MIT Joint Program on the Science and Policy of Global Change

Technology and Technical Change in the MIT EPPA Model

Henry D. Jacoby, John M. Reilly, James R. McFarland and Sergey Paltsev

Report No. 111

July 2004

The MIT Joint Program on the Science and Policy of Global Change is an organization for research, independent policy analysis, and public education in global environmental change. It seeks to provide leadership in understanding scientific, economic, and ecological aspects of this difficult issue, and combining them into policy assessments that serve the needs of ongoing national and international discussions. To this end, the Program brings together an interdisciplinary group from two established research centers at MIT: the Center for Global Change Science (CGCS) and the Center for Energy and Environmental Policy Research (CEEPR). These two centers bridge many key areas of the needed intellectual work, and additional essential areas are covered by other MIT departments, by collaboration with the Ecosystems Center of the Marine Biology Laboratory (MBL) at Woods Hole, and by short- and long-term visitors to the Program. The Program involves sponsorship and active participation by industry, government, and non-profit organizations.

To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

Henry D. Jacoby and Ronald G. Prinn,
Program Co-Directors

For more information, please contact the Joint Program Office

Postal Address: Joint Program on the Science and Policy of Global Change
77 Massachusetts Avenue
MIT E40-428
Cambridge MA 02139-4307 (USA)

Location: One Amherst Street, Cambridge
Building E40, Room 428
Massachusetts Institute of Technology

Access: Phone: (617) 253-7492
Fax: (617) 253-9845
E-mail: globalchange@mit.edu
Web site: http://MIT.EDU/globalchange/

♻ ***Printed on recycled paper***

Technology and Technical Change in the MIT EPPA Model[*]

Henry D. Jacoby, John M. Reilly, James R. McFarland and Sergey Paltsev

Abstract

Potential technology change has a strong influence on projections of greenhouse gas emissions and costs of control, and computable general equilibrium (CGE) models are a common device for studying these phenomena. Using the MIT Emissions Prediction and Policy Analysis (EPPA) model as an example, two ways of representing technology in these models are discussed: the sector-level description of production possibilities founded on social accounting matrices and elasticity estimates, and sub-models of specific supply or end-use devices based on engineering-process data. A distinction is made between exogenous and endogenous technical change, and it is shown how, because of model structure and the origin of key parameters, such models naturally include shifts in production process that reflect some degree of endogenous technical change. As a result, the introduction of explicit endogenous relations should be approached with caution, to avoid double counting.

Contents

1. INTRODUCTION

Technical change is among the most important and least well-understood influences on greenhouse gas emissions and the costs of their control. Yet we cannot come close to predicting the specific details and costs of the alternative technology options that will be available in the distant future. Instead, in order to avoid ignoring altogether the possibility that new options will be developed, the modeling community has frequently resorted to including a "carbon-free backstop technology," assumed to be available at some future time at an imagined cost and at large scale. Though often necessary, this approach is unsatisfying because it leaves open a

---

[*] Prepared for the Principal Investigators Workshop, US DOE Integrated Assessment Program, Snowmass, Colorado, 5-6 August 2003.

number of troubling questions: Does the technology rely on a resource available in limited quantity or variable quality? Does it create other environmental problems? Can it be used equally as a transportation fuel, in residential heating, or to generate electricity? What is the likelihood of the option being available as assumed: One chance in two? One in 20?

Dissatisfaction with the generic backstop thus leads to calls for greater detail in describing new technologies and their evolution over time. But concern then properly expands to include the full range of alternatives, for what matters in the end is their cost and characteristics relative to each other. For example, one may look forward to technological improvement in a low emitting technology and foresee a time when it will be less costly than fossil alternatives. But such an assessment should not ignore the potential for technological change in the production and use of fossil fuels. They are a moving target. Other possible errors in the specification of future alternatives include imagining a "competitive" energy supply but failing to consider supporting technologies needed to utilize it, or celebrating a clean end-use technology while failing to credit its energy carrier with emissions upstream. Given these difficulties in predicting scientific and technical advance and the market viability of potential future options, the modeling community is well advised to set modest goals for this aspect of climate policy studies, and maintain a focus on uncertainty in studies of future developments.

Here we explore these issues in the context of a particular application: the MIT Emissions Prediction and Policy Analysis (EPPA) model. This model has been designed to serve several functions in climate change studies, and to one degree or another the behavior of its modeled technologies is relevant to all. First, the EPPA model is a component of the MIT Integrated Global System Model (Prinn *et al.*, 1999). In this role it is used to simulate emissions over a century horizon in the absence of climate policy. In these studies (*e.g.*, Webster *et al.*, 2002, 2003) technology and technical change influence emissions growth and thus affect the magnitude of human influence on the climate system.

The model also serves as a facility for analyzing the national costs of proposed emissions control policies, both for the near term of a decade or so but also for studies of the stabilization of atmospheric greenhouse gases (GHGs) in the long term. Here the influence of current technology and technical change depends on the application. The representation of current technology is naturally very important for analysis of specific control measures in the short run, like Kyoto Protocol-type emissions restrictions. Technology change, on the other hand, plays a small role in these short-run analyses because of the long lag times for development and implementation. Also, assessment of the desired level of policy stringency today may be only slightly affected by assumptions about technological availability in 2020, 2050, or beyond (Nordhaus and Boyer, 2000; Webster, 2002). The insensitivity of current effort to forecast future technology results from the fact that we can adjust in the future as knowledge improves. For example, a GHG pricing policy may spur innovation, and if so it is likely to be desirable to strive for an even more ambitious target, because cost is lower than we thought. On the other hand, innovation may not respond to incentives, and then we may need to reconsider our earlier weighing of the benefits and costs of an ambitious long-term target. In either case, these are adjustments we can make year by year, as we see how technology actually responds. In contrast, studies of the national or regional costs of long-term stabilization, based on fixed emissions control paths over time, are sensitive both to the representation of current technology and to assumptions about future technological change. Finally, the model also is used to study the prospects for particular energy use devices or sources of energy supply, such as improvements in automotive vehicle design (Schafer and Jacoby, 2004) or electric generation with carbon capture and storage (McFarland *et al.*, 2004). The technology description of the specific option is naturally of crucial importance to the result.

In each of these applications of the model, therefore, it is important to keep track of the particular question at hand and ways that current technology and future technical change may influence it.

Like all models of complex systems, EPPA reflects a number of compromises—among details of economic sectors and their technologies, levels of complexity in mathematical specification, and computational feasibility. It is an evolving structure, capable of incorporating new insights and empirical results regarding technical change as they are produced by studies dedicated to specific technologies and factors influencing change. Here we describe the ways that technology and technical change are represented in the current version of this model, highlighting areas of application where ongoing research may make the greatest contribution to improvements in policy assessment.

We begin in Section 2 with a brief review of the ways that technology and technology change are represented economic models. The main focus is on computable general equilibrium (CGE) models, of which EPPA is an instance. Two different types of technology representations are found in these models: sector-level descriptions of production possibilities, and models of specific supply or end-use devices. Section 3 introduces the economic production and emissions components of the model at the sector level, along with a description of the way that capital structure and vintaging intersect with the technology specification. Section 4 considers technical change, still with a focus on sector-level production, and the exogenous and endogenous mechanisms of change that are built into the EPPA model. Section 5 then turns to the handling of particular supply sources, based on bottom-up engineering process descriptions. These options produce substitutes for some of the energy products that are modeled at the sector level. The way these options are modeled is described, along with two issues that arise when they are implemented in aggregate models. First is quality of output. While the product of a new device or design may be superficially similar to that of an existing one, there may be important differences that make it an imperfect substitute. Second is the issue of market penetration, which involves a complex interaction of adjustment costs and potential learning by doing. Models can allow unrealistically rapid penetration of a new option if they fail to account for the costs of scaling up a new industry or quickly displacing existing capital stock. Also, the costs of modeled alternatives that are not now economic may be mis-specified if the effects of experience and associated R&D are ignored.

Finally, in Section 6 we draw together a list of the key challenges to understanding of technology in climate policy, and opportunities for research to improve its representation in CGE-type models.

2. TECHNOLOGY REPRESENTATION IN CGE MODELS

In most models applied to analysis of greenhouse gas emissions, "technology" is implemented as an economic production function, specifying the quantities of various inputs that are required to produce a unit of a particular output. Because different forms of analysis are applied to this issue, however, different interpretations attach to this deceptively transparent concept.[1] The fundamental building block of technology description is the particular production process, described in terms of fixed proportions of factor inputs (labor, capital, energy, materials, *etc*.) required to produce a unit of a particular output—what is referred to as a Leontief technology. Two examples are a gasoline-powered car and a gas-electric hybrid car producing the same transportation services. In a Leontief sense these may be classified as different technologies, and a shift from one to another described as a technology change. Many models of specific economic sectors, like energy, are based on collections of functions of this form—an example being engineering process models like MARKAL (*e.g.*, Kypreos, 1996).

However, for analysis of the forces driving GHG emissions there is need to consider not only energy supply and its emissions but also factors influencing demand, and the origins of a number of other climate-relevant emissions. Moreover, such analysis needs to include a number of countries or regions linked by international trade. Maintenance of a high level of technology detail is not possible; some compromise is necessary and CGE-type models are one approach to the task. Production activities of like characteristics are aggregated into sectors (*e.g.*, agriculture, transport, services, electric supply) with the production function—*i.e.*, the technology—represented at this aggregate level. Of course, at the sectoral level there are many ways (Leontief processes) to produce the sector output, the precise mix of factor inputs being determined by relative prices. A function used to describe these sector-level production possibilities can be thought of as the envelope of processes at the more detailed level of specification. Thus substitution among inputs at the aggregate level (perhaps driven by changes in relative prices) may be within the definition of a single technology at the aggregate level but still be seen as a shift in technology by observers thinking at a detailed engineering-process level. In the discussion below, the term "technology" is used in the aggregate production function sense, with

---

[1] For a detailed discussion of the issues involved, see Sue Wing (2003).

the description “Leontief technology” applied when a fixed-coefficient engineering-process concept is implied.

Next is the issue of what is meant by “new” technology, or technology “change.” In a CGE model, a function describing “current” technology would allow only those factor combinations that are feasible with current knowledge, under different combinations of relative prices. To stretch the example above, personal transport might be provided by a gasoline car, a gas-electric hybrid, or a horse and buggy—all alternatives available today at some set of relative input prices and thus all contained within current technology. “New” technology, then, encompasses production possibilities not now available at any reasonable set of relative input prices. Thus, fossil, hydroelectric, nuclear and conventional wind power are all contained within current technology, whereas fusion or a radically different wind power design represent new technology—implying, as they do, a different aggregate production function for the electric sector. If an aggregate production function is narrowly defined to represent only current possibilities, then, technology change involves a modification of the function’s form—either allowing a decrease in cost at constant factor prices, and/or opening-up wider substitution possibilities that could be exploited with a change in input prices (Binswager, 1978). As will be seen below, the functions actually implemented in CGE models may encompass a mix of current and new possibilities.

2.1 CGE Model Structure and Estimation

CGE models represent the circular flow of goods and service in an economy.[2] Factor inputs are supplied to the producing sectors, which in turn apply them to the provision of goods and services to one another and to final consumers. Following the definitions above, the sub-models of the production sectors thus attempt to represent the output possibilities available to an economy—describing how factor inputs are transformed into the various intermediate goods, and ultimately into products and services that satisfy the wants and needs of consumers. The circular flow of products and resources is completed when the consumers supply needed inputs of labor, capital, and resources (which they own, directly or indirectly) to the production process. This same circular flow can be seen in the economy’s financial system. Consumers receive payments for the factor services they supply, and they use this income to pay the producing sectors for the goods and services they receive. The model computes the market-clearing prices of all produced goods and services and of the input factors. Thus the prices of goods reflect the costs of the factor inputs (wages, the return to capital, and payments to natural resources) and the cost of intermediate inputs purchased from other producing sectors. The model steps forward in time (or solves multiple periods simultaneously in a forward-looking formulation) driven by population and productivity change, capital investment, resource depletion, and external policy influences.

---

[2] This description focuses on the handling of technology. For a description of other features, see Babiker *et al.* (2001).

Such a model starts from a base-year description of real and financial flows in the economy in the form of a Social Accounting Matrix or SAM. A simplified version of a SAM is shown in **Figure 1**. The production side of the economy is aggregated into a set of sectors, each of which usually produces a single aggregated good or commodity. Looking along a row in Figure 1, the amount of a good or commodity that is produced must be sufficient to serve the sum of demands from other producing sectors plus the final demands of government, investment, consumer use, and exports (minus imports). Viewing down a column, the amount of the good produced by an industry is just exhausted in the payments to its inputs, plus taxes. Taking agriculture as an example, these payments include the goods and services needed from other sectors (*e.g.*, equipment, chemicals, energy) plus the payments for capital services, labor, resources (*i.e.*, land) and taxes.

The data in the input-output matrix, **X** in the figure, thus represents the technology in use in the base or benchmark year, telling the amounts of various inputs that were then applied to produce a unit of each sector's output. It is, in effect, a Leontief-type representation at the sector level, showing as it does one set of factor portions for each modeled output. As such it is a "snapshot" of the economy as it was in the base year with its particular relative prices. Even with current technology these factor proportions could change with changes in relative input prices, tax rates, or a CO_2 emissions penalty. To simulate the future, a set of sectoral production functions is constructed for which the data in the SAM represent only a single static point. These functions reflect the relative ease of substitution among the required inputs, which in turn will determine how the production structure will change under variation in relative prices. The EPPA model applies a constant elasticity of substitution (CES) functional form for this purpose.

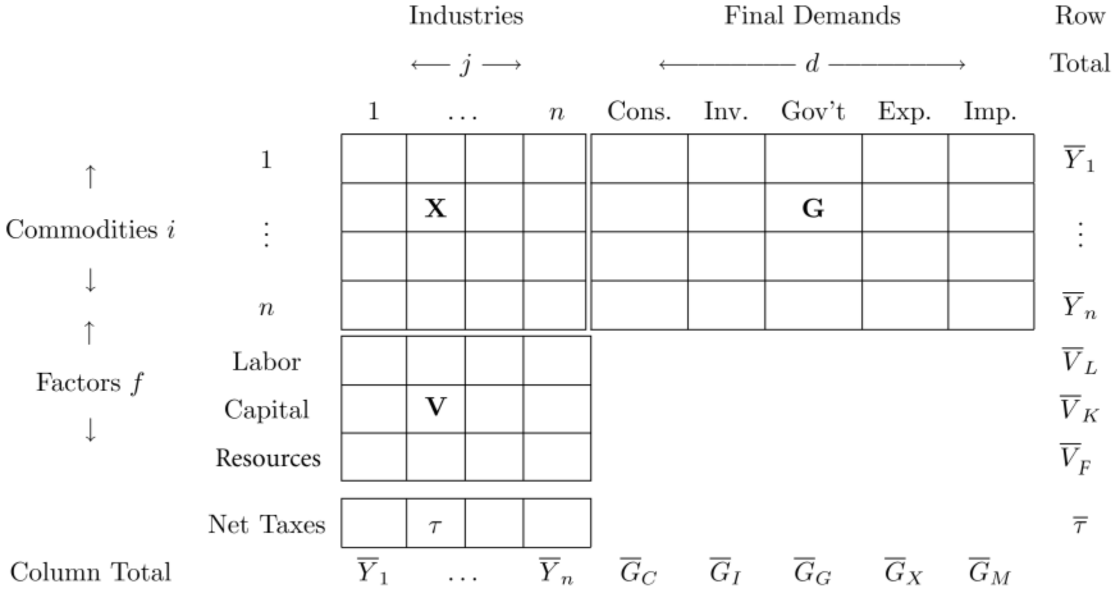

Figure 1. Social Accounting Matrix (SAM). [Adapted from Sue Wing (2001).]

To take as an example good Y produced by inputs of labor (L) and capital (K), the CES relation is

$$Y = \left(a_L L^{\rho_{LK}} + a_K K^{\rho_{LK}}\right)^{\frac{1}{\rho_{LK}}} \tag{1}$$

where the parameter ρ_{LK} is related to an elasticity, σ, commonly used to express the ease of substitution between input factors:

$$\sigma_{LK} = \frac{1}{1-\rho_{LK}}. \tag{2}$$

The factor shares in such a formulation (a_L and a_K in Eq. 1) are computed from data in the SAM.[3]

In multi-sector models each sector will have inputs not only of capital and labor but also of resources and intermediate goods, including the sector's own product (*e.g.*, steel used in chemical manufacture, if both are included in an aggregated sector). Because the same degree of substitution does not apply to all the input factors, the relation usually is specified by a nest of CES functions (as will be seen below) with appropriate elasticity estimates, still with factor shares derived from the SAM.

2.2 Technology Parameters in Aggregate Production Sectors

In a CGE model, then, these elasticity estimates (along with factor shares derived from the SAM) are the parameters describing the technology for each sector. They are estimated based on empirical studies of past economic performance, limits of physical laws and rules of economic consistency, and expert judgment. Because the models are used to analyze issues with different time horizons—as seen in the EPPA applications above—the estimates may reflect both the understanding of substitution possibilities under current technology and judgments about how these possibilities may change with scientific advance and technology R&D. As noted below, this fact about parameter estimation creates an unavoidable difficulty in creating a clear distinction within any CGE model result between substitution (current technology) and technical change (new technology).

In addition to the possibility that new technology may to some degree be reflected in the σ estimates, two exogenous forces leading to technical change commonly are included in CGE models. First, it is well established that economic growth cannot be explained only by the growth of labor and accumulation of capital. A residual productivity factor always remains. In part this residual can be attributed to technical improvement, although it also may reflect other changes, such as increased labor education and skills, better management practices, and improvements in social capital (effective laws, stable political climate, supportive culture, *etc*.). This phenomenon conventionally is represented in one of two ways—either as a change in total factor productivity, or as an increase in labor productivity. For the rest of this discussion scant attention will be

---

[3] For Leontief technology (no substitution among inputs), σ would equal 0. At higher levels of σ the inputs are more easily substituted for one another, up to σ = ∞ where they are indistinguishable.

devoted to assumptions about this key force of growth in the economy, but it is well to remember that, as the main determinant of economic change, it influences all aspects of a future forecast, including energy use and GHG emissions.

Second, it has not proved possible in previous studies to attribute all changes in energy efficiency to specific processes or changes in other factor inputs. Indeed, many countries have experienced reductions in the energy intensity of GDP even over long periods of the last century when real energy prices were falling, and this is usually taken to indicate energy-saving technical change. Unfortunately, a number of complexities arise in introducing this phenomenon in economic models. To some degree the change may be a result of shifts in the sectoral composition of output, so that the residual that can be attributed to technical change depends on the sectoral aggregation of the particular model. Also, the change may result to some extent from improved management and organization. Frequently, this phenomenon is reflected in CGE models by an augmentation of the productive contribution of a unit of energy by means of parameters reflecting Autonomous Energy Efficiency Improvement (AEEI), with an attempt to make allowance for its complex origins.

2.3 Incorporating Non-Extant Energy Supply Sources

In many climate policy applications there is a desire to consider the fate of specific devices or designs that may be currently available as options but are not reflected in the SAM, or that simply merit specific assessment. In its SAM-based aggregation, for example, a CGE model may have separate sectors for producing electric power from various fossil sources, hydro, and nuclear. But none of these reflects the peculiar structure of a new sector that might produce power from biomass. Thus, usually in the energy supply sectors, additional future options are made available which produce a substitute for one of the aggregate sectors, and that use some mix of the economy's primary factors and intermediate goods and services. These alternatives may be "new" in the sense defined above, but more generally they are options that could be implemented with current knowledge—just not at current relative prices. Often the cost relations for these non-extant technologies are based on bottom-up engineering cost data, so that CGE models that include them are a hybrid.

3. PRODUCTION STRUCTURE OF THE MIT EPPA MODEL

The MIT EPPA Model is a recursive-dynamic multi-regional CGE of the type summarized above. Version 4 of the model used here has been updated in a number of ways from Version 3 documented by Babiker *et al.* (2001). It includes non-CO_2 GHGs, greater disaggregation of technologies in the electric sector, and updated evaluation of economic growth and resource availability (Hyman *et al.*, 2003; McFarland *et al.*, 2004; Reilly *et al.*, 2003). Its SAM is built on the GTAP data set, which accommodates a consistent representation of energy markets in physical units as well as detailed accounts of regional production and bilateral trade flows (Hertel, 1997). This new version of the model has been updated to GTAP5-E, with a base year of

1997. GTAP5-E includes the most recent input-output tables for the US and other countries, and provides substantial flexibility in regional disaggregation. From 2000 onward, EPPA is solved recursively at 5-year intervals.

The regional structure of the model is shown in **Table 1**. The Annex B Parties are aggregated into seven nations or multi-nation groups. Under this aggregation Russia includes a number of regions of the Former Soviet Union (FSU) that are not in Annex B. GTAP data are now available to disaggregate Russia, which we plan to do in the near future. There are nine Non-Annex B regions with China, India, Indonesia, and Mexico individually identified.

Table 1. Countries and Regions in the EPPA Model

Annex B	**Non-Annex B**
USA	China
Japan	India
Europe[a]	Mexico
Canada	Indonesia
Australia & New Zealand	Persian Gulf
Russia[b]	Africa
Eastern Europe[c]	Latin America
	East Asia[d]
	Rest of World[e]

[a] The European Union (EU-15) plus countries of the European Free Trade Area (Norway, Switzerland, Iceland).

[b] Russia and Ukraine, Latvia, Lithuania and Estonia (which are included in Annex B) and Azerbaijan, Armenia, Belarus, Georgia, Kyrgyzstan, Kazakhstan, Moldova, Tajikistan, Turkmenistan, and Uzbekistan (which are not). The total carbon-equivalent emissions of these excluded regions were about 20% of those of the FSU in 1995. At COP-7 Kazakhstan, which makes up 5 to 10% of the FSU total, joined Annex I and indicated its intention to assume an Annex B target.

[c] Bulgaria, Czech Republic, Hungary, Poland, Romania, Slovakia, Slovenia.

[d] South Korea, Malaysia, Philippines, Singapore, Taiwan, Thailand.

[e] All countries not included elsewhere: Turkey, and mostly Asian countries.

3.1 Aggregate Production Sectors

Table 2 shows the production structure of the model.[4] In an elaboration of EPPA Version 3, the non-energy goods sectors now identify a services sector. Fossil energy supply sectors are defined as shown, with resources credited to the appropriate regions. The oil sector includes consideration of ongoing development of tar sands, which are only distinguishable by their position on the cost curve from what are frequently called “conventional” sources. The greatest detail is provided in electric power, with separate aggregate sectors for fossil, hydroelectric and nuclear generation.

To illustrate the nesting of production functions applied in the model, **Figure 2** shows the structure applied to the Energy Intensive Industry (EINT) and Other Industries (OTHR) sectors. The nesting for other sectors differs depending on their particular characteristics (for details see

---

[4] There also is production in the household sector—maintaining a car to provide the service of personal transportation—but this feature is omitted for simplicity.

Table 2. Production Structure of the EPPA Model

Aggregated Production Sectors		**Non-Extant Supply Sources**
Goods		Shale Oil
Agriculture	AGRI	Unconventional Gas
Energy Intensive Industry	EINT	Wind & Solar
Other Industries	OTHR	Biomass
Services	SERV	Natural Gas-Combined Cycle (NGCC)
Transport	TRAN	NGCC with Capture and Sequestration
Energy		IGCC with Capture and Sequestration
Crude Oil	OIL	
Refined Oil	ROIL	
Coal	COAL	
Natural Gas	GAS	
Electricity	ELEC	
Fossil (oil, gas and coal)		
Nuclear		
Hydroelectric		
Final Demand Sectors		
Household Transport		
Household Other		
Government		
Primary Factors		
Labor		
Capital		
Land (agriculture and biomass)		
Resources (oil, natural gas, coal, shale, nuclear, hydro)		

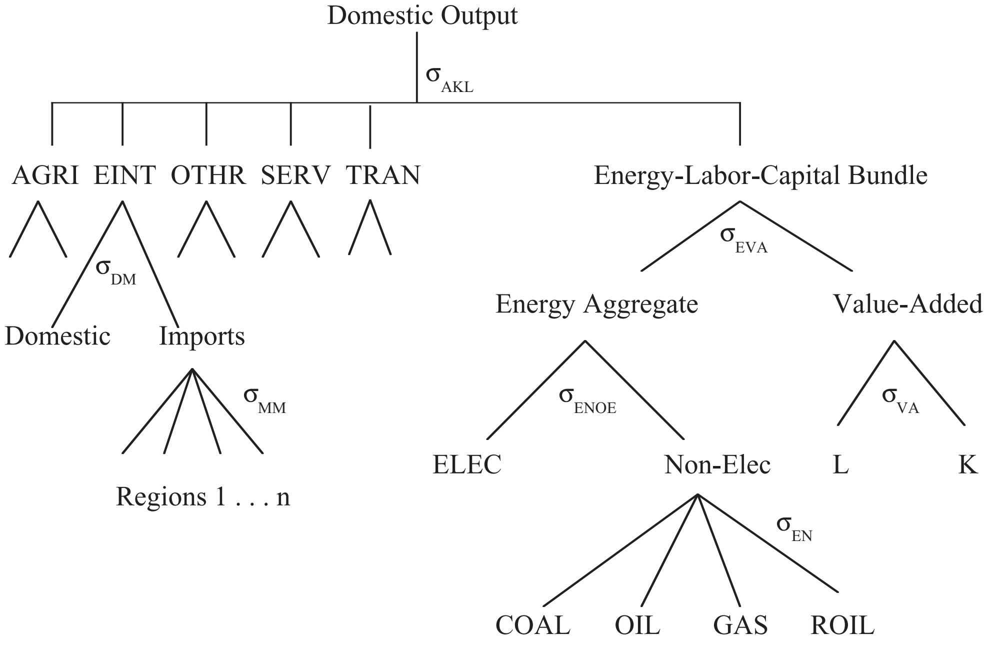

Figure 2. Production Structure of EINT and OTHR Sectors.

Babiker *et al.*, 2001). But all of the goods sectors share the features of substitution between energy and value added of primary factors (with elasticity σ_{EVA}), a representation of capital-labor substitution (elasticity σ_{VA}), and substitution between electric and non-electric energy (σ_{ENOE}). Easily seen in the nesting are the inputs of intermediate goods, including electric and other forms of energy, and of the primary factors of labor and capital.

In addition to CO_2, EPPA also estimates emissions of the other Kyoto gases (Hyman *et al.*, 2003). The model includes both a prediction of emissions over time, as a function of activity levels in the aggregate sectors, and an endogenous analysis of the costs of reducing them. Also, the model computes emissions of a number of other substances that are important for the atmospheric chemistry of the greenhouse gases and production of aerosols (*e.g.*, NO_X, SO_X, CO, NMVOCs, NH_3, black carbon).

Besides capital and labor the primary factors of production include land and fossil energy resources (coal, conventional oil, natural gas, and shale). Each of the energy technologies requires input of a specific resource factor, with its interpretation and parameterization depending on the case. For the fossil fuels it is an input to the model of resource extraction, which influences the pattern of exploitation over time. For hydroelectric power it represents the water resource, which grows (or not) over time to represent the expansion of hydro capacity in regions where that is possible. The nuclear resource factor is parameterized to the nuclear fuel input share, and in principle could be related to a uranium resource depletion model as in fossil resources. However, as currently used in the model, nuclear supply is fixed or can decline over time to represent regulatory limits on expansion or possible phase-out.

3.2 Non-Extant Supply Options

Shale oil and coal gasification are represented as separate technologies, not currently used, but able to produce a perfect substitute for oil and natural gas respectively if prices rise high enough. Biomass generation and the natural gas combined cycle (NGCC) and integrated coal gasification combined cycle (IGCC) technologies also produce electricity that is a perfect substitute for that from the aggregate sectors. The NGCC technology (without capture) is needed to provide the correct competitive environment for NGCC and IGCC technologies with capture and storage included (see McFarland *et al.*, 2004). To reflect their intermittent output (of which more below) solar and wind sources are modeled as producing imperfect substitutes for the output from aggregate electric sectors. They are represented by CES nestings (see Babiker *et al.*, 2001) with the factor proportions set to establish a technology-specific mark-up above the cost of the supply alternative it the base year. As noted, these mark-ups are based on bottom-up analysis of the individual technologies.

For the non-extant technologies the resource factor can be used to represent limited factors that tend to drive up adjustment costs in the short run and influence the pace of introduction—such as engineering or specialized manufacturing, environmental and other regulatory barriers.

3.3 Capital Structure and Vintaging

An important EPPA feature, influencing technology behavior in the aggregate sectors, is its modeling of capital structure and its evolution over time (Babiker *et al.*, 2001). Each regional economy is modeled as having two forms of capital in any period. One is “malleable” in that its mix of inputs can be altered to be consistent with then current input prices. This portion includes all new investment in each period, plus a portion of the (un-depreciated) capital inherited from previous periods. The other component, constituting the remainder of the inherited old capital is “rigid” in that inputs are fixed at the proportions set in the year of investment (*i.e.*, Leontief technology) so they cannot adjust to the new relative input prices. A “vintage” parameter in the model determines the fraction of old capital that is so frozen in its technical characteristics. The degree of rigidity of old capital stock will influence the speed with which sectors can adjust their production processes in response to changing input prices, and thus affect the cost of imposing emissions controls (Jacoby and Sue Wing, 1999).

4. TECHNICAL CHANGE IN SECTOR-LEVEL PRODUCTION

As implied by the discussion above, it is difficult to compare measures of technical change across different models. Apart from the differences in terminology—Leontief vs. aggregate production function concepts—it is difficult to separate technology phenomena from other structural change. For example, a common technology-related summary measure for an economy is the GHG intensity of economic output. Regrettably, attempts to attribute an observed change in intensity to different sources—such as technical change, shifts in patterns of consumption, changes in the sectoral composition of output, or associated changes in relative prices—will differ depending on the level of disaggregation of the economy and other structural characteristics of the model applied to the question. What for a model with ten sectors would be judged an exogenous improvement in energy efficiency might, for a model with 50 sectors, be seen as an endogenous shift from iron and steel production to aluminum or plastics, along with some price-induced substitution in each sector. In a bottom-up model of iron and steel industry, meanwhile, energy saving might be traceable to a specific change in technique or perhaps greater use of recycled steel. Therefore what is described as technical change at a sectoral level in a CGE model is, to some degree, an artifact of the aggregation chosen and other aspects of model structure. These distinctions can to some extent be explored using the EPPA model as an example.

4.1 Exogenous Change

The main exogenous technological change factors incorporated in EPPA are improvements in labor productivity growth (LPG), land productivity, and energy use productivity (AEEI). Also, the model includes a set of a productivity factors describing the evolution of the emissions coefficients for each non-CO_2 greenhouse gas, similar to the AEEI for energy. Each of these is an input-enhancing factor.[5] Labor productivity growth, coupled with projected population increase, is a key factor determining economic growth in the model. The assumption in EPPA is that improvements reflected in the AEEI parameter will be adopted in the reference case, so thus there is no residual of less-than-zero cost abatement options that would accompany the introduction of a GHG policy.[6]

In the Annex B countries, the energy efficiency of the electric sector is modeled as improving at a rate of 0.40 to 0.45% per year while non-electric sectors increase in energy efficiency by 1.2 to 1.3% per year. The slower improvement in the electric sector assures that, over the 100-year horizon of the model, the electric production efficiency does not exceed a thermodynamic limit or engineering estimates of the maximum potential improvement. It is also necessary to choose a low elasticity of substitution between fuel and capital and labor in the electric production because this parameter allows further improvement in efficiency in response to rising fuel prices, as perhaps augmented by a GHG emission penalty (For more discussion, see McFarland *et al.*, 2004).

The performance of aggregate energy intensity differs among developing countries, with some improving and some not. The latter pattern probably reflects structural change toward more energy intensive infrastructure development that is hidden in the EPPA aggregation. To capture this phenomenon we create three groups of developing country regions based on per capita income levels. The two lower income groups have a negative AEEI—energy intensity grows—for several decades as they complete their structural adjustment and then it improves. The wealthiest of these start with an AEEI of zero and then gradually improve. The assumption is that, as per capita income rises to levels more like the developed countries; these regions will experience AEEI rates closer to those that developed countries have achieved over the past several decades.

4.2 Endogenous Change

From the viewpoint of some engineering process models, where a shift among Leontief-level activities may be viewed as a change (*e.g.*, recall the earlier gas vs. hybrid car example) all of the substitutions in production as produced by a CGE model may be thought of as endogenous changes in "technology." Even applying the conventional microeconomic definition of technology (as a set of production possibilities that might be accessed at different relative prices) the EPPA model will show shifts in production process that are properly classified as including some level of endogenous technical change. Four such areas of change can be identified.

---

[5] The non-CO_2 emissions productivity factors only enhance productivity when there is a positive GHG price (*i.e.*, in policy cases but not in the reference case). Emissions-reducing technology is obviously not cost-saving if there is no cost associated with the emitting the gas.

[6] In contrast, bottom-up studies sometimes portray these enhancements as free (or better than free) responses to emissions control measures.

Factor Substitution In Response to Price and Income Change. Because the estimation of key elasticities unavoidably involves some combination of substitution possibilities available today and those that may be added in the future, changes in relative prices lead to shifts in production (as reflected in the associated mix of inputs) that imply some new technology—and thus endogenous change. This will occur, for example, in the substitution between energy and non-energy inputs, in response to rising relative fuel prices or a GHG emissions penalty.[7] Substitution between other inputs can also affect single factor measures of technology such as labor productivity or agricultural yields. Similar effects originate in the household sector. The ability of households and other demand sectors to substitute among goods allows consumers to shift away from GHG intensive goods to less GHG intensive ones, in response to rising prices of energy or GHG control measures. The structure of consumption within EPPA also shifts in response to rising income. Elasticities of substitution are positively related to per capita income, and the share parameters for agriculture and vs. other goods are negatively related to per capita income. As these forces lead production away from the benchmark levels in the SAM, some of the movement represents endogenous changes in technology.

Non-GHG Emissions Factor Improvement. Emission factors for the non-GHG gases fall as a function of income, reflecting the observation that higher income countries have lower emissions intensities. This change may, in part, reflect demand for environmental quality through regulation that is not represented explicitly in EPPA. Even so, it reflects an endogenous improvement in technology with respect to its pollution emissions.

Capital Accumulation and Vintaging. Capital accumulation (savings and investment in excess of depreciation) tend to lower the cost of capital and thus to create substitution toward capital and away from energy. To the degree some new options are reflected in the elasticities, this involves technical change. Also, the vintaged structure of EPPA continuously updates the technology structure of each sector. More broadly, the returns to capital include not only the returns to the normal physical capital stock but also, unless knowledge stock is modeled explicitly (as per Sue Wing, 2001, or Goulder and Schneider, 1999) reflect returns to knowledge embodied in that stock. Thus substitution between capital and energy implicitly includes a substitution between knowledge and energy, and augmentation of the capital stock can also be considered, in part, an augmentation of knowledge.[8]

Modeling of Non-Extant Supply Options. Though presently not the case in EPPA, CGE models may include non-extant supply technologies, assumed to become available only at some time in the future, which represent endogenous change if an when they penetrate supply markets (*e.g.*, advanced nuclear power). Also, as described below, representations of these options may include cost reduction with experience (learning by doing), which also introduces a form of endogenous technical change.

Given these features of CGE models, great care should be taken in considering the introduction of a new endogenous process of technical change, perhaps replacing a currently exogenous process with an explicit endogenous one. The new process should not be casually added on top of those already existing in the model, at the risk of double-counting.

---

[7] In addition, simulations may assume a value of σ_{EVA} that increases over time, further increasing the range of possible technological change.

[8] This interpretation does not deal with some particular features of knowledge generation such as the non-appropriable spillovers of knowledge among sectors, and nations.

4.3 The Relative Importance of Technology Parameters

As a result of ongoing work on uncertainty in the MIT Integrated Global System Model (Webster *et al*., 2003), of which EPPA is a part, preliminary results are available on a set of tests of the sensitivity of key EPPA results to its input parameters (Cossa, 2004). Based on modeler's judgment, informed by experience of previous experiments of this type, those parameters likely to have the greatest influence on total emissions and control costs have been selected for analysis. Then the model is simulated with each of these parameters varied, one by one, by plus and minus one standard deviation (this range determined, again, by modeler's judgment of the uncertainty in each).[9] One model result being considered in the analysis is the US welfare cost of a "Kyoto forever" emissions policy, observed in 2010 and 2050. The results for 2010 are shown in **Figure 3**.

The widths of the bars in this so-called tornado diagram indicate the relative influence of the top ten among the variables studied, considered independently. Technology-related variables take on substantial importance. The ease of substitution between energy and value added, SIG-EVA (σ_{EVA} in Figure 2), turns out to be the most important, reflecting as it does the relative flexibility of the production structure in response to policy shock. For near term adjustment, the vintaging parameter (which determines how much of inherited capital cannot be adapted in its input structure) is also important. Next are three variables that influence the degree of emissions

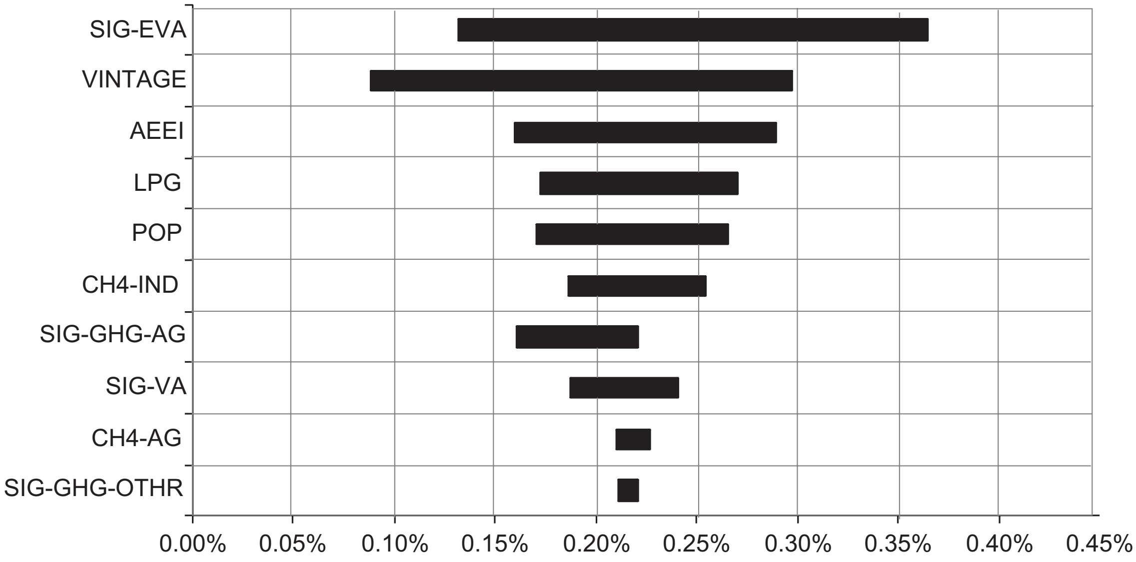

Figure 3. Tornado Diagram: 2010 Welfare Cost of Kyoto Restriction.

---

[9] The approach here approximates the relative importance of these different factors, but not too much should be made of the exact ranking. It depends on the range used (our estimate of the standard deviation) and, less obviously perhaps, it also depends on the reference values chosen for all of the other variables, the country shown, and the policy imposed. A more careful elicitation of the uncertainty distribution for each parameter, a full Monte Carlo analysis, and then statistical attribution of uncertainty to each parameter would be a more rigorous approach, perhaps revealing non-linear interactions.

reduction that must be achieved in 2010: LPG and population growth (POP) determining the economic growth over the period, and AEEI showing the degree to which the task is alleviated by autonomous forces. Parameters influencing the emissions of methane in agriculture and industry take positions six and eight, but again key elasticities are ranked seventh and ninth. (For the cost results in 2050, the vintaging drops far down the ranking and the various elasticities rise in importance.)

Finally, the tenth factor in relative influence on 2010 welfare cost is a “mark-up” factor related to the costs of non-extant technologies (described in greater detail below). This experiment was not designed to fully explore uncertainty in the non-extant technologies, but the results are informative nonetheless. It is not surprising that the costs of these new technologies have a small influence on a time horizon as short as 2010. But even in the results for 2050 (when the GHG constraint is much tighter) this measure of uncertainty about these costs is dominated by the variables (except for vintaging) that take the top ranks in 2010. These results reinforce the view that variables related to aggregate technology structure are high priority targets for research and, as suggested below, uncertainty analysis.

5. MODELING NON-EXTANT SUPPLY OPTIONS

The non-extant supply sources, listed in Table 2, are all implemented as production functions, with various outputs modeled as substitutes for energy products from the aggregate sectors. All produce perfect substitutes—for oil, gas or electricity as appropriate—except for the intermittent sources, wind and solar power. All require inputs of labor, capital, intermediate goods, and an appropriate resource factor. They differ from one another in detail, but in general the factor proportions are set so as to impose a mark-up above current substitutes, the magnitude of this premium determined from current engineering studies. In some cases a resource factor is used to represent adjustment costs that affect the rate at which a technology takes market share once it enters. Changes in input prices, and output prices of competing sources, determine when introduction will occur. Thus to some degree their use is subject to prices changes. In particular, capital deepening, as a result of a falling relative cost of capital, aids the capital-intensive sources such as wind and solar electricity.

Several issues arise in modeling these non-extant technologies, and two are elaborated here: the quality of product, and influences on market penetration including adjustment costs and potential effects of learning by doing. These topics represent an important area of research in the modeling of technical change and its influence in climate policy.

5.1 Quality of Product

Most studies of the cost of wind and solar power, and their potential reduction with cumulative experience, express the results in terms of cost per kWh. This result, then, is frequently compared with the busbar cost of fossil electric energy in order to prepare estimates of its relative competitive position, or to conduct benefit-cost studies of programs to “buy down” the cost by government subsidies (International Energy Agency, 2000). A difficulty with these studies is that, their supply being intermittent, these sources do not produce a perfect substitute for fossil or nuclear generated electricity. Take wind power as an example. The value of a kWh from a coal plant includes a component representing the high availability of the plant capacity. Wind, on the other hand, is perhaps not best thought of as providing a substitute for fossil generation but as contributing negative stochastic load. In a centrally-planned electric system, wind turbines would not receive a capacity credit equivalent to a fossil generating plant. In a deregulated system, where dependable plant capacity is rewarded in day-ahead or other futures markets, wind may get little or not credit—its main return coming in the market for spot generation.

However its output is formulated, an issue arises as to how to incorporate such an intermittent source in a CGE model. Two approaches now under study are shown in **Figure 4**. Note that electricity from wind is modeled by a nesting of CES functions, involving inputs of labor, capital, equipment from the OTHR sector, and a resource factor representing limitations in the wind resource itself. The markup for wind at this level could be adjusted over time, say in response to cumulative output, but at present it is held constant awaiting improvement on the larger question, which is how to integrate this technology into the modeled electric power system. Currently the method in Figure 4a is implemented in the EPPA model. Aggregated-sector supplies of fossil, nuclear and hydroelectric power are treated as perfect substitutes ($\rho = \infty$), as are supplies from NGCC technology without capture and storage, and NGCC and IGCC technologies with capture and storage. Wind supply, however, is modeled as producing an imperfect substitute ($\rho < 0$).[10] An alternative formulation is shown in Figure 4b. In this method, a kWh of power from a wind source is treated as a perfect substitute for fossil and other sources ($\rho = 0$), but then a unit of the wind

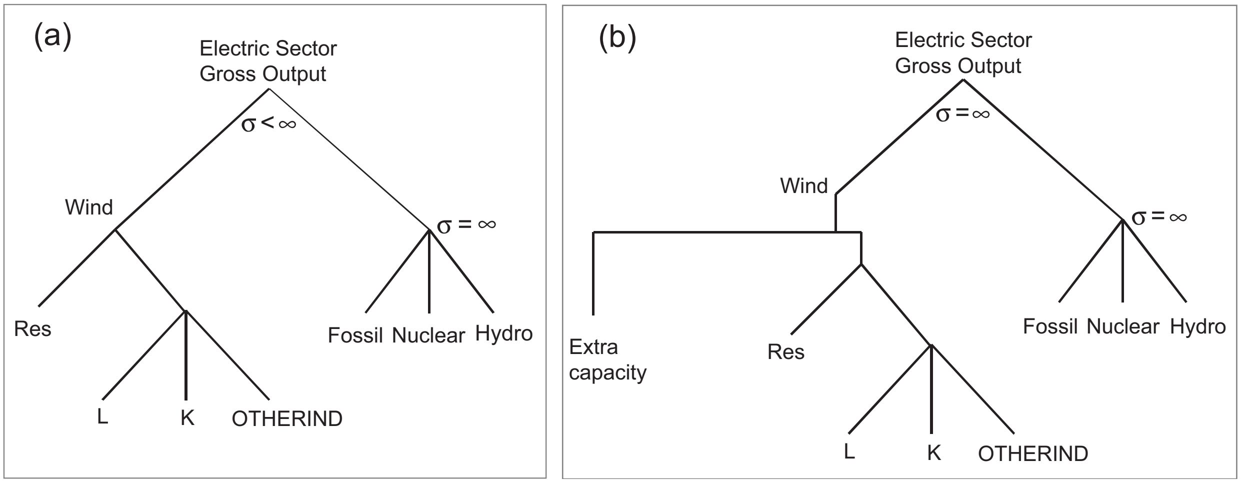

Fig. 4. Alternative Formulations of Wind Power: (a) Imperfect Substitution; (b) Partial Capacity Credit.

---

[10] A CES function controls the substitution at the top of the nest in Figure 4a and, because this functional form tends to be share preserving, this approach will not allow large-scale expansion of wind without recalibration over time.

production must include, in fixed proportions, a unit of standby capacity or energy storage (*e.g.*, pumped hydro, compressed air)—so that it is a true substitute as viewed by the system planner or as valued in a deregulated generation market.

The relative role of wind power, naturally, is very sensitive to the value chosen for ρ or the standby requirement and, because these features are poorly understood, these quantities tend to function as tuning parameters in model simulations. Further research on the capacity value of wind resources is needed to improve its representation in CGE-type models (an no doubt in other types of models as well). The same holds, of course, for solar power.

5.2 Adjustment Costs and Experience

Even given an estimate of the bottom-up costs of a non-extant technology, and any corrections for differences in quality, issues remain in the modeling within a CGE context. Two are of greatest importance. First, even if the costs of the technology itself are unchanging with time and experience, the pace at which a new technology, once cost competitive, can take market share is dependent on a number of factors that may be loosely classified as adjustment cost. And second, whatever the pace of expansion might be at constant technology cost, the possibility exists of cost reduction though cumulative experience—a process perhaps enhanced by R&D expenditure and scale economies, but which is conventionally summarized as "learning by doing." These two influences overlap, calling for extra care in model formulation and selection of parameters. We can look at each of these in turn, using as an example integrated coal gasification combined cycle (IGCC) generation with carbon capture and sequestration (CCS).

Adjustment Costs and Penetration Rates. Once the output of such a new technical option becomes cheaper than alternative sources, an unrestrained mathematical model may show it taking market share at a very rapid rate. In practice, however, a number of factors influence the pace at which a new technology can expand. The prices of specialized resources—such as knowledgeable engineering and specialized manufacturing and services—can be driven up if expansion is too rapid. Also, interpreting the term somewhat broadly, "specialized resources" can be taken to include requirements such as environmental and other regulatory approvals, and the observational, analytical and legal work needed to attain them. Also, non-competitive features of market structure can cause delays in development and expansion.

Integrated assessment models apply different methods to impose these elements of institutional and physical reality. The approach taken in the EPPA model is to include an input factor that represents these influences. The approach can be demonstrated using **Figure 5** (for now ignoring the dotted-line segments). To provide the needed carbon accounting, electric provision with CCS is modeled as comprised of a process of generation and transmission coupled with a system of fuel supply and carbon sequestration. In the EPPA model, electric output is measured and valued at the point of transfer to industries, consumers, and government. Thus one component includes the cost of the IGCC generation plant (Gen) and the cost of

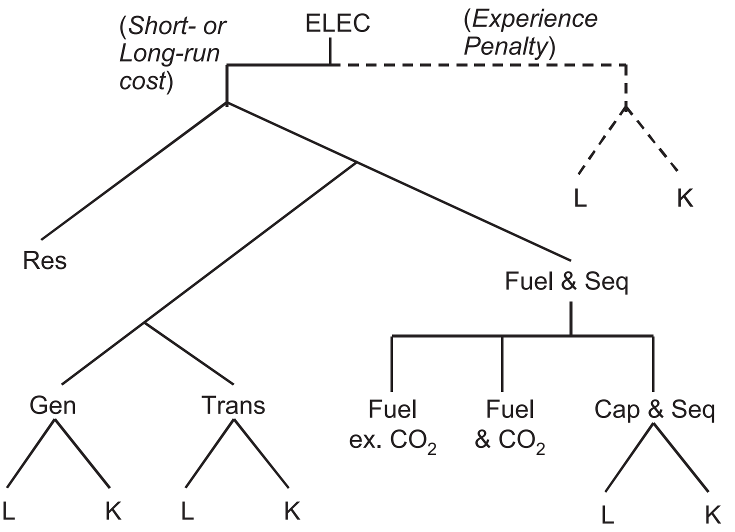

Figure 5. NGCC and IGCC with Carbon Capture and Sequestration.

transmission (Trans). CCS technologies do not avoid carbon emissions altogether. For incorporation in EPPA carbon accounting, therefore, the fuel and sequestration (Fuel and Seq) component divides the fuel input into two portions: one whose CO_2 is sequestered and the other whose carbon is released. For example, in an IGCC facility with capture, the split is 90% "ex. CO_2" and 10% "& CO_2" in the figure. Then a combination of capital and labor is required for the CO_2 disposal. The various factor shares in the nesting (the a's illustrated in Eq. 1) are calibrated so that the cost of supply from this technology is some mark-up above that from the aggregated sector for which it provides a substitute product. For IGCC/CCS this base-year mark-up, if constructed today, is set at 1.5 times the cost of pulverized coal generation without CCS.[11]

With just the part of the nesting described until now, there is little restraint to the calculated expansion once the carbon price becomes high enough to make the IGCC/CCS economically competitive. Note, however, that the model includes an additional input, Res, which is a required input to supply from this source. This variable represents specialized inputs, required to support expansion.[12] The pace of expansion in any period is not fixed, but the faster it proceeds the higher the costs of these specialized resources, which serves to restrain the pace of growth. The magnitude of this factor increases period to period in relation to the growth in cumulative output (representing a combined process of industry expansion and accumulation of regulatory experience) and the level of price pressure. The expansion of the Res factor is calibrated to mimic the experience of such introduction elsewhere, with the early decades of nuclear power providing the clearest precedent.

---

[11] The mark-ups used in this example draw on unpublished work by McFarland and Herzog. Recall that the valuation is at the point of consumption, so the comparison includes the influence of transmission cost, assumed to be the same for the two options. The implied difference in busbar cost is greater than a factor of 1.5.

[12] For discussion of other factors influencing the pace of expansion, not explicit in the model, see McFarland and Herzog (2003).

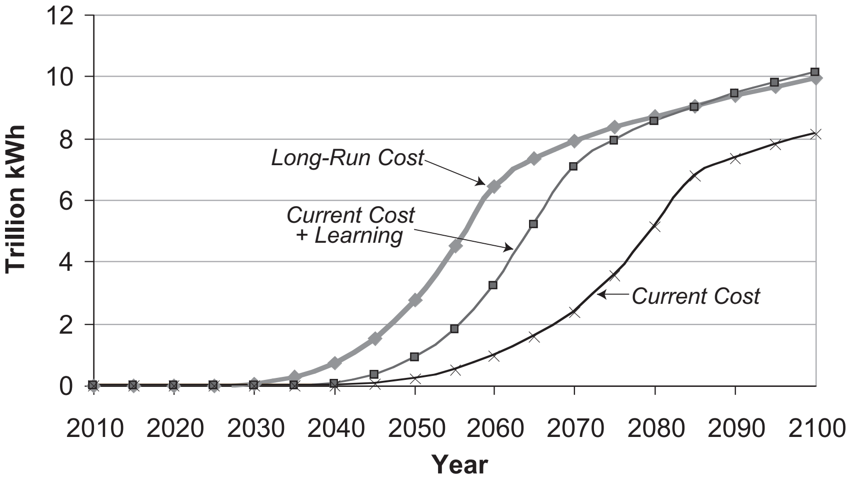

Figure 6. Penetration of IGCC/CCS Technology.

The result of this procedure is shown in **Figure 6**, which presents a series of simulations of the expansion of IGCC/CCS in the US under a hypothesized imposition of a “Kyoto forever” emissions constraint.[13] An example is the expansion of this technology if the cost of implementation in 2000 were to continue throughout the period. Under this assumption about the cost of the plant itself, IGCC/CCS would not be economic until 2045. From that point forward, the rate at which it takes market share is limited by the gradually growing quantity of the specialized resource, Res. With variation in the calibration of the Res process, time of first penetration would not change, but its rate of growth would vary. This process likely will be different for different technologies and national circumstances.

Learning by Doing and Cost Reduction. Frequently, technologies that are non-extant today are anticipated to be economic in the future not only because the price of the energy form for which they substitute will rise over time (perhaps because of a GHG penalty) but because their costs will fall. The reduction may be modeled to be the result of R&D expenditure and scale economies, but in some cases it is expected that the improvement could result from growing experience with the technology. Conventionally, this process is treated as a separate matter from the issue of specialized resources and adjustment cost raised above, although there is evident overlap in the concepts and their interrelation is a useful topic for future research.

Here we summarize the current status of ongoing work on the implementation in EPPA of a model of possible reduction in technology cost driven by cumulative experience, which has been formulated to allow experimentation with this process.[14] Again we use the non-extant technology

---

[13] The calculations shown here were performed using EPPA Version 3, as CCS has not yet been implemented in Version 4 described above. In subsequent drafts of the paper EPPA results will be substituted. The points made here will not be influenced by the change.

[14] A recursive dynamic (*i.e.*, myopic) model like EPPA faces limitations in analyzing learning phenomena. To the extent that potential investors in a technology subject to learning do look ahead (and if they can capture the future rents created by cost reduction from learning) the pace of market penetration will tend to be underestimated. For analysis using a forward-looking model, see Manne and Richels (2002).

IGCC/CCS as an example. In any model of learning, there are two key parameters: the learning rate, and (since the process conventionally is formulated as a logarithmic process) the asymptote or minimum unit cost toward which experience will drive the technology. Bottom-up analysis of this technology has suggested that (ignoring the benefit of avoided carbon charges) it will never be as cheap a generating source as pulverized coal generation, and that the best that can be expected after exhaustion of all the learning benefits is a markup of 1.08 over the current cost of coal-fired power without capture. Again the premium is measured at the point of transfer to consumer sectors in the model.

If IGCC/CCS were available now, or in the next decade or so, at that long-run cost, then the technology would take market share more rapidly than in the case above where its cost never fell below a mark-up of 1.5 over pulverized coal. That result is shown in Figure 6 as the penetration of the technology under conditions of "Long-Run Cost". In some studies of this technology, its possible contribution has been computed using the estimated asymptote of the cost, but assuming that it will not be available at this reduced cost until some specified time in the future (*e.g.*, (McFarland *et al.*, 2004). Using this procedure, any role of cumulative experience in lowering cost is at best implicit in the time lag assumed before the technology is available at the assumed (lowest) cost.

A method that will allow study of this process is illustrated in Figure 5, where now the dotted-line component of the figure comes into play. Now the left side of the nesting, expressed in solid lines yields a cost that reflects the long-run asymptote in a model of learning. In this example the markup is 1.08, as noted above. However, as indicated by the dotted line portion, output from this technology also requires an additional expense, which we may call an "inexperience penalty." Before the technology is introduced, this penalty is 0.42 in this example, summing to a markup of 1.5. The CO_2 penalty (corrected for changes in factor prices) must raise the competition above the resulting cost for this technology to see initial introduction.

It is assumed in the example that, without subsidy as discussed below, this cost penalty does not fall in the absence of actual production experience.[15] However, as experience is gathered through cumulative generation, the penalty falls, ultimately approaching zero. The implied learning rate is a subject for study, but in this example it is 15% per doubling. The result in terms of market penetration is shown in Figure 6 as "Current Cost + Learning." The technology enters at the same time as in the no-learning or "current cost" case but grows more rapidly in output. The production profile reflects the effects of modeled learning and also general equilibrium effects on the carbon price itself.[16]

---

[15] Such a formulation could be combined with either an autonomous reduction or one modeled as a function of R&D expenditure in the absence of production experience.

[16] This formulation may also provide a basis for study of proposals to "buy down" the cost of a non-extant technology through subsidy of the early periods of learning. This might be done by comparing the cost difference, year by year, of forcing from "current cost" penetration to some more rapid path.

6. SUMMARY AND DISCUSSION OF RESEARCH TARGETS

Given the scope and complexity of the climate issue, a number of different forms of models of economic growth, technology development and emissions are going to be required. The CGE type of model, like EPPA and its several cousins in the US and elsewhere, has many advantages. Particularly important are its facility for analysis of the way energy use and other GHG emitting activities are interwoven in the economy, its ability to study mitigation policies that are applied at the national and sectoral level, and how these measures reverberate through international trade, and its framework for consistent accounting of quantities, prices and welfare effects.

Naturally, these many advantages come at a price, the main sacrifice in the climate context being in the ability to represent energy sources of interest, or particular visions of technical change, in great detail. For many applications of integrated assessment this shortcoming is not serious, but for studies focused on particular technological options, narrowly defined—like wind power, a carbon sequestration scheme, or a clean Diesel car—model limitations become more troublesome. Nonetheless, there is need to include the most important of these specific, sub-sector-level options, like the non-extant technologies described above. And this combination of functions leads the two general realms of research in understanding and modeling technology and technical change that we have laid out above. One is the analysis of technology at the level of sectoral aggregation of the model, and the other is the representation of technology of what we have termed “non-extant” sources, and their evolution.

With regard to analysis at the sector level, we have argued (and demonstrated with a simple sensitivity analysis) that parameters that define the technology characteristics of the model—such as labor productivity growth (LPG), AEEI, vintaging parameters and key elasticities—are important to the results that are obtained for policy assessments. Unfortunately, all these variables reflect technical processes about which there is substantial uncertainty. The residuals such as productivity growth and AEEI have been a subject of theoretical and empirical work for over a half-century, yet remain poorly understood. In this circumstance there is no substitute for analysis that explores uncertainty in these parameters. This requirement then points to further work on the use of expert elicitation in studying parameter distributions, and the development of historical data as input to this process (*e.g.*, Webster *et al.,* 2003). The same need arises for the key elasticities.

Study of uncertainty in key elasticities also applies to the modeling and analysis of the non-extant technologies, but for these a number of other issues deserve attention as well. Two are highlighted above. The best way to formulate analysis of technologies that produce a different quality of product—like the intermittency of wind and solar power—is still an open question. The second of the two approaches summarized above (Figure 4b) seems the more attractive, but application of this idea requires additional side analysis of the stochastic behavior of wind resources and their integration into power systems along with competing sources that have other stochastic characteristics. A similar analysis probably applies to solar power—not the seasonal solar input but the intervening effects of weather.

Related to the issue of product quality, but not covered here is the proper characterization of the way a particular non-extant electric source, with its particular output cost, will be fitted into the load dispatch of a power system. Calculation of the technology cost as input into an EPPA-type model depends on a question that is beneath the level of aggregation of the model, which is whether the new plant is likely to be dispatched on base load, in intermediate load, or as a peaking unit (*i.e.*, its capacity factor). McFarland and Herzog (2003) describe an approach used for CCS in the EPPA model, which involves making an assumption about the result of load dispatch. Sands (2004) explores an alternative approach (still in a CGE context) which involves splitting the electricity nesting to distinguish peaking from base load service, so that the model itself can make a crude version of the capacity factor choice.

These challenges of modeling the non-extant technologies result from the fact that the essentially top-down structure of a CGE structure is being stretched to mimic the behavior of bottom-up analyses. At some point, it surely becomes preferable to attain the joint advantages of these two approaches with a looser coupling of the technology detail of engineering process models to the general equilibrium representation of the economy (*e.g.*, Schafer and Jacoby, 2004)—a choice that is yet another issue for continuing research.

Acknowledgments

The CGE model underlying this analysis was supported by the US Department of Energy, Office of Biological and Environmental Research [BER] (DE-FG02-94ER61937), the US Environmental Protection Agency (X-827703-01-0), the Electric Power Research Institute, and by a consortium of industry and foundation sponsors. Thanks are due to Mustafa Babiker for help with calculations and to Richard Eckaus for constructive comment. Remaining errors are the responsibility of the authors.

7. REFERENCES

Babiker, M., J. Reilly, M. Mayer, R. Eckaus, I. Sue Wing and R. Hyman (2001). The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Revisions, Sensitivities, and Comparisons of Results. MIT Joint Program on the Science and Policy of Global Change, Report No. 71 (http://mit.edu/globalchange/www/MITJPSPGC_Rpt71.pdf).

Binswager, H. (1978). Induced Technical Change: Evolution of Thought. In: *Induced Innovation: Technology, Institutions and Development*, H. Binswager and V. Ruttan, *et al*. (editors), Baltimore, Johns Hopkins Press.

Cossa, P. (2004). *Uncertainty Analysis of the Cost of Climate Policies.* SM Thesis, Technology and Policy, Massachusetts Institute of Technology.

Goulder, L. and S. Schneider (1999). Induced Technical Change and the Attractiveness of CO_2 Abatement Policies. *Resource and Energy Economics*, **21**: 211-253.

Hertel, T., editor. (1997). *Global Trade Analysis: Modeling and Applications.* New York: Cambridge University Press.

Hyman, R.C., J.M. Reilly, M.H. Babiker, A. De Masin and H.D. Jacoby (2003). Modeling Non-CO_2 Greenhouse Gas Abatement. *Environmental Modeling and Assessment*, **8**(3): 175-186.

International Energy Agency (2000). *Experience Curves for Energy Technology Policy*. Paris, OECD/IEA.

Jacoby, H. and I. Sue Wing (1999). Adjustment Time, Capital Malleability and Policy Cost. *The Energy Journal*, Special Issue: 73-92.

Kypreos, S. (1996). The MARKAL-MACRO Model and the Climate Change. Paul Scherrer Institut, PSI Bericht Nr., 96-14, July.

Manne, A. and R. Richels (2002). The Impact of Learning-by-Doing on the Timing and Costs of CO_2 Abatement. AEI-Brookings Joint Center Working Paper 02-8 (May).

McFarland, J. and H. Herzog (2003). Incorporating Carbon Capture and Storage Technologies in Integrated Assessment Models. Principal Investigators Workshop, US DOE Integrated Assessment Program, Snowmass, Colorado, 5-6 August.

McFarland, J., J. Reilly and H. Herzog (2004). Representing Energy Technologies in Top-down Economic Models Using Bottom-up Information. *Energy Economics*, in press (doi:10.1016/j.eneco.2004.04.026); MIT Joint Program on the Science and Policy of Global Change Report No. 89 (http://mit.edu/globalchange/www/MITJPSPGC_Rpt89.pdf).

Nordhaus, W. and J. Boyer (2000). *Warming the World: Economic Models of Global Warming.* Cambridge, MA, MIT Press.

Prinn, R., H. Jacoby. A. Sokolov, C. Wang, X. Xiao, Z. Yang, R. Eckaus, P. Stone, D. Ellerman, J. Melillo, J. Fitzmaurice, D. Kicklighter, G. Holian and Y. Liu (1999). Integrated Global System Model for Climate Policy Assessment: Feedbacks and Sensitivity Studies. *Climatic Change*, **41**(3/4):469-546.

Reilly, J., H. Jacoby and R. Prinn (2003). Multi-Gas Contributors to Global Climate Change: Climate Impacts and Mitigation Costs of Non-CO_2 Gases. Pew Center on Global Climate Change, Arlington, VA.

Sands, R.D. (2004). Dynamics of carbon abatement in the Second Generation Model. *Energy Economics*, in press (doi:10.1016/j.eneco.2004.04.034).

Schafer, A. and H. Jacoby (2004). Technology Detail in a Multi-Sector CGE Model: Transport Under Climate Policy. *Energy Economics*, in review; MIT Global Change Joint Program Report No. 101 (http://mit.edu/globalchange/www/MITJPSPGC_Rpt101.pdf).

Sue Wing, I. (2001). *Induced Technical Change in Computable General Equilibrium Models for Climate Policy Analysis.* Ph.D. Dissertation, Technology, Management and Policy, Massachusetts Institute of Technology.

Sue Wing, I. (2003). Representing Induced Technological Change in Models for Climate Policy Analysis. Principal Investigators Workshop, US DOE Integrated Assessment Program, Snowmass, Colorado, 5-6 August.

Webster, M. (2002). The Curious Role of "Learning" in Climate Policy: Should We Wait For More Data? *The Energy Journal,* **23**(2): 97-119.

Webster, M., M. Babiker, M. Mayer, J. Reilly, J. Harnisch, R. Hyman, M. Sarofim and C. Wang (2002). Uncertainty in Emissions Projections for Climate Models. *Atmospheric Environment,* **36**(22): 3659-3670.

Webster, M., C. Forest, J. Reilly, M. Babiker, D. Kicklighter, M. Mayer, R. Prinn, M. Sarofim, A. Sokolov, P. Stone and C. Wang (2003). Uncertainty Analysis of Climate Change and Policy Response. *Climatic Change,* **61**(3): 295-320.

REPORT SERIES of the **MIT** *Joint Program on the Science and Policy of Global Change*

1. **Uncertainty in Climate Change Policy Analysis** *Jacoby & Prinn* December 1994
2. **Description and Validation of the MIT Version of the GISS 2D Model** *Sokolov & Stone* June 1995
3. **Responses of Primary Production & C Storage to Changes in Climate and Atm. CO_2 Concentration** *Xiao et al.* Oct 1995
4. **Application of the Probabilistic Collocation Method for an Uncertainty Analysis** *Webster et al.* January 1996
5. **World Energy Consumption and CO_2 Emissions: 1950-2050** *Schmalensee et al.* April 1996
6. **The MIT Emission Prediction and Policy Analysis (EPPA) Model** *Yang et al.* May 1996
7. **Integrated Global System Model for Climate Policy Analysis** *Prinn et al.* June 1996 (*superseded by No. 36*)
8. **Relative Roles of Changes in CO_2 & Climate to Equilibrium Responses of NPP & Carbon Storage** *Xiao et al.* June 1996
9. **CO_2 Emissions Limits: *Economic Adjustments and the Distribution of Burdens*** *Jacoby et al.* July 1997
10. **Modeling the Emissions of N_2O & CH_4 from the Terrestrial Biosphere to the Atmosphere** *Liu* August 1996
11. **Global Warming Projections: *Sensitivity to Deep Ocean Mixing*** *Sokolov & Stone* September 1996
12. **Net Primary Production of Ecosystems in China and its Equilibrium Responses to Climate Changes** *Xiao et al.* Nov 1996
13. **Greenhouse Policy Architectures and Institutions** *Schmalensee* November 1996
14. **What Does Stabilizing Greenhouse Gas Concentrations Mean?** *Jacoby et al.* November 1996
15. **Economic Assessment of CO_2 Capture and Disposal** *Eckaus et al.* December 1996
16. **What Drives Deforestation in the Brazilian Amazon?** *Pfaff* December 1996
17. **A Flexible Climate Model For Use In Integrated Assessments** *Sokolov & Stone* March 1997
18. **Transient Climate Change & Potential Croplands of the World in the 21st Century** *Xiao et al.* May 1997
19. **Joint Implementation: *Lessons from Title IV's Voluntary Compliance Programs*** *Atkeson* June 1997
20. **Parameterization of Urban Sub-grid Scale Processes in Global Atmospheric Chemistry Models** *Calbo et al.* July 1997
21. **Needed: A Realistic Strategy for Global Warming** *Jacoby, Prinn & Schmalensee* August 1997
22. **Same Science, Differing Policies; *The Saga of Global Climate Change*** *Skolnikoff* August 1997
23. **Uncertainty in the Oceanic Heat and Carbon Uptake & their Impact on Climate Projections** *Sokolov et al.* Sept 1997
24. **A Global Interactive Chemistry and Climate Model** *Wang, Prinn & Sokolov* September 1997
25. **Interactions Among Emissions, Atmospheric Chemistry and Climate Change** *Wang & Prinn* September 1997
26. **Necessary Conditions for Stabilization Agreements** *Yang & Jacoby* October 1997
27. **Annex I Differentiation Proposals: *Implications for Welfare, Equity and Policy*** *Reiner & Jacoby* October 1997
28. **Transient Climate Change & Net Ecosystem Production of the Terrestrial Biosphere** *Xiao et al.* November 1997
29. **Analysis of CO_2 Emissions from Fossil Fuel in Korea: 1961–1994** *Choi* November 1997
30. **Uncertainty in Future Carbon Emissions: *A Preliminary Exploration*** *Webster* November 1997
31. **Beyond Emissions Paths: *Rethinking the Climate Impacts of Emissions Protocols*** *Webster & Reiner* November 1997
32. **Kyoto's Unfinished Business** *Jacoby, Prinn & Schmalensee* June 1998
33. **Economic Development and the Structure of the Demand for Commercial Energy** *Judson et al.* April 1998
34. **Combined Effects of Anthropogenic Emissions & Resultant Climatic Changes on Atmosph. OH** *Wang & Prinn* April 1998
35. **Impact of Emissions, Chemistry, and Climate on Atmospheric Carbon Monoxide** *Wang & Prinn* April 1998
36. **Integrated Global System Model for Climate Policy Assessment: *Feedbacks and Sensitivity Studies*** *Prinn et al.* June 1998
37. **Quantifying the Uncertainty in Climate Predictions** *Webster & Sokolov* July 1998
38. **Sequential Climate Decisions Under Uncertainty: *An Integrated Framework*** *Valverde et al.* September 1998
39. **Uncertainty in Atmospheric CO_2 (Ocean Carbon Cycle Model Analysis)** *Holian* October 1998 (*superseded by No. 80*)
40. **Analysis of Post-Kyoto CO_2 Emissions Trading Using Marginal Abatement Curves** *Ellerman & Decaux* October 1998
41. **The Effects on Developing Countries of the Kyoto Protocol & CO_2 Emissions Trading** *Ellerman et al.* November 1998
42. **Obstacles to Global CO_2 Trading: *A Familiar Problem*** *Ellerman* November 1998
43. **The Uses and Misuses of Technology Development as a Component of Climate Policy** *Jacoby* November 1998
44. **Primary Aluminum Production: *Climate Policy, Emissions and Costs*** *Harnisch et al.* December 1998
45. **Multi-Gas Assessment of the Kyoto Protocol** *Reilly et al.* January 1999
46. **From Science to Policy: *The Science-Related Politics of Climate Change Policy in the U.S.*** *Skolnikoff* January 1999
47. **Constraining Uncertainties in Climate Models Using Climate Change Detection Techniques** *Forest et al.* April 1999
48. **Adjusting to Policy Expectations in Climate Change Modeling** *Shackley et al.* May 1999
49. **Toward a Useful Architecture for Climate Change Negotiations** *Jacoby et al.* May 1999
50. **A Study of the Effects of Natural Fertility, Weather & Productive Inputs in Chinese Agriculture** *Eckaus & Tso* July 1999
51. **Japanese Nuclear Power and the Kyoto Agreement** *Babiker, Reilly & Ellerman* August 1999
52. **Interactive Chemistry and Climate Models in Global Change Studies** *Wang & Prinn* September 1999
53. **Developing Country Effects of Kyoto-Type Emissions Restrictions** *Babiker & Jacoby* October 1999
54. **Model Estimates of the Mass Balance of the Greenland and Antarctic Ice Sheets** *Bugnion* October 1999
55. **Changes in Sea-Level Associated with Modifications of Ice Sheets over 21st Century** *Bugnion* October 1999
56. **The Kyoto Protocol and Developing Countries** *Babiker, Reilly & Jacoby* October 1999
57. **Can EPA Regulate GHGs Before the Senate Ratifies the Kyoto Protocol?** *Bugnion & Reiner* November 1999
58. **Multiple Gas Control Under the Kyoto Agreement** *Reilly, Mayer & Harnisch* March 2000

Contact the Joint Program Office to request a copy. The Report Series is distributed at no charge.

REPORT SERIES of the MIT *Joint Program on the Science and Policy of Global Change*

59. **Supplementarity: *An Invitation for Monopsony?*** *Ellerman & Sue Wing* April 2000
60. **A Coupled Atmosphere-Ocean Model of Intermediate Complexity** *Kamenkovich et al.* May 2000
61. **Effects of Differentiating Climate Policy by Sector: *A U.S. Example*** *Babiker et al.* May 2000
62. **Constraining Climate Model Properties Using Optimal Fingerprint Detection Methods** *Forest et al.* May 2000
63. **Linking Local Air Pollution to Global Chemistry and Climate** *Mayer et al.* June 2000
64. **The Effects of Changing Consumption Patterns on the Costs of Emission Restrictions** *Lahiri et al.* August 2000
65. **Rethinking the Kyoto Emissions Targets** *Babiker & Eckaus* August 2000
66. **Fair Trade and Harmonization of Climate Change Policies in Europe** *Viguier* September 2000
67. **The Curious Role of "Learning" in Climate Policy: *Should We Wait for More Data?*** *Webster* October 2000
68. **How to Think About Human Influence on Climate** *Forest, Stone & Jacoby* October 2000
69. **Tradable Permits for GHG Emissions: *A primer with reference to Europe*** *Ellerman* November 2000
70. **Carbon Emissions and The Kyoto Commitment in the European Union** *Viguier et al.* February 2001
71. **The MIT Emissions Prediction and Policy Analysis Model: *Revisions, Sensitivities and Results*** *Babiker et al.* Feb 2001
72. **Cap and Trade Policies in the Presence of Monopoly and Distortionary Taxation** *Fullerton & Metcalf* March 2001
73. **Uncertainty Analysis of Global Climate Change Projections** *Webster et al.* March 2001 (*superseded by No. 95*)
74. **The Welfare Costs of Hybrid Carbon Policies in the European Union** *Babiker et al.* June 2001
75. **Feedbacks Affecting the Response of the Thermohaline Circulation to Increasing CO_2** *Kamenkovich et al.* July 2001
76. **CO_2 Abatement by Multi-fueled Electric Utilities: *An Analysis Based on Japanese Data*** *Ellerman & Tsukada* July 2001
77. **Comparing Greenhouse Gases** *Reilly, Babiker & Mayer* July 2001
78. **Quantifying Uncertainties in Climate System Properties using Recent Climate Observations** *Forest et al.* July 2001
79. **Uncertainty in Emissions Projections for Climate Models** *Webster et al.* August 2001
80. **Uncertainty in Atmospheric CO_2 Predictions from a Global Ocean Carbon Cycle Model** *Holian et al.* Sep 2001
81. **A Comparison of the Behavior of AO GCMs in Transient Climate Change Experiments** *Sokolov et al.* December 2001
82. **The Evolution of a Climate Regime: *Kyoto to Marrakech*** *Babiker, Jacoby & Reiner* February 2002
83. **The "Safety Valve" and Climate Policy** *Jacoby & Ellerman* February 2002
84. **A Modeling Study on the Climate Impacts of Black Carbon Aerosols** *Wang* March 2002
85. **Tax Distortions and Global Climate Policy** *Babiker, Metcalf & Reilly* May 2002
86. **Incentive-based Approaches for Mitigating GHG Emissions: *Issues and Prospects for India*** *Gupta* June 2002
87. **Sensitivities of Deep-Ocean Heat Uptake and Heat Content to Surface Fluxes and Subgrid-Scale Parameters in an Ocean GCM with Idealized Geometry** *Huang, Stone & Hill* September 2002
88. **The Deep-Ocean Heat Uptake in Transient Climate Change** *Huang et al.* September 2002
89. **Representing Energy Technologies in Top-down Economic Models using Bottom-up Info** *McFarland et al.* Oct 2002
90. **Ozone Effects on NPP and C Sequestration in the U.S. Using a Biogeochemistry Model** *Felzer et al.* November 2002
91. **Exclusionary Manipulation of Carbon Permit Markets: *A Laboratory Test*** *Carlén* November 2002
92. **An Issue of Permanence: *Assessing the Effectiveness of Temporary Carbon Storage*** *Herzog et al.* December 2002
93. **Is International Emissions Trading Always Beneficial?** *Babiker et al.* December 2002
94. **Modeling Non-CO_2 Greenhouse Gas Abatement** *Hyman et al.* December 2002
95. **Uncertainty Analysis of Climate Change and Policy Response** *Webster et al.* December 2002
96. **Market Power in International Carbon Emissions Trading: *A Laboratory Test*** *Carlén* January 2003
97. **Emissions Trading to Reduce GHG Emissions in the US: *The McCain-Lieberman Proposal*** *Paltsev et al.* June 2003
98. **Russia's Role in the Kyoto Protocol** *Bernard et al.* June 2003
99. **Thermohaline Circulation Stability: *A Box Model Study*** *Lucarini & Stone* June 2003
100. **Absolute vs. Intensity-Based Emissions Caps** *Ellerman & Sue Wing* July 2003
101. **Technology Detail in a Multi-Sector CGE Model**: ***Transport Under Climate Policy*** *Schafer & Jacoby* July 2003
102. **Induced Technical Change and the Cost of Climate Policy** *Sue Wing* September 2003
103. **Past and Future Effects of Ozone on Net Primary Production and Carbon Sequestration Using a Global Biogeochemical Model** *Felzer et al.* October 2003 [Revised January 2004]
104. **A Process-Based Modeling Analysis of Methane Exchanges Between Alaskan Terrestrial Ecosystems and the Atmosphere** *Zhuang et al.* November 2003
105. **Analysis of Strategies of Companies under Carbon Constraint** *Hashimoto* January 2004
106. **Climate Prediction: *The Limits of Ocean Models*** *Stone* February 2004
107. **Informing Climate Policy Given Incommensurable Benefits Estimates** *Jacoby* February 2004
108. **Methane Fluxes Between Terrestrial Ecosystems and the Atmosphere at Northern High Latitudes During the Past Century: *A Retrospective Analysis with a Process-Based Biogeochemistry Model*** *Zhuang et al.* March 2004
109. **Sensitivity of Climate to Diapycnal Diffusivity in the Ocean** *Dalan et al.* May 2004
110. **Stabilization and Global Climate Policy** *Sarofim et al.* July 2004
111. **Technology and Technical Change in the MIT EPPA Model** *Jacoby et al.* July 2004

Contact the Joint Program Office to request a copy. The Report Series is distributed at no charge.