Modeling Energy Markets and Climate Change Policy

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I. INTRODUCTION

This article will discuss various economic models of energy supply and demand that have been used for global climate change policy analysis. Although these models are quite diverse in their structure and focus, all systems determine market-clearing equilibrium prices that balance production and consumption levels for different fuel types. This comparison focuses on the energy supply and demand adjustments that significantly influence the costs of various strategies for limiting carbon emissions, although the models also incorporate reduced-form representation of the climatic effects that determine the benefits of abatement.

II. ALTERNATIVE MODELING APPROACHES

Although a number of different economic models have been applied to the global climate change problem, this chapter will focus on 16 modeling systems by teams, most of whom have recently participated in model-comparison studies conducted by Stanford University's Energy Modeling Forum. The models are identified in Table 1 along with their principal investigators and sponsoring organization. Half of these teams are based in the US and half outside of it. This chapter will focus on the model structures that appear to be most important for determining the effects of climate policies. Weyant provides comprehensive discussions of the many major findings or insights from applying these models to this issue. (Table 1)

Although each model has unique characteristics and has proven to be extremely valuable for studying certain types of issues, the structures of the models can be described in terms of five basic categories shown in Table 2. Many of the models now employ combinations of traditional modeling paradigms. (Table 2)

One category of models focuses on carbon as a key input to the economy. These models do not distinguish between energy types and therefore are similar to models of aggregate energy use. Trends toward less carbon-intensive fuels are incorporated into their projections for carbon. They consider the cost of reducing carbon emissions from an unconstrained baseline by using an aggregate cost function in each country/region. This approach uses a simple vintaging structure to incorporate the time lags in reducing carbon intensity in response to increases in the price of carbon. In these models, all industries are aggregated together, and GDP is determined by an aggregate production function with capital, labor, and carbon inputs. These models generally omit inter-industry interactions, include trade in carbon and carbon emissions rights but not in other goods and services, and assume full employment of capital and labor. The RICE and FUND models are examples of this category of models.

Another closely related category of models focuses heavily on the energy sector of the economy. These models consider the consumption and supplies of fossil fuels, renewable energy sources, and electric power generation technologies, as well as energy prices, and transitions to future energy technologies. In general, they explicitly represent capital stock turnover and new technology introduction rate constraints in the energy industries, but take a more aggregated approach in representing the rest of the economy. In these models, all industries are aggregated together, and GDP is determined by an aggregate production function with capital, labor, and energy inputs. These models generally omit inter-industry interactions and assume full employment of capital and labor. The MERGE3, CETA, MARKAL-Macro, NEMS and GRAPE models are examples of this category of models. MERGE3 and CETA have the same basic structure, with nine and four regions, respectively. GRAPE includes a somewhat broader set of technology options, including especially carbon sequestration technologies.

A third category of models are those that include multiple economic sectors within a general equilibrium framework. They focus on the interactions of the firms and consumers in various sectors and industries, allowing for inter-industry interactions and international trade in non-energy goods. In these models, adjustments in energy use result from changes in the prices of energy fuels produced by the energy industries included in the inter-industry structure of the model (e.g., coal, oil, gas, electricity). Explicit energy sector capital stock dynamics are generally omitted. These multi-sector general equilibrium models tend to ignore unemployment and financial market effects. The IGEM, MIT-EPPA, and WorldScan models are examples of this type of model. G-Cubed does consider some unemployment and financial effects and is, therefore, a hybrid general equilibrium/macro-econometric model. G-Cubed, MIT-EPPA, and WorldScan all include trade in non-energy goods.

A fourth basic class of models combines elements of the first two categories. They are multi-sector, multi-region economic models with explicit energy sector detail on capital stock turnover, energy efficiency, and fuel switching possibilities. Examples of this type of hybrid model are the AIM, ABARE-GTEM, SGM and MS-MRT models. These models include trade in non-energy goods, with AIM including energy end-use detail, GTEM and MS-MRT including some energy supply detail, and the SGM considering five separate supply sub-sectors to the electric power industry.

By including unemployment, financial markets, international capital flows, unemployment, and monetary policy, the Oxford model is the only model included here that is fundamentally macro-economic in orientation. However, as shown in Table 2, the G-Cubed and IGEM models do consider some unemployment and financial effects, as well as international capital flows.

III. THE KEY ROLE OF ENERGY PRICES

Economic models assign an important role to the price of energy in determining the economy's adjustment to climate change policies. The models compute the price of carbon that would be required to keep emissions level controlled at some pre-determined level. Although it is easiest to think about these scenarios as carbon taxes or permits (which may or may not be tradable), the additional carbon costs also reveal important information about any program that seeks to reduce carbon emissions.

Most economic models solve a set of mathematical equations to obtain the prices of goods and services. The simultaneous solution of these equations represents an equilibrium in which supply equals demand among consumers and producers. In this framework, an energy price increase can be either the motivation for, or the result of, GHG emissions reductions. For example, governments may impose emissions taxes to motivate GHG reductions. Emissions taxes raise the costs of fuels directly, and economies will adjust to reduce the use of those higher-cost fuels, substituting goods and services that result in fewer GHG emissions. On the other hand, governments may cap the total amount of emissions, distribute or sell emissions "allowances," and let the market determine the price and distribution of these allowances. Such a "cap and trade" system will induce changes in prices that are difficult to predict. Since a cap would essentially restrict the supply of carbon-based fuels, GHG consumers would bid up the price until demand for such fuels no longer exceeded supply. In this way the higher prices reduce emissions, but also allocate the GHGs to their highest-value uses.

The effects of higher fossil fuel prices would diffuse throughout the economy. Prices of secondary energy sources, like electricity and oil products, would rise as the higher primary fuel costs are passed through into electricity rates, fuel oil and gasoline prices. Higher fuel costs would also increase operating costs in transportation, agriculture, and especially industry. Although energy costs make up only 2.2 percent of the total costs in U.S. industry, they constitute up to 25 percent of the total costs in the most energy-intensive sectors (e.g., iron and steel, aluminum, papermaking, and chemicals). Each industry's ability to pass these cost increases along to customers through higher product prices would depend on the strength of the demand for its products, and on the severity of international competition. Since many of the major trading partners of the United States would also be implementing similar climate policies, it is likely that the energy cost increase would result in higher prices for a broad range of consumer products. Households could also be affected through increased heating, transportation, and utility bills and, to a lesser degree, food bills and other costs of living.

A host of adjustments by producers and consumers in the economy would take place in parallel with the price increases, and, in fact, these substitutions would also serve to limit the extent of the price increases that would ultimately result. Higher energy costs would induce firms to accelerate the replacement of coal-based or obsolete plants with more energy-efficient or less carbon-intensive equipment. Utilities and their customers would seek alternatives to carbon-intensive coal-fired power plants, stimulating the market for hydro-, nuclear, gas-fired, and renewable electricity. As coal prices rise relative to natural gas prices, modern gas-fired combined cycle power plants would become even more competitive. Older, less-efficient coal-fired plants would probably be retired from service, or reserved for intermittent operations. Energy-intensive industries would also face a number of adjustment decisions: whether to retire obsolete facilities and concentrate production at more modern, low-cost facilities; whether to modify their furnaces to burn gas instead of coal; whether to generate their own electricity; whether to invest in a wide variety of energy-conserving process changes; whether to redesign products to save energy; and whether to alter their product mix. Ultimately, there would be an effective diminution in the value of the existing stock of plant and equipment because it is optimized for the set of input prices that prevailed when it was installed and would be sub-optimal for the new price regime.

In the short run, consumers and producers would reduce their energy consumption by either consuming less energy services (for example, turning their thermostats down or driving their automobiles less), or producing less output. Consumers and producers may also, potentially, reduce energy use without reducing output by identifying energy efficiency measures previously believed to be uneconomic.

In the intermediate time frame, there might be opportunities for fuel switching (or substitutions between other inputs) that would not involve substantial outlays for new equipment or infrastructure (for example, switching the fuel used in a multi-fuel-capable boiler from oil or coal to gas). In addition, consumers may be able to substitute goods that require less energy to produce (which would become relatively less expensive) for more energy-intensive ones (which would become relatively more expensive). In the long term, new technologies would be purchased that either use less GHG-intensive fuel or are more fuel-efficient. In addition, new, less GHG-intensive, technologies might become available over time as a result of R&D expenditures or cumulative experience. The emergence of these new technologies might be related to the energy price increases, the base case trend of all other prices, or simply the passage of time.

Higher energy prices would lead to less energy use, and less energy use would decrease the productivity of capital and labor. These productivity changes would, in turn, generally result in a slowdown in the accumulation of capital equipment and infrastructure, and in lower wages for workers. Ultimately, even after all the adjustments have been made, consumers would have somewhat less income, which might cause them to adjust the amount of time they spend on work rather than leisure. The resulting adjustment in labor depends on two opposing effects. Workers would want to work more to make up for their loss in real income, but the lower wage would make working worth less relative to leisure. Replacing work with leisure would involve an additional change in welfare. Offsetting these welfare losses would be the benefits of reduced climate change, and the benefit of making those responsible for GHG emissions pay for the damages they cause.

The complicated web of economic adjustments that would take place in response to rising prices of energy, or energy scarcity, makes the task of projecting the costs of GHG mitigation a challenge. Interpreting the results they produce is further complicated because different modeling systems emphasize different dimensions of the adjustment process. Also, different policy makers may be interested in different policy regimes, and in different impacts of climate change and climate change policies.

IV. FACTORS INFLUENCING THE RESPONSE TO CLIMATE POLICIES

Baseline economic, technological and political conditions, the opportunities to substitute away from fossil fuels, the nature of the capital stock turnover process, and the dynamics of technological progress are four very important factors that determine a model's response to climate change policies.

A. Baseline Conditions

One set of important issues is the base case emissions and climate impact scenarios, against which the costs and benefits of GHG mitigation policies are assessed. They are largely the product of assumptions that are external to the analysis. Each GHG mitigation cost analysis relies on input assumptions in three areas:

- population and economic activity;
- energy resource availability and prices; and
- technology availability and costs.

Most of the researchers projecting the cost of reducing carbon emissions have relied on worldwide population growth projections made by others (e.g., the World Bank or the

United Nations). These external projections are generally based on results from very simple demographic models. There is less uncertainty about projections for the developed countries, where population is expected to peak very soon, than for the developing countries, where population is typically assumed to peak somewhere around the middle of this century. Very few of the researchers analyzing GHG emissions reductions make their own projections of economic growth. Most rely on economic growth projections made by others, or on external assumptions about labor force participation and productivity growth.

Another key set of assumptions concerns the price and/or availability of energy resources. The prices of fossil fuels -- oil, natural gas, and coal -- are important because producers and consumers generally need to substitute away from these fuels when carbon emissions are restricted. Optimistic assumptions about natural gas availability and/or substitutability can make carbon emissions reductions easier to achieve in the short run. Natural gas plays an important role because its carbon emissions are about 60 percent of those from coal, and 80 percent of those from oil, per unit of energy consumed. In addition, the amount of unconventional oil and gas production that will ultimately be technically and economically feasible is highly uncertain. It depends on future economic incentives for oil and gas exploration and production, which could (absent climate policies) retard the development of carbon-free renewable and higher-efficiency end-use energy technologies. How oil exporters would react to a climate policy that would reduce the demand for oil imports is another key dimension of the energy supply picture.

A final set of key assumptions includes those made about the costs and efficiencies of current and future energy-supply and energy-using technologies. These factors tend to be critical determinants of energy use in both the base case and control scenarios. Most analysts use a combination of statistical analysis of historical data on the demand for individual fuels and process analysis of individual technologies in use or under development, in order to represent trends in energy technologies. Particularly important, but difficult, is projecting technological progress within the energy sector itself. Jorgenson and Wilcoxen attempt to systematically and empirically estimate future trends in energy productivity at a national level, but such efforts are rare. Typically, analysts take one of two approaches: (1) the costs and efficiencies of energy-using and energy-producing technologies are projected based on process analysis, and the characteristics of these technologies are extrapolated into the future, or (2) the trend in energy demand per unit of economic activity, independent of future price increases, is assumed (as described below under technological change). Some recent analyses have attempted to blend the two approaches. At some point these two approaches tend to converge, as the end-use process analyst usually runs out of new technologies to predict. It is then assumed that the efficiency of the most efficient technologies for which there is an actual proposed design will continue to improve as time goes on.

Projections of the benefits of reductions in GHG emissions are also highly dependent on the base case scenario employed. The greater the base case damages (i.e., the damages that would occur in the absence of any new climate policies), the greater the benefits of a specific emissions target. The magnitude of the benefits from emissions reductions depends not only on the base case level of impacts but also on where they occur, and on what sectors are being considered. In fact, a number of additional socioeconomic inputs (e.g., income by economic class and region; infrastructure and institutional capability to adapt to changes, etc.) are required because they determine how well the affected populations can cope with any changes that occur. The task of projecting base case climate change impacts is particularly challenging because: (1) most assessments project that serious impacts resulting from climate change will not begin for several decades; and (2) most of the impacts are projected to occur in developing countries where future conditions are highly uncertain. How well developing countries can cope with future climate change will depend largely on their rate of economic development.

B. Representation of Substitution Possibilities

As efforts are made to reduce GHG emissions, fossil fuel combustion and other GHG-generating activities become more expensive. Producers adjust to these price increases by substituting inputs (i.e., switching to inputs that generate fewer GHG emissions in manufacturing any particular product), and by changing their product mix (i.e., producing different products that require less GHG emissions to make).

The extent to which inputs can be shifted depends on the availability and cost of appropriate technologies as well as the turnover rate of capital equipment and infrastructure. These two factors, as well as consumer preferences, determine an industry's ability to produce and sell alternative mixes of products. Increases in the costs of fossil fuels and products that depend on fossil fuel combustion will reduce consumers' real incomes. Consumers will simultaneously decide: (1) the extent to which they wish to adjust their mix of purchases towards less carbon-intensive products, and (2) how to adjust their mix of work and leisure time to compensate for the reduction in their real income.

1. Short-term vs. Long-term Substitution

If businesses and households have several decades to complete the substitution process, the current stock of energy equipment and associated infrastructure does not constrain the substitutions that they may make. Businesses and households are limited primarily by the available technologies, and by their own preferences regarding how much of each available product they would buy at the prevailing prices.

If climate policy is long term, the transition to a lower carbon energy system can be relatively smooth and the costs relatively moderate. To reach such an outcome, economic incentives should be designed to motivate producers and consumers to invest in more energy-efficient and less carbon-intensive equipment when their existing equipment has reached the end of its useful life. Useful life is an economic concept that compares the costs of operating existing equipment with the costs of purchasing and operating new equipment. One may buy a new and better computer after three years, even though the old computer could be "useful" for 10 years, because the new one has superior cost and performance characteristics. Or one may keep an old car running because the performance advantage of the new car is not worth the cost.

Over shorter time spans, however, existing plant and equipment can significantly constrain the behavior of firms and households, adding transition costs to the long-run costs of GHG control policies. Policies implemented on this time scale (i.e., within ten years) will lead to reductions in energy services (e.g., industrial process heat and home heating and cooling), some easy fuel switching, and an increase in the purchase and use of available energy-efficient products and services. They will also influence the rate of retirement and replacement of existing equipment. Energy-producing and energy-using equipment is relatively expensive and long-lived. Thus, it will generally take a substantial increase in energy prices to induce those who own such equipment to replace it before the end of its useful life.

The importance of capital stock dynamics creates a formidable challenge for the analytical community. Some data on the characteristics of the energy-producing and energy-using capital stock are available. It would be ideal to have information on the costs of operating and maintaining every piece of equipment currently in use. This would enable analysts to calculate all the tradeoffs between retiring equipment early and using other strategies to achieve the specified targets. Unfortunately, the data that is available is generally aggregated across large classes of consumers and generally includes all existing capacity without regard to when it was installed. An important exception is power plant data, which is very disaggregated and includes the age of the equipment. However, even these data are generally not sufficient to ascertain precisely the point at which the carbon price incentives will influence the rate of replacement of plant and equipment. Limitations on data require the analyst to make a number of assumptions regarding the aggregation and interpretation of the available data.

2. Two Approaches to Representing Substitution Possibilities

In many models, technologies are represented with "production functions" that specify what combinations of inputs are needed to produce particular outputs. The production function specifies the rate at which each input can be substituted for each other input in response to shifts in input prices. As new capital investment occurs and older capital is retired, the technology mix within the model will change.

Two basic types of production functions may be specified:

- aggregate production functions; and
- technology-by-technology production functions, also known as process analysis.

Some models (e.g., G-Cubed, SGM, and EPPA – see Table 1 for model identification) use smooth and continuous aggregate production functions that allow incremental input substitutions as prices change, even if the resulting input configuration does not correspond to a known technology. These models do not represent individual technologies. Such models often assume "nested" production functions. For example, at one level, substitutions are possible between energy, capital, and labor in producing final commodities; at a second level, substitutions are possible between electricity and fuel oil in producing energy; and, at a third level, substitutions are possible between coal and natural gas in producing electricity. Models employing continuous aggregate production functions do not account for individual technologies.

In contrast, other models (e.g. MARKAL-Macro and NEMS) draw from a menu of discrete technologies, each requiring fixed input combinations—i.e., each technology is essentially represented with its own production function. This approach is often referred to as "process analysis." These combinations correspond to those employed in actual, or anticipated, technologies that the modeler specifies. The technology-rich MARKAL-Macro model specifies over 200 separate technologies. For discrete technology models, different technologies become cost-effective as input prices change. Modelers then assume that these technologies are selected and used to produce outputs. Process analysis represents capital stock turnover on a technology-by-technology basis. The data and analysis requirements for this type of model can be substantial.

A number of systems use a process analysis approach within the energy sector and an aggregate production approach for the remainder of the economy (e.g., MERGE, MARKAL-Macro). When using either approach, it is important to be able to distinguish between the causes of changes in the selections the models make among the existing technologies. Sometimes the technology choice changes because prices change, and sometimes it changes because new technologies become available.

Some models represent both individual energy supply technologies and individual energy consumption technologies, and do not represent the remainder of the economy explicitly. With these models, however, the analyst must either: (1) assume that "end-use" energy demands (such as the demand for home heating and automotive transport) do not respond to changes in the prices of those services, or (2) employ a complex statistical estimation technique (that requires some historical data on the cost of end-use energy equipment) to estimate the price responsiveness.

The choice of production function depends, in part, on the time frame under consideration and the level of technological disaggregation. Short-term models intended to shed light on precise technology choices specify production functions for large numbers of separate technologies. In contrast, models concerned with longer-term effects can safely characterize technological trends using aggregate production functions. Many models blend the two approaches. While they allow for smooth input substitution in determining new capital investment, they fix input proportions for all equipment installed in a certain year (sometimes called a vintage). Similarly, a model may have smooth production functions for conventional fuels, yet stipulate discrete technologies for a particular non-carbon fuel (e.g. EPPA).

3. Capital Stock Turnover and Malleability

In modeling capital investment in plant and equipment and turnover, each system must use assumptions about the flexibility the investor has in choosing technologies and in changing their characteristics after installation. Data availability and computational considerations limit the choice of modeling assumptions that can be employed. Fortunately, there are some simple formulations that seem to give plausible results in most circumstances.

In almost all models it is assumed that in making decisions about new capital investment, the decision maker (firm, individual, or government entity) has complete flexibility (particularly in the mix of capital and energy inputs required) in choosing among available technologies *before* their purchase. The models differ, however, in their assumptions about how much the characteristics of the capital equipment can be changed *after* it has been installed. These adjustments may be desirable if changes in input prices occur, but retrofitting to a certain set of characteristics is generally more expensive than installing equipment with the same characteristics initially. On the other hand, technological improvements may reduce the costs of the retrofitting over time.

Most models make one of two polar assumptions about this process. To describe these assumptions, the metaphor of soft putty and hardened clay has proved useful ("putty" representing a flexible scenario and "clay" representing a hardened or inflexible scenario). In a "putty-clay" or "putty-putty" formulation, the first term refers to the assumption about the degree of flexibility in original capital investment, and the second term refers to the assumption about the degree of flexibility in modifying that capital after it is installed.

- In a putty-clay formulation, it is assumed that the original equipment cannot be modified once installed. "Putty-clay" assumptions are more realistic in cases where relative prices are changing rapidly. Here, new capital investments embody state-of-the-art technology, and use input mixes that are appropriate for the price expectations that exist at the time of the investment. These characteristics then remain with that vintage until it is scrapped.
- In a putty-putty formulation it is assumed that capital – old or new – can be reconfigured once installed to fit the current price situation in each time period. Under the so-called "putty-putty" assumption, the capital stock is a single entity that is neither broken down into separate vintages, nor constrained to retain its initial technology and input mix. The term putty-putty is used to indicate that capital can be continuously reshaped both before and after investment has taken place. The inherited capital stock adjusts to changes in prices and technology as fully as brand new capital. In effect, the entire capital stock continually adapts itself to reflect current technologies and prices.

The precise details of the capital adjustment process differ from model to model. In some, there is a composite stock of old capital that reflects some average mix of inputs. In others, each vintage is identified and depreciated separately. In many models the old capital stock cannot be altered. In others (e.g., NEMS), it can be retrofitted if doing so is more profitable than making brand new investments, or if it is required by regulation.

Modelers are just starting to experiment with various hybrids of the two, titled "putty-semi-putty" formulations, in which some retrofitting is allowed at some additional cost. One type of "putty-semi-putty" specification allows plant and equipment to be retired before the end of its useful life if the operating cost of the old equipment is greater than the operating plus capital costs of replacement equipment. In this case, the remaining capital costs of the old equipment would have to be written off, so the changes in prices or new technologies would have to be quite significant for this to occur. Prices do rise to these levels in some models in Kyoto Protocol simulations in which the flexibility mechanisms are severely restricted.

D. Capital Stock Adjustment Process

Jacoby and Wing describe three characteristics of these models that are important in analyzing the time horizon for meeting the Kyoto targets:

- the time frame;
- the level of detail about capital stock and production structure; and
- the specification of economic foresight.

The first and most obvious is the time interval over which a model solves its equations. If a model uses a ten-year time interval, the relatively long time period limits the model's ability to be used in analyzing phenomena occurring within a decade, such as the consequences of accepting a 2008-2012 Kyoto target after the year 2000. The results of such models may thus obscure important short-run dynamics of adjustment.

The second important attribute of the models is the level of aggregation in the capital stock and the production structure. The level of aggregation affects how models represent the sources of rigidity in the production sectors of the economy. For example, the choice about whether to aggregate output and capital by sector or by technology, determines the degree of substitution that is possible within the model's structure. Within a specific aggregate, substitutions are, by construction, assumed to be costless. Additional capital stock produces outputs using a combination of inputs that reflects: (1) current and expected input prices, and (2) the constraints and limits of existing technologies.

Models capture the aging of capital in different ways. In evaluating short-term adjustment to climate policies, the distinction between putty-putty and putty-clay specifications is critical. In the face of a stringent near-term policy, the putty-putty assumption may produce unrealistic results because this specification implies that large parts of the current capital stock can be transformed into more efficient and less carbon-intensive alternatives. However, for analysis of the long run, after fuel prices have settled at a new equilibrium level relative to other goods and services, the distinction is less important. In this post-adjustment phase, the inherited capital stock will be increasingly fuel-efficient and competitive under prevailing conditions, because those conditions will more closely match the conditions in place at the time the investments were made.

The third important characteristic of models of the capital stock turnover process is the way they treat foresight. Models may specify economic behavior as forward-looking or myopic. Forward-looking models assume that agents with perfect foresight find the path of emissions reductions that minimize discounted costs over the entire modeling horizon, choosing the timing and stringency of control measures so as to optimally smooth the costs of adjustment. In contrast, myopic models assume that economic agents seek to minimize the costs of policy on a period-by-period basis, and take little or no action in advance of the onset of carbon constraints. Model results can be very sensitive to assumptions about investor foresight. Models that assume perfect foresight allow emissions targets to be met at lower costs because investment decisions are made in the full certainty that emissions limits will be set and achieved. Models that assume some degree of myopia generate higher costs because investors must scramble to alter the capital stock as the target period approaches, prematurely scrapping existing capital (e.g., coal-fired power stations) and quickly investing in less carbon-intensive alternatives.

Of the models reviewed here, the great majority assume perfect foresight, while only one is constrained to be myopic (EPPA). Some models (like G-Cubed) allow alternative assumptions under different runs and/or can set expectations differently for different sectors. The NEMS and SGM models can allow industrial or utility investors to give greater consideration to future conditions than individual consumers do.

In practice, investors do not have perfect foresight, nor do they suffer from complete myopia. While there is inevitable uncertainty regarding future economic conditions, policymakers can reduce uncertainties by making credible commitments to meet targets or to initiate market-based policies. Model results clearly demonstrate that the more convinced investors are that emissions targets will become binding, the less costly the transition to lower carbon emissions.

E. Technological Change

How these opportunities will change with time and with people's experience with new technologies also have important effects. Technological change can be thought of as increasing the amount of a product that can be produced from a given amount of inputs, or as expanding the universe of opportunities for substitution of inputs and products that were described in the last section. Technological change is discussed separately from input and product substitution here because the underlying determinants are somewhat different, because technological change is less well understood, and because of the opportunities for synergy between public support and private investment in stimulating new technology development.

Schumpeter (1942) identified three distinct types of technological change that take place continually in modern economies: (1) invention of completely new ways of satisfying human needs and wants, or the creation of new needs not previously identified or satisfied, (2) innovation, which takes place through continual improvement and refinement of existing ways of doing things, and (3) diffusion of new technologies throughout and across economies. These processes are all important for climate policy. It often takes decades for innovation and invention to pay off. Even diffusion may be difficult to accelerate over a decade, though, because it takes time to distribute information, analysis, and experience from one user to another.

New technologies can allow firms to produce a particular product using a mix of inputs not previously available, including, for example, less energy. In addition, new technologies can lead to new products. These new products compete with existing products, with further implications for carbon emissions reduction policies. If these new technologies and new products produce less carbon, then carbon emissions will be lower, fewer emissions reductions will be needed, and/or emissions reductions will be less expensive. Projecting how technological change might progress over time, both with and without climate policies, is challenging. The processes by which technological change occurs are very complex and the data required to estimate how these changes have been made in the past are generally not available. However, there are several ways economic models represent technological change, as presented below.

1. Induced Technological Change

Inventions of productive technologies or processes are, by their very nature, hard to predict. However, past experience has shown that they can be revolutionary enough to justify large expenditures in basic research in strategic areas. Innovations could be of great help in lowering the costs of reducing GHG emissions. Thus it would be worthwhile to find an appropriate combination of government interventions and private sector incentives that encourage innovation. Thus far, however, most of the policy debate on the influence of technological change on climate change policy has focused not on technology policy options, but rather on how restrictions on GHG emissions reduce aggregate mitigation costs over time. This latter effect has been labeled "induced technological change" (or ITC for short). ITC has to do with price-induced behavior—i.e., what private firms will do in response to higher prices. It does not incorporate what firms will do anyway in trying to become more competitive through investing in R&D, or what they would do in response to government sponsorship of R&D or other direct government technology policies. There has been a good deal of discussion about the potential for induced technological change to substantially lower, and perhaps even eliminate, the costs of CO_2 abatement policies. These discussions have exposed very divergent views as to whether technological change can be induced at no cost, or at some cost.

Every ITC model must represent some incentive to induce technical change in one or more ways such as:

- the form of profits from innovations, as in the top-down models, which focus on the behavior of economic aggregates rather than the behavior of individual actors or the use of individual technologies;
- at a more aggregate and abstract level, by means of cost-functions, R&D production functions, or empirical estimates. Similarly, the decision-maker(s) considered may either be decentralized industries, representative firms, or a central planner;
- by the inclusion of intra-sectoral knowledge spillovers which are advances that individual firms within a sector cannot keep to themselves. For example, the level of investment may be determined by the rate of return the firm expects to earn on the R&D investment as compared with other available investment opportunities. However, the rate of innovation may far exceed that implied by the rate of return alone because other firms in the industry may be able to replicate the innovation;
- and by the dimension in which technological change is assumed to progress (i.e., new products or processes, substitution of inputs, or reorganization of production and distribution arrangements).

Some ITC models are based on empirical observations of past responses to energy price and policy changes. One advantage of this type of model is that different sectors may exhibit different rates of technological progress. However, only one model, IGEM, estimates all these parameters simultaneously because of the large amount of data necessary and the heavy computational burdens of such estimations. Another advantage is that this type of model implicitly takes into account real-world factors that are relevant to technological change and that are difficult to incorporate into conventional economic frameworks. Thus, this model relies on empirical observations of real events, not on a simplified representation of the phenomenon. All types and sources of short-term technical change are included. One disadvantage of this aggregation, though, is that the approach may omit specific known technologies that are beginning to be introduced but that are not yet revealed in the available data. In addition, information about the underlying costs of R&D is lost. Also missing is explicit attention to how firms determine their R&D investments. Firms take into account both the cost of engaging in R&D *and* the expected benefits in terms of future profitability. Thus, models are unable to evaluate optimal policies with full consideration of the costs of R&D. Another disadvantage is that the model is as limited as the data set from which it is constructed. Only one historical path can be observed, and it is assumed that tomorrow's economy will respond to energy price changes in the same way as yesterday's economy. Thus, long-term technological change is beyond the feasible reach of this type of model. "Long-term" here refers to periods over which substantial technological development and major inventions may occur.

Nonetheless, empirical modeling of ITC may be valuable for short- to medium-term projections, or for estimating the short- to medium-term cost of policies on the economy. Empirical models may also be valuable in comparing or calibrating short-term projections from other types of ITC models. Also, the consideration of ITC helps clarify two key matters of debate: (1) whether prior studies (without ITC) have overstated the cost of achieving given emissions reduction targets, and (2) the optimal size and timing of a carbon tax.

2. Autonomous Energy Efficiency Improvement (AEEI)

In contrast to the ITC models, many models include exogenous technical change. ("Exogenous" can mean external to the model, or independent of price, or both.) A simple characterization of technological improvement, employed in many of the models, is a single scaling factor – the autonomous energy efficiency improvement ("AEEI") -- that makes aggregate energy use per unit of output decline over time, independent of any changes in energy prices. (Many modelers specify the AEEI as a percentage of Gross Domestic Product (GDP) growth, so that the value changes over time.) Although the definition of the AEEI varies from model to model, in all models it implicitly represents the effect of technological progress. In some models it also represents one or both of two additional trends: (1) changes in the structure of the economy, resulting in a shift in the relative contribution of energy-intensive industry output to total economic output; and (2) an improvement in energy efficiency over time, reflecting the gradual removal of market barriers that prevent some energy consumers from choosing more efficient energy technologies.

Although the AEEI approach allows for energy improvements over time, it is limited in two respects. First, using the AEEI approach to represent technological change ignores price-induced technological progress (ITC). In reality, higher prices do spur greater innovation and more rapid diffusion of energy-saving technologies. Second, it is not clear what an appropriate rate for AEEI should be. This is important, especially for longer-term projections, which are very sensitive to differences in assumed rates. More sophisticated specifications (often used in conjunction with an AEEI parameter) attempt to paint a more detailed picture of technological change by incorporating some degree of price sensitivity, distinguishing different sectors, and assessing changes to specific technologies.

3. Learning By Doing

In practice, much technological advance comes from learning-by-doing (LBD) -- the incremental improvement of processes through small modifications and adjustments. It is not until a technology is actually used that important lessons are learned that can be applied to its subsequent development. LBD is an integral part of the innovation process. Observation of past technological innovations show that initial installations are quite expensive, but that costs drop significantly the more the technology is used, and the more lessons are learned from using it. This type of learning may be the result of either exogenous or endogenous (induced) technological change.

The LBD approach does not reveal how learning occurs and whether the learning is associated with invention, innovation or diffusion. Thus, it can not evaluate which policies might be appropriate for increasing the learning associated with a technology. The approach also suffers from its inability to establish whether future cost reductions result from increased cumulative experience with the technology or whether they occur with the passage of time, which is closely associated with cumulative experience.

Although most models do not attempt to capture LBD, two models do mimic the process. MERGE assumes endogenous diffusion rates: the more investment there is in advanced technologies in the early years of the projection, the greater is the rate of adoption in the later years. In the NEMS model, learning-by-doing is represented in the electricity generation sector, where the capital costs of particular types of new plants decline as more such plants are built.

V. CONCLUSIONS

As long as climate change policies are geared towards keeping a dynamic economy tied to some historical benchmark emissions level, projections of baseline economic and emissions conditions will dominate the costs of emissions control strategies. An equally important consideration is the adopted policy regime, like the extent to which international emissions trading is permitted. In general the more flexibility permitted in where, when, and which GHG reductions may be used to satisfy a commitment, the smaller the economic impacts.

In addition to these baseline and policy assumptions, the model structures also influence the cost estimates associated with climate change actions. Especially important are how each model's structure accounts for the rate and extent to which available inputs and products can be substituted for one another and the rate of improvement in the substitution possibilities themselves over time (i.e., technological change). The representation of the substitution possibilities depends both on the available technologies and on how the retirement of existing equipment and introduction of new technologies are represented. The more flexibility the model includes in the choice of technologies, retirement of old equipment and introduction of new technologies, the lower the economic impacts of emissions reductions.

Technological change occurs when new technologies allow a particular good or service to be produced with fewer inputs, or when a new product is developed. Most models used to project GHG emissions and mitigation costs assume that technological change takes place steadily over time, but does not depend on changes in prices or the implementation of government policy options. Thus, different technologies are selected as prices change, but no new technologies are added to the menu. Recently, analysts have started developing ways by which price-ITC and price-induced increases in the rate of diffusion of new technologies can be included.

The technological change that occurs over time, and that is included in most of the models, reduces the costs of mitigating carbon emissions because it decreases the base case trajectory of GHG emissions. However, it is probably unrealistic to assume that changes in energy prices will not alter the course of technological progress. In the short run, price increases should encourage the diffusion of new technologies. In the intermediate term, they should lead to a more rapid rate of increase in the rate of improvement of existing technologies, and earlier remodeling or replacement of other facilities and equipment. In the long run, they should stimulate the development of brand new technologies. Both kinds of changes should reduce the average rates of GHG emissions per unit of output.

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Table 1
Models Analyzing Post-Kyoto EMF Scenarios

MODEL	AUTHORS
ABARE-GTEM (Australian Bureau of Agriculture and Resources) Economics - Global Trade and Environment Model)	B. Fisher, V. Tulpule, D. Kennedy, S. Brown (ABARE)
AIM (Asian-Pacific Integrated Model)	T. Morita, M.Kainuma (NIES, Japan) Y. Matsuoka (Kyoto University)
CETA (Carbon Emissions Trajectory Assessment)	S. Peck (EPRI) T. Teisberg (Teisberg Assoc.)
FUND (Climate Framework for Uncertainty, Negotiation, and Distribution)	Richard Tol (Vrije Universiteit Amsterdam, Netherlands)
G-Cubed (Global General Equilibrium Growth Model)	W. McKibben (Australian National University) P. Wilcoxen (University of Texas), R. Shackleton (U.S. OMB)
GRAPE (Global Relationship Assessment to Protect the Environment)	Atsushi Kurosawa (Institute of Applied Energy and Research Institute of Innovative Technology for Earth, University of Tokyo, Japan)
IGEM (Intertemporal General Equilibrium Model))	D. Jorgenson (Harvard University) P. Wilcoxen (University of Texas) R. Goettle, M. Sing Ho, D. Slesnick (Dale W. Jorgenson Associates)
MARKAL-Macro	S. Morris (Brookhaven National Laboratory) A. Manne (Stanford University), P. Tseng (U.S. DOE)
MERGE 3.0 (Model for Evaluating Regional and Global Effects of GHG Reductions Policies)	A. Manne (Stanford U.) R. Richels (EPRI)
MIT-EPPA (Emissions Projection and Policy Analysis Model)	H. Jacoby/ J. Reiner (MIT) I. Sue Wing (MIT)
MS-MRT (Multi-Sector - Multi-Region Trade Model)	D. Montgomery/P. Bernstein (Charles River Assoc.) T. Rutherford (U. Colorado)
NEMS (National Energy Modeling System)	R. Earley, S. Holte, M. Hutzler, A. Kydes, R. Eynon, et. al (U.S. Energy Information Agency)
Oxford Model (Oxford Econometrics Model)	Adrian Cooper (Oxford Econometrics) John Walker (Oxford Econometrics)
continued	

RICE (Regional Integrated Climate and Economy Model)	W. Nordhaus (Yale University) J. Boyer (Yale University)
SGM (Second Generation Model)	J. Edmonds, H. Pitcher, R. Sands (Pacific Northwest National Lab)
WORLDSCAN (Central Planning Bureau/ Rijksinstitut voor Volksgezondheid Milieuhygiene)	A. Gielen/H.Timmer (Central Planning Bureau, Netherlands) J. Bollen (RIVM, Netherlands)

Table 2
Model Types

ECONOMY MODEL	Fuel Supplies & Demands By Sector	Energy Technology Detail	Carbon Coefficients
Aggregate Production/Cost Function		CETA MARKAL-Macro MERGE3 NEMS GRAPE	FUND RICE
Multi-sector General Equilibrium	MIT-EPPA WorldScan	ABARE-GTEM AIM MS-MRT SGM	
	G-Cubed IGEM		
Multi-sector Macro-econometric	Oxford		

ENERGY/CARBON MODEL