} share of energy good e in energy composite in sector j
a_{mj} share of non-energy good m in materials composite in sector j
a_{Ti}^D domestic market share of output in sector i
a_{Ai}^D domestic market share of Armington domestic-import composite i

Activity Levels:

Y_j production in sector j
g_{iX} export supply of good i
g_{iM} import demand for good i
A_i supply of Armington good i
D_i supply of domestic good i
x_{ij} demand for intermediate good i in sector j
v_{Lj} demand for labor in sector j
v_{Kj} demand for capital services in sector j
v_{Hj} demand for knowledge services in sector j
v_{Fj} demand for natural resources in sector j
C aggregate consumption
I aggregate investment
R aggregate research and development
S aggregate saving
Z aggregate income of the representative agent

A.2 General Equilibrium in a Complementarity Format[35]

In Arrow-Debreu equilibrium industries make zero profits, excess demand is zero in all markets, and the expenditure of the representative agent exhausts the value of her endowments. The expression of general equilibrium in a complementarity format consists of associating each zero profit condition with a dual activity level and each market clearance condition with a dual price level.[36]

The price of each sector's output is determined by its unit cost function (A-1) that is the dual of ϕ_j. The representative agent equates the value of each unit of consumption, investment or R&D to the value of utility in accordance with her expenditure function (A-2) that is the dual of U. The marginal utility of income p_U is the numéraire price in the model (A-3). Zero profit in the export transformation and import aggregation sectors imply the dual unit cost functions (A-4) and (A-5), respectively. The dual of ζ is the gross-of-carbon-tax price on each energy good (A-6a), which is a linear combination of its Armington price, its carbon intensity and the price of emission permits.

Each sector's activity level represents its supply, which in equilibrium is balanced by the sum of the demands for its output.[37] The demands for commodity imports (A-7) and exports (A-8) are exogenous, and pin down the levels of activity in domestic and Armington composite sectors. These supplies balance the demands for exports (A-9) and Armington commodities (A-10), respectively. The latter is determined by the agent's use of these goods for the purposes of consumption, investment and R&D, as well as industries' activity levels, which determine the demands for intermediate goods (A-11). The sectoral components of aggregate demand for primary factors (A-12)-(A-15) exhaust the endowments of the representative agent in each period. The revenue from factor rentals, auctioned emission permits (A-16) and Armington commodity taxes (A-6) and taxes on R&D make up the agent's income (A-17), out of which the demands for consumption (A-18) and saving (A-19)—and their constituents, investment (A-20), R&D (A-21) and public provision (A-22)—are financed.

The MPSGE software package (Rutherford, 1995; Rutherford, 1999) is used to calibrate the technical coefficients (a) in equations (A-1)-(A-22) based on the SAM constructed in Section 3 and the parameters in Tables 4 and 5. The result is a square system of nonlinear equations that is formulated as a mixed complementarity problem and numerically solved by the PATH solver (Dirkse and Ferris, 1995) for GAMS (Brooke et al., 1998) to yield the equilibrium vectors of prices and activity levels in each period.

Zero Profit Conditions (activity levels):

Unit production cost (Y_j):[38]

$$\text{(A-1a)}\quad p_j = \begin{cases} \left[a_{Hj}\, w_H^{1-\sigma_{Hj}} + (1-a_{Hj})\, p_{Qj}^{1-\sigma_{Hj}}\right]^{\frac{1}{1-\sigma_{Hj}}} & j \in \langle mfg, svc, cel\rangle \\ \left[a_{Hj}\, w_H^{1-\sigma_{Hj}} + (1-a_{Hj})\, p_{QFj}^{1-\sigma_{Hj}}\right]^{\frac{1}{1-\sigma_{Hj}}} & j \in \langle res, ncel\rangle \end{cases}$$

Intermediate-primary factor-natural resource composite:

[35] In this section the time subscripts on prices and activity levels are suppressed for ease of exposition.

[36] For excellent expositions, see Mathiesen (1985) and Böhringer (1998).

[37] By Shephard's Lemma, these are the derivatives of the unit cost functions of the activities that use the output of that particular sector as an input.

[38] Depending on the value of σ_H this is either a Cobb-Douglas or CES cost function.

(A-1b) $p_{QFj} = a_{Fj} w_{Fj} + (1 - a_{Fj}) p_{Qj} \;\; j \in \langle res, ncel \rangle$

Intermediate-primary factor composite:

$$\text{(A-1c)} \;\; p_{Qj} = \begin{cases} \left[a_{KLj}\, p_{KLj}^{1-\sigma_{Qj}} + (1 - a_{KLj})\, p_{Mj}^{1-\sigma_{Qj}} \right]^{\frac{1}{1-\sigma_{Qj}}} & j = ncel \\ \left[a_{KLj}\, p_{KLj}^{1-\sigma_{Qj}} + a_{EMj}\, p_{EMj}^{1-\sigma_{Qj}} \right]^{\frac{1}{1-\sigma_{Qj}}} & \text{otherwise} \end{cases}$$

Sectoral capital-labor composite:

$$\text{(A-1d)} \;\; p_{KLj} = \left[a_{Kj}\, w_K^{1-\sigma_{KLj}} + (1 - a_{Kj})\, w_L^{1-\sigma_{KLj}} \right]^{\frac{1}{1-\sigma_{KLj}}}$$

Sectoral energy-materials composite:

$$\text{(A-1e)} \;\; p_{EMj} = \left[a_{Ej}\, p_{Ej}^{1-\sigma_{EMj}} + (1 - a_{Ej})\, p_{Mj}^{1-\sigma_{EMj}} \right]^{\frac{1}{1-\sigma_{EMj}}}$$

Sectoral energy composite:

$$\text{(A-1f)} \;\; p_{Ej} = \left[\sum_e a_{ej}\, (\tilde{p}_e^A)^{1-\sigma_{Ej}} \right]^{\frac{1}{1-\sigma_{Ej}}}$$

Sectoral materials composite:

$$\text{(A-1g)} \;\; p_{Mj} = \left[\sum_m a_{mj}\, (\tilde{p}_m^A)^{1-\sigma_{Mj}} \right]^{\frac{1}{1-\sigma_{Mj}}}$$

Unit expenditure function (Z):

$$\text{(A-2a)} \;\; p_U = \left(\frac{p_C}{a_C} \right)^{a_C} \left(\frac{p_S}{1 - a_C} \right)^{1-a_C}$$

Aggregate saving (S):

$$\text{(A-2b)} \;\; p_S = \left[a_I\, p_I^{1-\sigma_S} + (1 - a_I)\, ((1 - \tau_R) p_R)^{1-\sigma_S} \right]^{\frac{1}{1-\sigma_S}}$$

Aggregate consumption (C):

$$\text{(A-2c)} \;\; p_C = \prod_i \left(\frac{\tilde{p}_i^A}{a_{iC}} \right)^{a_{iC}} \times \left(\frac{p_G}{a_{GC}} \right)^{a_{GC}}$$

Aggregate investment (I):

$$\text{(A-2d)} \;\; p_I = \prod_i \left(\frac{\tilde{p}_i^A}{a_{iI}} \right)^{a_{iI}} \times \left(\frac{p_G}{a_{GI}} \right)^{a_{GI}}$$

Aggregate R&D (R):

(A-2e) $p_R = \prod_i \left(\frac{\tilde{p}_i^A}{a_{iR}} \right)^{a_{iR}}$

Aggregate public provision (G):

(A-2f) $p_G = \prod_i \left(\frac{\tilde{p}_i^A}{a_{iG}} \right)^{a_{iG}}$

Numeraire:

(A-3) $p_U = 1$

Constant elasticity of transformation domestic-export composite (D_i):

(A-4) $p_i = \left[a_{Ti}^D p_i^{D\,1-\sigma_{Ti}} + (1 - a_{Ti}^D) p_i^{W\,1-\sigma_{Ti}} \right]^{\frac{1}{1-\sigma_{Ti}}}$

Armington domestic-import composite (A_i):

(A-5) $p_i^A = \left[a_{Ai}^D p_i^{D\,1-\sigma_{Ai}} + (1 - a_{Ai}^D) p_i^{W\,1-\sigma_{Ai}} \right]^{\frac{1}{1-\sigma_{Ai}}}$

Definition of gross-of-tax Armington composite price:

(A-6a) $\tilde{p}_e^A = (1 + \tau_e^A) p_e^A + q/\theta_e$

(A-6b) $\tilde{p}_m^A = (1 + \tau_m^A) p_m^A$

Market Clearance Conditions (prices):
Import market (p_i^W):

(A-7) $(1 - a_i^D) A_i \left(\frac{p_i^A}{p_i^W} \right)^{\sigma_{Ai}} = g_{iM}$

Export market (p_i):

(A-8) $(1 - a_{Ti}^D) Y_i \left(\frac{p_i}{p_i^W} \right)^{\sigma_{Ti}} = g_{iX}$

Domestic market (p_i^D):

(A-9) $a_{Ti}^D\, Y_i \left(\frac{p_i}{p_i^D} \right)^{\sigma_{Ti}} = a_{Ai}^D\, A_i \left(\frac{p_i^A}{p_i^D} \right)^{\sigma_{Ai}}$

Armington domestic-import composite market (p_i^A):

(A-10) $A_i = a_{iC}\, C \left(\frac{p_C}{\tilde{p}_i^A} \right)^{\sigma_C} + a_{iI}\, I \left(\frac{p_I}{\tilde{p}_i^A} \right)^{\sigma_I} + a_{iR}\, R \left(\frac{p_R}{\tilde{p}_i^A} \right)^{\sigma_R} + \sum_j x_{ij}$

Definition of Intermediate use of Armington goods:

(A-11a)

$$x_{ej} = \begin{cases} \Big[a_{ej}\, a_{Ej}\, a_{EMj}\, (1-a_{Hj})\, Y_j\, p_j^{\sigma_{Hj}}\, p_{Qj}^{(\sigma_{Qj}-\sigma_{Hj})}\, p_{EMj}^{(\sigma_{EMj}-\sigma_{Qj})} \times \\ \qquad p_E^{(\sigma_{Ej}-\sigma_{EMj})}\, (\tilde{p}_e^A)^{-\sigma_{Ej}}\Big] & j \in \langle mfg, svc, cel\rangle \\ \Big[a_{ej}\, a_{Ej}\, a_{EMj}\, (1-a_{Fj})\, (1-a_{Hj})\, Y_j\, p_j^{\sigma_{Hj}}\, p_{Qj}^{(\sigma_{Qj}-\sigma_{Hj})} \times \\ \qquad p_{EMj}^{(\sigma_{EMj}-\sigma_{Qj})}\, p_E^{(\sigma_{Ej}-\sigma_{EMj})}\, (\tilde{p}_e^A)^{-\sigma_{Ej}}\Big] & j \in \langle res\rangle \end{cases}$$

(A-11b)

$$x_{mj} = \begin{cases} \Big[a_{mj}\, a_{Mj}\, a_{EMj}\, (1-a_{Hj})\, Y_j\, p_j^{\sigma_{Hj}}\, p_{Qj}^{(\sigma_{Qj}-\sigma_{Hj})}\, p_{EMj}^{(\sigma_{EMj}-\sigma_{Qj})} \times \\ \qquad p_M^{(\sigma_{Mj}-\sigma_{EMj})}\, (\tilde{p}_m^A)^{-\sigma_{Mj}}\Big] & j \in \langle mfg, svc, cel\rangle \\ \Big[a_{mj}\, a_{Mj}\, a_{EMj}\, (1-a_{Fj})\, (1-a_{Hj})\, Y_j\, p_j^{\sigma_{Hj}}\, p_{Qj}^{(\sigma_{Qj}-\sigma_{Hj})} \times \\ \qquad p_{EMj}^{(\sigma_{EMj}-\sigma_{Qj})}\, p_M^{(\sigma_{Mj}-\sigma_{EMj})}\, (\tilde{p}_m^A)^{-\sigma_{Mj}}\Big] & j \in \langle res\rangle \end{cases}$$

Labor market (w_L):

(A-12)

$$v_{Lj} = \begin{cases} (1-a_{Kj})\, a_{KLj}\, (1-a_{Hj})\, Y_j\, p_j^{\sigma_{Hj}}\, p_{Qj}^{(\sigma_{Qj}-\sigma_{Hj})}\, p_{KLj}^{(\sigma_{KLj}-\sigma_{Qj})}\, w_L^{-\sigma_{KLj}} & j \in \langle mfg, svc, cel\rangle \\ (1-a_{Kj})\, a_{KLj}\, (1-a_{Fj})\, (1-a_{Hj})\, Y_j \times \\ \qquad \left(\frac{p_j}{p_{QFj}}\right)^{\sigma_{Hj}}\, p_{Qj}^{(\sigma_{Qj}-\sigma_{Hj})}\, p_{KLj}^{(\sigma_{KLj}-\sigma_{Qj})}\, w_L^{-\sigma_{KLj}} & j \in \langle res, ncel\rangle \end{cases}$$

Capital input market (w_K):

(A-13) $$v_{Kj} = \begin{cases} a_{Kj}\, a_{KLj}\, (1-a_{Hj})\, Y_j\, p_j^{\sigma_{Hj}}\, p_{Qj}^{(\sigma_{Qj}-\sigma_{Hj})}\, p_{KLj}^{(\sigma_{KLj}-\sigma_{Qj})}\, w_K^{-\sigma_{KLj}} & j \in \langle mfg, svc, cel\rangle \\ a_{Kj}\, a_{KLj}\, (1-a_{Fj})\, (1-a_{Hj})\, Y_j \times \\ \qquad \left(\frac{p_j}{p_{QFj}}\right)^{\sigma_{Hj}}\, p_{Qj}^{(\sigma_{Qj}-\sigma_{Hj})}\, p_{KLj}^{(\sigma_{KLj}-\sigma_{Qj})}\, w_K^{-\sigma_{KLj}} & j \in \langle res, ncel\rangle \end{cases}$$

Knowledge input market (w_H):

(A-14) $$v_{Hj} = a_{Hj}\, Y_j\, \left(\frac{p_j}{w_H}\right)^{\sigma_{Hj}}$$

Resource input market (w_{Fj}):

(A-15) $$v_{Fj} = a_{Fj}\, (1-a_{Hj})\, Y_j\, \left(\frac{p_j}{p_{QFj}}\right)^{\sigma_{Hj}}$$

Aggregate emissions constraint (q):

(A-16) $$\kappa \geq \sum_e \theta_e A_e$$

Income of the representative agent (p_U):

(A-17) $Z = w_L \sum_j v_{Lj} + w_K \sum_j v_{Kj} + w_H \sum_j v_{Hj} + \sum_j w_{Fj} v_{Fj} + \sum_j \tau_j^A p_j^A A_j + \tau_R p_R R + q\kappa$

Consumption good market (p_C):

(A-18) $C = a_C Z \left(\frac{p_U}{p_C} \right)$

Savings good market (p_S):

(A-19) $S = (1 - a_C) Z \left(\frac{p_U}{p_S} \right)$

Investment good market (p_I):

(A-20) $I = a_I S \left(\frac{p_S}{p_I} \right)^{\sigma_S}$

R&D good market (p_R):

(A-21) $R = (1 - a_I) S \left(\frac{p_S}{p_R} \right)^{\sigma_S}$

Public provision market (p_G):

(A-22) $G = a_{GC} C \left(\frac{p_C}{p_G} \right) + a_{GI} C \left(\frac{p_I}{p_G} \right)$

A.3 The Dynamic Process of the Economy

The static equilibrium model is embedded within a dynamic process that is responsible for updating both the endowments of labor, natural resources, physical and intangible capital, and the import supply and export demand. Labor and natural resource endowments are determined by the iso-elastic supply curves (A-23) and (A-24), respectively. Capital and knowledge assets accumulate according to standard perpetual inventory equations (A-25) and (A-26), respectively, and are multiplied by their respective benchmark rates of return to determine the each period's endowments of capital and knowledge services, (A-27) and (A-28). Finally, the supply of imports and the demand for exports in each industry are constrained by equations (A-29) and (A-30) to be the same proportions of Armington supply throughout the simulation as in the SAM.

Quasi-variable factor supplies:

(A-23) $\sum_j v_{Ljt} = \overline{V}_L \left(p_{Lt} \right)^{\eta_L}$

(A-24) $v_{Fjt} = \overline{v}_{Fj} \left(w_{Fjt} \right)^{\eta_{Fj}} \quad j \in res$

Stock accumulation:

(A-25) $K_{t+1} = I_t + (1 - \delta_K)K_t$

(A-26) $H_{t+1} = R_t + (1 - \delta_H)H_t$

Service flows:

(A-27) $\sum_j v_{Kjt} = (r_K + \delta_K)K_t$

(A-28) $\sum_j v_{Hjt} = (r_H + \delta_H)H_t$

Trade (constant sectoral import and export shares):

(A-29) $g_{iMt} = \overline{g}_{iM}\, A_{it}/\overline{A}_i$

(A-30) $g_{iXt} = \overline{g}_{iX}\, A_{it}/\overline{A}_i$

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