Technology and the economics of climate change policy

Prepared for the Pew Center on Global Climate Change

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Contents

Foreword *Eileen Claussen, President, Pew Center on Global Climate Change*

Climate change policy analysis is fraught with uncertainty and controversy, but at least one thing is perfectly clear: technological innovation is the key to addressing climate change. Moving the economy to a greenhouse-friendly future will necessitate a profound economic transition — a transition that simply cannot come to pass without technological progress.

In this report, an impressive team of economists led by Jae Edmonds and Joe Roop explains how economic models of climate change take technological innovation into account. The authors demystify a highly technical subject that is essential to sound policy formulation, raising five central insights:

- *All future projections of technological change are a matter of assumption.* Much is known about how technological change has occurred in the past and what will drive it in the future. However, all projections require assumptions about the future role of technological change in the way the economy grows, in the way energy is used, and in the options available as alternatives to fossil fuels.
- *Technological progress reduces the cost of climate change mitigation.* This result is robust across a broad range of model types and assumptions.
- *Significant technological progress occurs over long time horizons.* This fact should be taken into account in establishing lead times for climate policies.
- *Policies and prices can "induce" technological change.* Thus both policy-makers and businesses play a major role in fostering technological change.
- *Modeling "induced" technological change (that is, change stimulated by climate policies or price changes) is important because it more closely reflects reality.* However, modeling this phenomenon is in its infancy.

This report on technological change addresses one of the factors identified by the Pew Center as having the largest influence on economic modeling results. An earlier Center report, "An Introduction to the Economics of Climate Change Policy," by John Weyant describes the five factors, which include: how baseline greenhouse gas projections are measured, what climate policies are considered, how the substitution of goods and services by producers and consumers is represented, and whether and how GHG reduction benefits are addressed. Two other Pew Center reports explore in detail the role of climate policies, with an emphasis on international emissions trading, and the role of substitution in determining the outcome of economic modeling.

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Executive Summary

Stabilizing the global concentration of greenhouse gases (GHGs) in the atmosphere presents one of the grand challenges for humanity in the twenty-first century. This objective will be pursued while most of the world's peoples seek to attain higher standards of living. These goals will be extraordinarily difficult to reconcile with current technologies. Fortunately, technology does not stand still.

The world today depends predominantly on fossil fuels to supply its energy needs. These fuels lead to the release of more than 6 billion metric tons of carbon per year along with significant quantities of other GHGs. Restricting these emissions means developing and deploying new technologies that either do not use fossil fuels, prevent carbon from entering the atmosphere, or remove carbon from the atmosphere.

Irrespective of the climate change problem, most analysts believe that "greenhouse-friendly" technologies such as nuclear, solar, wind, biomass, hydro, and conservation will continue to improve and achieve larger market shares in the future. But even if an energy revolution is fomented, it will take time: it has taken on average a century for the global market share of every major energy technology — from wood to coal to oil — to rise from 1 percent to 50 percent of global consumption.

Thus, understanding the way technology evolves and penetrates the market place is essential to understanding how to address climate change. Economists are in agreement that technological change can dramatically ease the transition to a sustainable climate. No matter how costly one believes this transition may be, technological progress makes it cheaper; no matter how urgent one believes it to be, technological progress allows for longer lead times.

As with all future gazing, one's understanding of future technology becomes murkier the further into the future one attempts to look. Nonetheless, in order to understand predictions regarding the effects of climate change or policies to address it, one must clearly understand the way technological change occurs and the way that process is represented in computer models used to analyze the problem. This paper examines those issues.

Modeling Technological Change

Current understanding of technological progress and its relationship to environmental goals comes from energy system models, which are mathematical and often computer-based representations of how the economy and environment interact. Models that explain how technological change relates to climate change can be organized into two idealized approaches — “top-down” and “bottom-up” models (even though many models contain elements drawn from more than one approach), and there are sometimes important distinctions within these groups. Because it is difficult to predict the future of technology, all models addressing this issue rely on some sort of assumption regarding the future course of technological progress.

Bottom-up models are based on engineering, and come to the problem of emissions limitations from the perspective of the cost and performance of emissions-reducing equipment and practices (such as energy-efficient space heating, lighting, or motors). They generally begin by assuming that a set of advanced technologies either does or will exist, with predetermined cost and efficiency characteristics. They then compare the world as it is now to the world that would exist if the assumed technologies were to be commonly used. Thus, their depiction of climate change policy will depend strongly on the assumptions they make regarding new technologies.

Very importantly, because of the narrow emphasis on the comparative cost and performance of individual technologies, these models usually do not reflect many other aspects of the economy’s response to climate change or climate change policy, such as broader price-induced changes in energy demand, or the way households work or save. They are poorly suited, therefore, to estimating the societal economic cost of climate change or related policies. Instead, their strength lies in forecasting the near-term impacts of specific advances and in illuminating the economic value of possible technological improvements.

Top-down models, in contrast, are generally broad economic models — they depict the way the economy and environment interact in the aggregate. They reproduce the history of technological change in its broad outline but do not necessarily provide details about design, costs, or performance of specific technologies. Rather, they start with a set of initial conditions based on the current state of the economy, and then extrapolate from past experience to look at the future implications of major economic and technological forces.

As they contain little or no explicit technological detail, many "top-down" models represent technological change in terms of a single societal rate at which energy efficiency will continually improve in the future, a rate usually based on observed values in the past. This *exogenous* depiction (so named because its description of technology comes from outside the model), therefore, requires the modeler to make an assumption regarding the value of this ongoing, "autonomous," improvement.

Other top-down models have attempted to replace this "exogenous" assumption with a more detailed representation of the very process by which technology is created and adopted by firms in the economy. This approach starts by assuming that the amount of innovative effort in the economy is a direct function of current and anticipated economic conditions, and is called endogenous technological change, because technological change is projected within the model.

What remains unresolved in all of these approaches is the precise relationship between economic stimuli such as research and development (R&D) expenditures, energy prices, taxes, and subsidies, and the direction and rate of technological change, and the subsequent effect on societal cost. The various types of models discussed here have represented these phenomena in different ways. In bottom-up models, the rate of technological change depends on how different the alternatives are to the present technology as well as how quickly they substitute for one another. For top-down models, the rate of change is determined by assumptions about the "autonomous energy efficiency improvement" (AEEI) or elasticities (responsiveness to price). In top-down models employing endogenous technological change, technological change is often represented as a function of past production, the amount of past R&D, or the extent of energy price changes. Thus, even these endogenous models operate on the basis of an assumption — one regarding what determines technological effort and how that effort translates into progress.

So, regardless of their different structures, all models of technological progress rely on some fundamental assumption regarding future technology, an assumption that plays a central role in determining model results.

Model structure, of course, is important, because different model structures will treat economic phenomena differently. Consider, for example, how changes in the price of energy will affect the rate of technological change. When energy prices increase, the costs of production increase for nearly all goods and services, but more for those goods and services that require larger amounts or more expensive kinds of energy. As these costs flow through the economy, both producers and consumers of these goods and services will search for alternatives to their use. This search leads to innovation and technological change that reduces the need for energy.

This phenomenon is captured in models in a variety of ways, depending on their structure. *Bottom-up* models will capture the effects of energy price increases by improving the cost advantage of assumed new technologies that will then penetrate the economy more rapidly. *Top-down, exogenous* models capture the effect of higher energy prices by allowing firms to substitute capital or labor for energy, but generally will not change the underlying "autonomous" rate of technological change. *Top-down*, *endogenous* models will capture the effect of rising energy prices directly by having technological change accelerate when prices increase, using whatever causal relationship the modeler chooses.

Assumptions Drive Results

While models may take many different approaches to representing technological change, they all tell a remarkably consistent story over the long term. Differences among studies are generally due to differences in assumptions, not to differences in the models themselves.

For example, studies employing bottom-up models usually produce lower estimates than top-down models do of the costs of climate change policy. Bottom-up modelers frequently interpret differences between economic potential and observed market penetration as evidence of inefficient "barriers" that can be overcome by appropriate government policies. Top-down modelers commonly emphasize the role of markets and prices in deciding whether alternative technologies will be used in production. Top-down modelers tend to assume that market actors in the economy are already making optimal choices about whether and when to use particular technologies. Thus top-down models tend to assume that if a technology is not penetrating the marketplace, there must be economic costs to using that technology. These interpretations are based on the modelers' assumptions, but are not themselves part of the structure of the models. The models themselves also make some difference. Bottom-up models are much more likely than top-down models to show substantial, immediate penetration of new technologies. This is because bottom-up models assume that individual technologies compete on the basis of cost and performance, and that a more efficient process will capture a significant part of the market. Top-down models on the other hand, assume that these technology choices are more complex, and are linked to a host of other production and consumption choices being made throughout the economy.

A recent Stanford Energy Modeling Forum (EMF) study demonstrated that the span of results from top-down models was sufficiently wide to encompass all of the bottom-up results. A related EMF study revealed that where it was possible to standardize assumptions for discount rates, capital-stock turnover rates, ancillary environmental benefits, and engineering descriptions of the technologies, any observed gap between top-down and bottom-up studies largely evaporated. Thus, the *type* of model proves to be a secondary consideration in determining the nature of its results: the *assumptions* that enter these models drive the process. For example, one study compared the cost of stabilizing the concentration of carbon dioxide at twice the preindustrial level under two scenarios: one assuming only currently available technologies, and one assuming technologies that forecasters expect to be available by the end of this century. There was a ten-fold difference in cost attributable to differences in technology adoption, performance, and cost alone. In short, the way a model represents the climate change problem over a period of decades, if not generations, cannot be understood until the assumptions it has made regarding technological progress have been made transparent.

Future Research on Technological Change

There are two promising approaches to developing a better understanding of the role of technology in addressing the climate change issue. The first is to combine the best features of the top-down and bottom-up models in a single modeling framework — introducing better engineering representations into a consistent, general, energy-economic setting. The second is to continue to pursue the development of fully endogenous models of technological change. Both approaches can help estimate the costs of policy as well as identify and rank technology opportunities.

The current state-of-the-art may leave analysts unable to predict the nature, rate, and direction of technological change without resorting to important assumptions. It is also clear that one cannot fully understand the climate change problem without understanding technological progress, and that without dramatic technological developments, the road to climate stabilization will be an arduous one.

I. Introduction

Technology produces both goods and services (which humans relish) and greenhouse gas (GHG) emissions (which they do not). Technology has made it possible for human societies to produce $25 trillion of new goods and services annually. However, many advanced technologies utilize fossil fuels, which has led to the release of large amounts of carbon to the atmosphere, and the scientific consensus is that these releases will cause the earth's climate to change.

The United Nations Framework Convention on Climate Change (UNFCCC), crafted in Rio de Janeiro in 1992, provides an international mechanism to address the climate change issue while recognizing the need for sustainable economic development. It entered into force in 1994, and has been ratified by more than 180 nations (as of June 30, 2000). The ultimate objective of the agreement is the stabilization of GHG concentrations in the atmosphere at levels that would prevent dangerous anthropogenic interference with the climate. Unless a "safe" concentration turns out to be very high, stabilizing the concentrations of GHGs will be a challenging problem.

Humans have released enough carbon to the atmosphere to raise atmospheric concentrations of carbon dioxide (CO_2), a GHG, by 33 percent[1] from preindustrial levels. Stabilizing the atmospheric concentration of CO_2 at, for example, twice the preindustrial concentration requires per capita global emissions to peak and then decline to half their 1990 value by the end of the twenty-first century. This would seem challenging enough, were it not for the fact that only poor nations currently have low levels of emissions. These nations aspire to the developed nations' affluence, and will pursue growth vigorously during the twenty-first century. Stabilizing GHG concentrations would be a monumentally difficult challenge with current technologies, but, fortunately, technology does not stand still.

Since before the industrial revolution, economies and societies have evolved as a result of technological change. A long progression of inventions — engines, power generation systems, industrial processes, and appliances — has changed people's lives. Society has moved from a reliance on wind, water, animal power, and wood to reliance first on coal, and then on natural gas and petroleum. This technological change has been a major cause of global climate change, but it has had benefits as well. Economic growth is, in part, the result of technological change that allows a healthier, better educated, and thus more productive work force. A more productive labor force leads to higher incomes and more savings that are converted into more or better factories and equipment, which in turn require energy in order to produce goods. Higher incomes also translate into the purchase of more goods and services, all of which consume energy in one form or another.

Energy *per se* is not the problem. It is the release of the GHGs that are a byproduct of the use of energy that is undesirable. Fossil fuels are the only sources of energy that result in net emissions of CO_2 to the atmosphere.[2] Even among fossil fuels, GHG emissions vary greatly.[3] Other energy forms such as solar photovoltaics (PV), wind, hydropower, nuclear, and fusion have no net direct emissions into the atmosphere. Furthermore, GHGs can now be captured after combustion, or carbon could eventually be removed prior to combustion, turning the fossil fuels into sources of energy that do not emit CO_2.[4] Thus, in addition to energy conservation, a great number of technological options are potentially available. The penetration of low-emissions energy technologies will depend on the evolution of these technologies compared to the higher-emissions alternatives.

Economic models of growth and energy use are tools for understanding how consumers and businesses search for better technologies, and how policy can influence the direction of and effort expended on that search. A common feature of these models is that they incorporate technological change in the way the economy grows, in the way energy is used, and in the options available as alternatives to fossil fuels.

The focus of this report is technological change, how it is represented in models of economic growth and energy use, and how these representations can affect estimates of the costs of reducing GHG emissions — i.e., mitigation costs. The next section provides a definition of technological change and a description of how technological change affects economic growth, energy use, and carbon mitigation in the economy. The third section describes how technological change is incorporated into models of climate change emissions and emissions mitigation. The fourth section then surveys the literature to see what identifiable differences alternative treatments of technological change make in forecasts of output, energy use, carbon emissions, and mitigation costs. The final section draws conclusions about the effect of technological change on estimates of mitigation costs.

II. What is the Technological Change Issue?

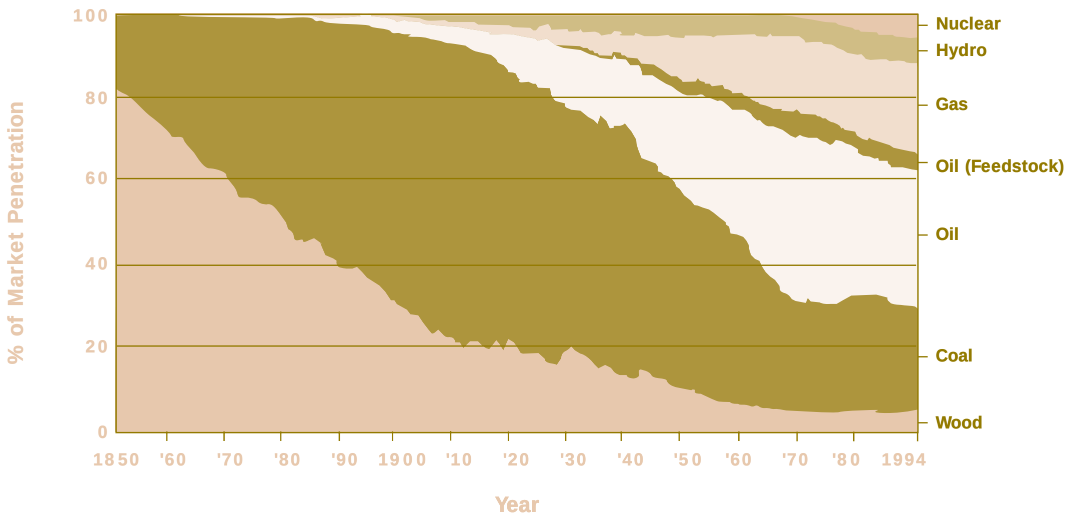
Technological change is a major driver in how a country's economic output increases. This happens for several reasons. If a country's population can be productively employed, its output grows as its population grows. As the amount of physical capital (machinery, transportation infrastructure, etc.) associated with that population "deepens" (becomes more abundant per worker), output per worker increases and that causes the economy to grow. The economy will also grow as the capital stock directly associated with individuals ("human capital," i.e., how educated and well-trained individuals are) grows. Finally, the economy also grows as a result of improved types, quality, and use of capital stock. This is called technological change.

Carbon emissions from this growth will depend upon the amounts and types of energy sources and energy technologies that are used, and other consequences of growth such as land clearing. Energy demand will depend on the efficiency with which energy is used and the responsiveness of the use of energy to changes in its price. The carbon emissions consequences of meeting this energy demand will depend on the timing and availability of low-carbon forms of energy and energy technologies. Technological change will include development of backstop technologies (i.e., technologies that substitute for carbon emitting technologies), will improve the efficiency with which energy is used, and will increase the efficiency with which energy can be discovered and extracted. In myriad ways, technological change will affect both the way a country grows and how its emissions evolve over time.

The Institute of International Applied Systems Analysis (IIASA) of Austria has found that it takes between 50 and 100 years for an energy form to increase its global market share from 1 percent to 50 percent.[5] Figure 1 shows the percentage of market penetration in the world's energy market for seven fuels from 1850-1994. Oil, for example, took 90 years to grow from 1 percent to 40 percent of the energy market and has still not reached the 70 percent market share coal reached in 1913. Natural gas has captured an increasing share of the market, rising from a 1 percent to a 25 percent share of the global energy system over the past 85 years. Despite the increased growth in oil and natural gas, other fuels such as hydro- and nuclear power have also grown, while coal and wood still account for nearly 25 percent of the global energy market share.

Figure 1

Global Market Penetration of Fuels from 1850-1994



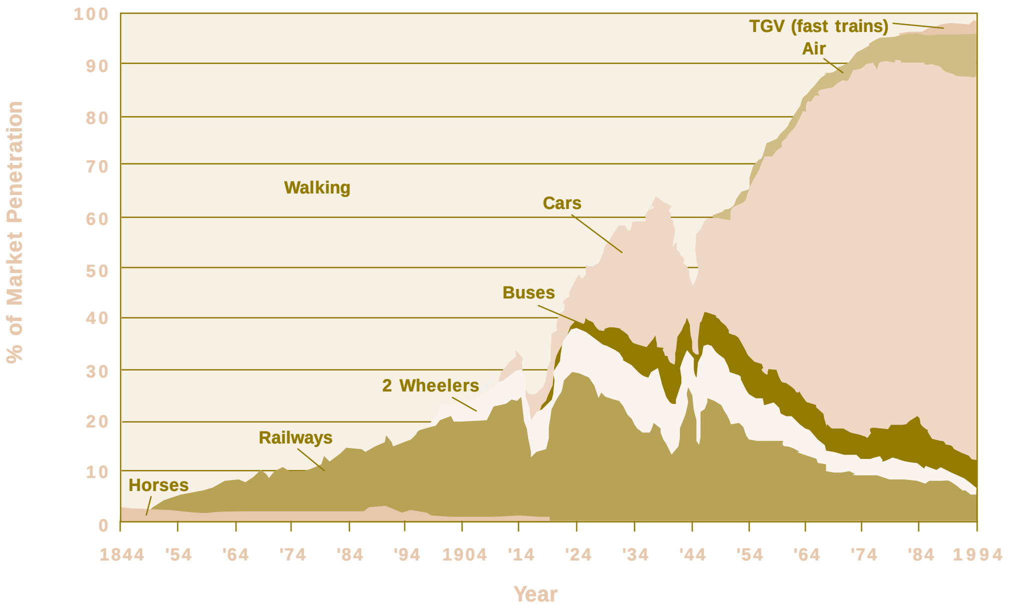
Source: Grübler, A. 1998. *Technology and Global Change.* Cambridge University Press. Cambridge, United Kingdom.

Technological change also has a profound effect on how people live over both the short- and long-term. Over short periods of time, technological change can result in startling changes in how people work and live. A recent example is the introduction of the personal computer. Since 1980, the computing power of desktop computers has increased by a factor of 100, while their cost has been reduced by a factor of four, adjusted for inflation. These changes, in turn, have opened up entirely new uses for computers and have changed the way in which many people work and live.

Over long periods of time, technological change affects communications, transportation, and how businesses function. One hundred years ago, the telephone, the automobile, and the incandescent light bulb were in their infancy. For example, as seen in Figure 2, prior to 1850, passenger transport in France was dominated by walking. It was not until 1940 that walking was overtaken by the combined market penetration of rail, buses, and cars. The market penetration of the internal combustion engine led to the personal automobile eclipsing all other modes combined during the 1960s, and then stagnating in the past two decades due to ascension of air travel and TGV (fast trains).

Figure 2

Market Penetration of Transportation Technologies in France (1844-1994)



Source: Grübler, A. 1998. *Technology and Global Change*. Cambridge University Press. Cambridge, United Kingdom.

Technological change alters the economy over time, affects the rate of economic growth, and helps determine carbon emissions. Increasing knowledge will affect future technological change, but it is not known exactly how research and development (R&D) directs technological change. Clearly technological change could have a large impact on the cost of climate change mitigation. The major issues are how technological change affects the economy and how technological change affects carbon emissions. These issues provide a backdrop to how technological change is treated in climate change models.

A. How Technological Change Affects the Economy

Technology and the economy are inseparable. In the 1950s, Robert Solow of the Massachusetts Institute of Technology developed a theoretical argument for the importance of technological change as the prime long-term determinant of continued increases in the standard of living. Simon Kuznets empirically codified this result in the 1970s. Both men were awarded Nobel Prizes for their work.[6] These and other studies have shown that growth can occur as a result of four basic causes. Following Mokyr,[7] these are:

- *Capital deepening.* If the capital stock grows at a rate faster than the growth of the working population, output per labor hour increases. The gain from forgoing consumption today to invest in capital for greater output tomorrow is what motivates investment. Technological change occurs when the capital put into place is more efficient than the older capital it replaces. Capital grows and output per labor hour increases, perhaps enhanced by improvements in labor quality, which is also an element of technological change.

- *More efficient allocation of resources.* This can be the result of improved division of labor or may occur as a result of specialization and trade. One of the best known examples of improved division of labor is the assembly line pioneered by Henry Ford. A modern example is "just-in-time" delivery of inventories. Controlling carbon emissions is an example of an activity that can be done more efficiently through trade, since emissions reductions have different unit costs in different places. Carbon emissions trading benefits are the topic of a companion paper published by the Pew Center last year,[8] and are taken into account in most global economic models.

- *Scale effects.* That is, doubling inputs more than doubles output. One reason is that increasing scale spreads fixed costs over more units. For example, the unit costs of producing one vehicle are lower using technology that produces a million cars per year than using technology that produces only a thousand cars per year. Scale effects are widely observed, but in macroeconomic and general equilibrium models, if scale effects occur, they are assumed to occur below the macro-economy level. Scale effects are especially difficult to include in models because they are not compatible with the usual assumption of pure competition made in these models, as Goulder and Schneider[9] have indicated.[10]

- *Increases in knowledge.* These can be fundamental insights into how the world works or simply better ways of organizing the production process to increase output. Much of the observed technological change comes from advances in knowledge that lead to gradual improvements in efficiency. These increases in knowledge are the long-term effects of learning-by-doing (LBD: becoming more productive as the process becomes more familiar) and gradual improvements in technology that Rosenberg[11] has documented so persuasively.

Beyond these gradual changes, however, lie the dramatic shifts in knowledge and technique that can so profoundly influence the structure of economic systems in the future. Mokyr refers to these dramatic changes as “macroinventions” and argues that without them, improvements through LBD would be subject to the same law of diminishing returns as all other economic activity.[12] It is the creation of entirely new technologies — the atmospheric engine of Newcomen (the breakthrough that allowed the development of the first successful steam engine), the converter of Bessemer (that allowed steel to be produced cheaply for the first time), and, more recently, the transistor — that allows progress to continue unabated. These new technologies typically start by providing a specialized service at a high cost in a specialized application. As experience is gained, the technology improves and its costs decline. The decline in cost enables the technology to migrate to a wider set of applications, where further experience leads to further modifications and improvements, and stimulates the development of complementary technologies. But these macroinventions cannot be easily anticipated and they usually take a long time to have an impact on the overall economy.

Whether gradual or “macro” in scale, technological change that results from increases in knowledge is an especially important source of economic growth. To the economist, that portion of our growth that cannot be explained by increases in inputs is considered technological change. Any improvement in the quality of inputs, other measurable indicators of economic efficiency (such as improved inventory control or “just-in-time” delivery of supplies), and things that are not measurable are all part of technological change.

After accounting for all the measurable changes both in inputs and in the efficiency of inputs, the “unexplained” technological change is a significant portion of total growth. In a thorough study of the sources of economic progress in the United States, Edward Denison concluded that of the 1.89 percent per year improvement in national income per person between 1929 and 1969, only 0.40 percentage points were attributable to increases in factor inputs. Of the rest, a 1.49 percentage point difference, 0.9 percentage points are attributable to “advances in knowledge and not elsewhere classified.” That is, technological change accounts for nearly 80 percent of economic growth, and 60 percent of this 80 percent cannot be explained by measurable changes in the quality or efficiency of inputs. In other words, nearly half of the cause of the growth over this period is unknown. This unexplained portion occurred over 40 years that included the worst depression in U.S. history. Over the shorter period 1948 to 1969, the unexplained residual was 1.16 percentage points of the total of 2.17 percent per year, or more than half.[13]

The perspective of the economist provides an alternative to the perspective of the technologist or engineer, to whom technological change is more understandable — i.e., it is any change in equipment or technique that allows quicker, better, and cheaper ways of getting work done. So the economist knows what causes technological change, but not what it is; the engineer knows what it is, but not what causes it. This difference in perspective is important in determining how technological change is included in economic models.

Technological change usually has its effect on growth over a period of time. The process that transforms inventions into improvements in output is characterized by the sequence: invention-innovation-diffusion. The diffusion of technologies that are economically superior is a gradual process, the more “macro” the invention, the longer it takes to penetrate the market.[14]

B. How Technological Change Affects Carbon Emissions

There are four different ways in which technological change can affect carbon emissions: some may be seen as being an unambiguous benefit, but technological change does not always reduce GHG emissions.

- Technological change can make carbon-based fuels cheaper (e.g., through improvements in the efficiency of fossil fuel extraction). Part of the reason for the current concern about GHG emissions is that technological change has increased reliance on carbon-based fuels while making them available at modest cost.[15]

- Technological change can also affect the overall rate of growth of the economy through improvements in labor productivity. As with changes in the efficiency of fossil fuel extraction, this too would tend to increase emissions, unless there were concomitant improvements in energy efficiency.[16]

- Technological change can increase the rate of improvement in alternatives to carbon-emitting energy technologies.

- Technological change can increase the rate of improvement in the efficiency with which carbon-based fuels are used.

These last two influences are the major routes by which technological change reduces carbon emissions. Thus they are discussed below.[17]

The Rate of Improvement in Alternatives to Carbon-Emitting Technologies

Non-carbon emitting technologies, such as biomass, wind, and hydro, were the dominant energy forms before the age of fossil fuels. New versions of these technologies, plus technologies that would allow the capture and sequestration of carbon from fossil fuels, could provide the technological mechanisms for controlling carbon accumulation in the atmosphere.

The Rate of Improvement in the Use of Energy

Improvement in the efficiency of energy use can occur as a result of price changes or technological change, or a combination of both. The efficiency of energy use will improve over time as new investments combine with new knowledge to provide the capital that uses energy more efficiently. These improvements may be stimulated by price increases in energy, such as the United States experienced in both the early and late 1970s. Improvements are usually reported as energy intensity declines — reductions in the amount of energy required to produce a specified level of output. For example, U.S. industrial energy intensity declined from about 25,000 British thermal units (Btu)/dollar of output in 1972 to about 17,000 Btu/dollar of output in 1987.[18]

C. An Unknown Technological Future

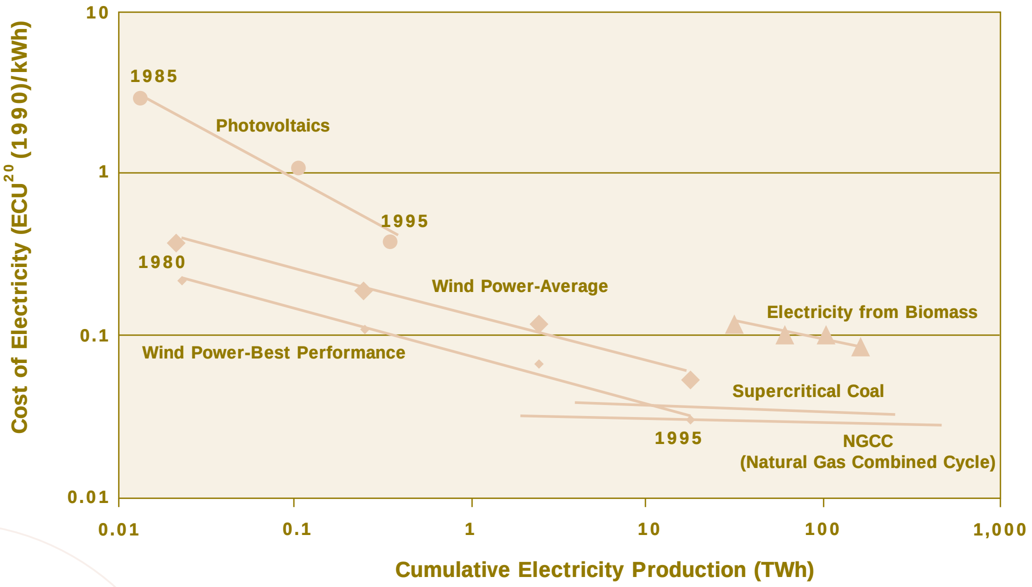
While much is known about past technological change, much less is known about future technological change. These uncertainties include where inventions will come from; what inventions will become successful; what any given dollar of R&D will return; how much learning will occur; how quickly a particular product or process will diffuse into wider use; or where the next big breakthrough will come. There is no evidence in the literature that any single technology will provide society with the ability to control the cost of emissions mitigation.

Still, centuries of experience suggest that a suite of new and improved technologies will become available over time, both through incremental improvements and through “macroinventions.” Incremental technological improvement, or “learning curves,” affects existing technologies, and takes advantage of existing infrastructure and supporting technological systems. Macroinventions open new markets and stimulate the creation and dissemination of new infrastructure and complementary technologies. The large-scale introduction of low-cost carbon capture and sequestration technologies would constitute a macroinvention.

Figure 3 illustrates how the electricity costs for five technologies in the European Union have declined as the level of installed capacity has increased. The figure shows how technologies such as wind, solar PV and biomass have much steeper learning curves than advanced fossil fuel technologies such as natural gas and coal, giving the impression that their costs could soon be equal. However, both coal (gasified clean coal) and natural gas technologies have an absolute cost advantage, although costs for electricity generated by wind have been nearly equal to the costs of electricity generated by coal and gas since 1995.[19]

Figure 3

Electric Technologies in the European Union 1980-1995



Source: International Energy Agency. 2000. *Experience Curves for Energy Technology Policy.* [pg. 21]
©OECD/IEA, 2000

With all the ways that technological change can affect the path of growth and resource use, which is most amenable to human intervention? What can be done to stimulate innovation and technological change? According to *The Economist*, in a recent article discussing a collection of papers on the chemical industry and economic growth:

> “What matters most? What is the main thing governments must do to spur economic growth? Ah, well, that remains a mystery.”[21]

While analysts cannot completely solve this mystery, it is possible to shed some light on what might be most effective in reducing the costs of GHG emissions mitigation via technological change. Technological advances in energy efficiency are believed to be extremely important in reducing the future cost of GHG emissions mitigation. The literature is unanimous on this point. It is hard to overestimate the importance of developing and commercializing new and improved energy technologies over the course of this century. The value of future improvements in GHG related technologies, relative to the present set of technologies, has been estimated to be in the trillions of dollars. Models are used to come up with such estimates. How technological advances are integrated into economic models of GHG emissions is the topic of the next section.

III. How Technological Change Appears in Economic Models of Climate Change

Economic models are simplified characterizations of economies that capture the important elements of an economic system for a particular problem at hand. Economic models try to capture the important elements of growth in economic systems and the important factors that determine what resources are used and how. They are predicated on a known current economic structure and operate under the assumption that this structure either will continue or that it will change in specified ways. Models can capture technological change as it relates to that structure, but models cannot integrate structural changes that are not easily foreseen.

Economic models of climate change, with a time horizon of many decades, rely on some metric of technological change to capture the march of technical progress over long periods. This march will affect the scale of human economic activity, the level of social welfare (i.e., how well-off society considers itself to be), and how economic actors use and produce energy. A change in any measure of well-being (for example a country's output) as small as seven-tenths of one percent per year can, over the course of a century, double that measure of well-being.

Although there is consensus that technological change drives down mitigation costs, there is considerable contention about how much and what kind of technological change there will be. A case has been made that the impact of technological change is underestimated in climate change models, and thus that the mitigation cost estimates are too high, but contrary evidence also exists.[22]

A. Taxonomy Used to Characterize Economic Models

Economic models of climate change are generally classified into two categories: top-down and bottom-up. These two categories emphasize differences in the way modelers reflect the way the world works. The top-down models are normally longer-term, and predicated on "market-clearing"[23] as a way to achieve economic efficiency. The top-down models do not rely on direct descriptions of technology, although they may include specific technologies. The bottom-up models are built on engineering foundations. They begin with the characterization of the cost and performance of the technology and show the consequences of using alternative technologies. These two categories are described in more detail below.

Top-down models

These models are disciplined by the form and structure of economic relationships — accounting rules that define economic aggregates such as Gross Domestic Product (GDP), and market clearing through price and quantity adjustments to achieve equilibrium. These models use a set of equations to describe the complex web of decisions made by producers and consumers. Top-down models may model the supply and demand balance in every market (general equilibrium models), or emphasize a particular set of markets such as energy markets (partial equilibrium models). They may be global, regional or country-specific, depending on their emphasis. Usually in these models, the rate at which energy efficiency improves is determined by three major parameters:

- the “autonomous energy efficiency improvement” (AEEI) parameter (which specifies how the amount of energy required to produce a given level of output would decline over time as a result of technological change, independent of energy prices);
- the responsiveness of changes in energy supply and demand to changes in the prices of other inputs (i.e., the elasticity of substitution between various energy forms and other inputs); and
- the price elasticity of demand for energy (i.e., the responsiveness of energy demand to changes in energy prices).

While typically these parameters are exogenous (assumptions of the model), in some cases they are treated as endogenous (produced by the model).

Bottom-up models

These models, in contrast to top-down models, are usually technological or energy-engineering models of industries or sectors with considerable technology detail in the provision of energy services. Because the emphasis is on engineering details, they usually focus on the shorter term. A rich suite of cost and performance information for various technologies allows more energy-efficient technologies to penetrate the market over time. The penetration of new technology is usually modeled based on the costs and performance characteristics of that technology relative to the less efficient technology. In contrast to the top-down models, the bottom-up models embed new technology and directly model the pattern of technology penetration without fully addressing the broader economic cause(s) of market penetration. These models are stronger on describing the *benefits* of investment in energy efficient technologies than on describing its causes.

Both top-down and bottom-up models use an underlying economic framework to allow for technological change. Top-down models use a few variables describing technological change to alter the costs of production at a commodity or industry level. Bottom-up models characterize technologies directly and in detail — technological change occurs as one technology is substituted for another based on economic considerations, usually life-cycle costs (i.e., costs over the expected life of the equipment or project). Bottom-up modelers frequently interpret differences between a technology's economic potential and its observed market penetration as evidence that there are "barriers" to its adoption that can be overcome by appropriate action. Top-down models commonly emphasize the dynamic function of markets and prices in determining the general composition, magnitude, cost, and performance of alternative technologies used in production. Top-down models are predicated on the assumption that market mechanisms will ensure efficiency and thus any observed barriers are rational.[24]

B. Taxonomy Used to Describe Technological Change in Economic Models

The distinction between top-down and bottom-up models is common in the literature, but not very descriptive of how technologies are introduced within the models. Economic models of GHG emissions introduce technological change in the four ways described below.

Technology Snapshots

This category of models describes, usually in considerable detail, what technologies will be available in the future. As history unfolds in these models, a new snapshot of the technology replaces the earlier snapshot through time. Alternative technologies are described in terms of costs, energy use per unit of output, etc. They are assumed to be available and to provide the same services that current technologies provide, but at a lower cost and with lower carbon emissions. The model then "selects" these technologies according to economic criteria. This approach provides a description of a particular suite of technologies over time, generally based on engineering foundations.

Backstop Technologies

These are a special sub-class of technology snapshots that substitute for fossil energy technologies at particular prices or times. These technologies are identified separately because they are widely used in economic climate change models, both in bottom-up and top-down models. These technologies are introduced because they have zero or low carbon emissions. By definition, a "backstop" must be able to produce as much energy service as the economy needs at a fixed — and usually relatively high — price. Thus the backstop technology or technologies establish the upper bound cost of providing or using energy. Backstop technologies are sometimes idealized generic model creations, but sometimes are more fully specified. For example, a specific backstop technology for power generation might be solar photovoltaics (PV), nuclear power, fusion energy, carbon sequestration, or hydrogen fuels.

Exogenous Technological Change

In these models, the effects of technological change are specified by assumption and are frequently calibrated to historic experience. The rate and the responsiveness may or may not be constant over time. Through the exogenous change approach, the modeler can explore the effect of different parameters of technological change on the costs of mitigating GHGs. The modeler specifies the magnitude of the effects of technological change by controlling the *rate* of efficiency improvements (generally the AEEI) and the substitution and demand elasticities.

Endogenous Technological Change (ETC)

This type of model attempts to model not only the state of technology and its rate of change, but also how that rate itself may be changed by other factors over time. The rate of technological change is determined within the model using a set of general rules and primary assumptions. For example, a learning-by-doing (LBD) model might have the rate of technological change be a function of cumulative production and potential performance of particular technologies. These models are more complicated than the simpler specifications they replace, and also demand that the modeler have some basis for estimating the potential performance and market penetration of included technologies, as well as the mechanisms which govern the realization of that potential. These models must predict the state of technology, the rate of change of that technological state, and factors that change the rate of change. The rates of technological change respond to different endogenous variables, depending on the model. These include price, cumulative production, and investment in R&D. The ETC approach produces a set of dynamic links between R&D in one period and energy use in another.

Most top-down models would fall within the Exogenous Technological Change category, but they might contain elements of ETC. It is also common for these models to allow for backstop technologies, especially in energy supply, where they can be used to set a maximum cost of controlling GHG emissions. Bottom-up models emphasize the causes and opportunity costs[25] of investment in energy and carbon efficiency. Bottom-up models are almost always Technology Snapshot models, although some of these models are also ETC models. That is, they examine a suite of technological alternatives at a point in time and examine how different elements of the suite might compete.

These different ways of modeling technological change cover the range of how technology is modeled, and they give rise to differences in modeling strategies, differences in time perspectives, and perceptions about how efficiently the economy is operating.

C. Costs in Economic Models of Climate Change

The penetration of new technologies into the marketplace will have a direct impact on the costs of GHG mitigation no matter how costs are measured. Hourcade and Robinson provide four broad categories of how costs can be measured.[26] These include:

- *Direct engineering costs* — the hiring of an architectural and engineering firm and/or the direct engineering costs such as equipment;
- *Financial costs* — the costs of acquiring financial capital;
- *Sectoral costs* — aggregates of any cost measure providing additional production capacity for a particular industrial sector. For example, top-down models calculate investment costs, which are the value of the stream of future consumption that is forgone when one is required to mitigate carbon emissions. Other models calculate resource costs, which are instantaneous opportunity costs of capital, labor, etc., used to produce and maintain the technology.

- *Macroeconomic costs* — aggregates over sectoral costs, or broader aggregate economic measures (e.g., GDP loss, although there is no direct relationship between changes in aggregate output as measured by GDP and changes in true economic welfare).[27]

Direct engineering and financial costs are usually combined to provide the life-cycle costs of a technology or project. They include the costs of siting the equipment plus annual energy, operations, and maintenance costs, all reduced to a net present value[28] or levelized[29] cost. Direct engineering and financial costs are especially relevant for Technology Snapshot characterizations of technological change.

Generally, costs of climate change mitigation are calculated based on the difference between some reference scenario and a different scenario with lower emissions. These differences may arise as a result of a variety of changes. They may be the engineering costs or financial costs associated with the adoption of a new, less carbon-emitting technology. They may be associated with costs in a particular sector of the economy, such as the electricity-producing sector, when a new technology is introduced (either aggregated from life-cycle costs or calculated as investment costs). At the sectoral level, they may also be counted as resource costs, e.g., the costs associated with diversion of inputs from production to R&D activities that reduce immediate output and consumption. Costs may also be counted at the macroeconomic level — e.g., as GDP loss — or as the national economic welfare loss from measures to reduce emissions. The rate at which technical improvements appear and are adopted will affect all of these costs.

Different approaches to modeling technological change lead to different definitions and estimates of costs. A useful distinction in understanding how technological change affects mitigation costs is how technological change is introduced and whether it is treated as exogenous (an assumption used by the model) or endogenous (a result of the model). However, even within the same general approach (e.g., the exogenous technological change approach), there are variants that will produce different definitions of costs (see Section IV).

IV. How Technological Change Affects Greenhouse Gas Mitigation Cost Estimates

Numerous international and regional studies have examined how climate change objectives could be achieved. Some of these studies compare the results of a variety of models. Other analysts have used individual models to examine mitigation costs, and have reported these results in journals, conference proceedings, and other venues. This chapter will report on a number of these studies identifying a number of model differences as highlighted in Table 1. This table describes how technology is addressed based on the characterizations used in Section III.B of this report. This vast literature[30] leads to a number of conclusions that are described in this section.

A. Model Assumptions Matter

Choosing the class of model (i.e., top-down or bottom-up) is less important to GHG mitigation cost estimates than other model differences and key assumptions. Several studies have looked at how differences in mitigation cost estimates depend more on key model assumptions and structure than the type of model used.[31] A separate Pew Center report by John Weyant examines this in detail.[32] Choosing the class of model (i.e., top-down or bottom-up) is less important to GHG mitigation cost estimates than models' differences in: (1) definitions of costs and benefits; (2) depictions of technological change dynamics; (3) how baselines are defined; (4) assumptions on what government policies are or will be put in place; and (5) how flexible consumer and producer choices are in the face of rising energy prices.

One study by Hourcade *et al.*[34] states that while the choice of models may affect the results, there remains a wide gap in results that is not explained by the type of model. Differences appear to be explained by assumptions regarding whether the reference case is already more or less economically efficient, and whether there are only a limited number of possible efficiency improvements. Top-down modelers tend to assume that the reference case (i.e., how things are in the absence of climate change policy) is more or less economically efficient. The consequences of this assumption are that any change — such as GHG reductions — imposes some cost, because it necessarily results in a loss of economic efficiency. Bottom-up modelers tend to assume, on the other hand, that the reference case is relatively

Table 1

Technological Change Characteristics of Models Cited[33]

Model	Model Category	Technology Change (TC)Characteristics	Reference
CETA Carbon Emissions Trajectory Assessment	Top-down	Exogeneous TC Technology Snapshot	Peck and Teisburg (1992)
CRTM Canadian Recursive Trade Model	Top-down	Exogeneous TC	Rutherford (1992)
DGEM Dynamic General Equilibrium Model	Top-down	Exogenous TC	Jorgenson and Wilcoxen (1990)
DIAM Dynamic Integrated Assessment Model	Bottom-up	Technology Snapshot Endogenous TC	Grubb *et al.* (1995)
DICE Dynamic Integrated Climate & Economy Model	Top-down	Exogenous TC	Nordhaus (1994)
ERB Edmonds, Reilly, Barnes Model	Top-down	Exogeneous TC Technology Snapshot	Barnes *et al.* (1992)
ETA-Macro	Top-down	Exogenous TC Technology Snapshot	Manne (1981)
FOSSIL-2	Bottom-up	Technology Snapshot	The AES Corporation and Energy and Environmental Analysis, Inc., (1991)
Global 2100	Top-down	Exogenous TC Technology Snapshot	Manne and Richels (1999)
Goulder and Colleagues	Top-down	Endogeneous TC	Goulder and Schneider (1999); Goulder and Mathai (1998)
Grübler and Gritsevskii	Bottom-up	Technology Snapshot Endogenous TC	Grübler and Gritsevskii (1999)
ICAM-3 Integrated Climate Assessment Model	Bottom-up	Technology Snapshot Endogenous TC	Dowlatabadi (1998)
MARKAL-Macro	Bottom-up	Technology Snapshot Endogenous	Manne and Wene (1994)
MESSAGE	Bottom-up	Technology Snapshot Endogenous TC	Messner (1999)
OECD-GREEN Dynamic General Equilibrium Model	Top-down	Exogenous TC	Burniaux *et al.* (1990)
SGM Second Generation Model	Top-down	Exogeneous TC Technology Snapshot	Edmonds *et al.* (1995)

inefficient. They tend to assume: (1) that there are market barriers to the adoption of advanced energy efficiency technology; (2) that government policies can overcome these barriers; and (3) that any other costs of these policies are relatively minor. These assumptions lead to the conclusion that there are "free" GHG reductions to be had. Although it is more common for bottom-up than top-down modelers to make these assumptions, these assumptions are not themselves part of the structure of the models.

The models themselves, however, do make some difference. Bottom-up models are much more likely than top-down models to show substantial and immediate penetration of new technologies. This is because bottom-up models assume that different technologies have substantially different efficiencies, and that these technologies compete on the basis of cost and performance. Thus the trade-off is primarily based on efficiency, and the more efficient process will capture a significant part of the market. Where costs and performance are favorable, technological change in these models occurs rapidly (sometimes instantaneously) as new technologies are adopted. Optimizing bottom-up models, such as MARKAL-Macro, have new technologies dominating the market as soon as they are available.

In contrast, top-down economic models introduce technological change through the relationships between economic inputs (e.g., raw materials) and outputs (e.g., finished goods). The models describe these relationships mathematically using parameters (such as the AEEI). Technological change in these models tends to occur through subtle and continuous changes in these relationships, not through the sudden penetration of new technologies.

A single individual who is building both a top-down and a bottom-up model could overcome the inherent differences in the two models. In top-down models, this could be done by making larger and more rapid adjustments in the parameters than top-down modelers would typically make. Or the analyst could make the assumption that particular backstop technologies set a cap on the cost of controlling GHG emissions. In the bottom-up model, the analyst could slow down the technology penetration by having the model consider other factors besides cost and performance (e.g., technological risk), or by requiring a greater cost advantage for the more efficient technologies before they can begin to penetrate the market.

B. Additional Technological Change Lowers Mitigation Costs

A variety of studies all come to the conclusion that if technological change accelerates, the cost of GHG mitigation declines. Several of these studies are described below.

The Energy Modeling Forum (EMF-12) studied an accelerated technology scenario using four different models: ERB,[35] Fossil-2,[36] Global 2100,[37] and CRTM.[38] The modelers introduced the new technologies as backstops. A new carbon-free fuel was assumed to cost $50 for the same amount of energy one could obtain from a barrel of oil. (Oil prices recently have ranged from $14 to $35 per barrel.)

A new carbon-free electric technology was assumed to cost 5 cents per kWh. (This is the average electricity price for the U.S. economy now.) All four of the models showed dramatically lower mitigation costs. "GDP losses for a 20 percent emissions reduction scenario were 65 percent lower for the accelerated technology scenario."[39]

A number of recent studies introduced a variety of new technologies and explored their effect on mitigation costs.[40] For example, Hourcade *et al.*[41] compared assumptions about backstop technologies from a number of studies of European Union countries. The article concluded that (1) emissions reduction costs decrease over time, simply because more technologies become available; and (2) the magnitude of this effect depends on the characteristics of the assumed backstop technologies. In this study, the Netherlands, for example, included fuel cells and hydrogen-fired equipment and therefore forecast large cost reductions over time.

Edmonds *et al.*[42] explored the costs of achieving different atmospheric CO_2 concentrations under different technology assumptions. They used MiniCAM[43] to estimate discounted GDP impacts for three technology scenarios: (1) no technological change or static technology; (2) some technological change — i.e., the technology forecast of the Intergovernmental Panel on Climate Change (IPCC);[44] and (3) advanced technologies.[45] The technology assumptions made a big difference in the costs of achieving different atmospheric concentrations. To achieve a ceiling of 450 ppmv, the impact on world GDP ranged from 2.73 percent at static technology, to 0.47 percent for IPCC technologies, to only 0.05 percent for advanced technologies. At the less stringent goal of 750 ppmv, costs were 1.03 percent, 0.02 percent and zero percent for the same technology scenarios, respectively.

In EMF-14,[46] the accelerated technology scenario introduced 400 exajoules of biomass in 2020, 20 percent of which is available at $1.20 per gigajoule and the remainder at $2.40 per gigajoule (1990 dollars). These backstops lowered mitigation costs. (One hundred exajoules of energy is about what the United States will consume in the year 2000.)

In a study by MacCracken *et al.*,[47] five advanced technologies were introduced into the ERB model. In addition to introducing new technologies, a variety of scenarios based on penetration rates, carbon emissions over time, and concentration levels were constructed.[48] These scenarios were compared to a set of reference cases that achieved a specific environmental objective (called a reference path) using existing technologies. For a given environmental objective, the advanced technology scenario cost estimates ranged from 20 to 80 percent of the reference costs. *However, the costs in any given scenario were highly dependent on the associated technology penetration rates — the lower the rates, the closer the costs to the reference case.* Relative to achieving a 550 ppmv target, achieving a more stringent 450 ppmv concentration generally doubles the cost, regardless of technology penetration rates. The model results further showed that, under an advanced technology scenario, there are large benefits of delaying the onset of emissions controls because the delay gives the new technologies more time to penetrate. In fact, delaying the onset of emissions controls allows one to achieve both a more stringent target and a lower cost. Advanced technologies combined with a delay allow a 450 ppmv target to be achieved for $75 billion. Advanced technologies without a delay allow a less stringent target (550 ppmv) to be achieved for $375 billion.

C. All Future Technological Change is a Matter of Assumption

While most of the debate in the literature is about whose forecasts of climate change impacts are most realistic, there is a tendency to lose sight of the fact that all future prognostications of technological change are ultimately derived from assumptions. Some of these assumptions are well-established energy folklore, but they are nonetheless assumptions. For example, many modelers once assumed the future availability of the Alcoa process, an energy-saving alternative to the Hall process for producing aluminum. However, after nearly 20 years of research and development, researchers have abandoned the Alcoa process. Modelers either make assumptions about the technology directly (technology snapshots), about the rate of change of various parameters (exogenous technological change), or about the effect of R&D, price changes, or production growth on improvements in technologies or reductions in costs (endogenous technological change).

D. The Form of Technological Change Used Affects Costs

There is virtually no cost to some forms of technological change. Whereas AEEI and LBD have low or zero costs, R&D and new technology substitution can add to mitigation costs. Both LBD and AEEI fall into the category of low- or no-cost technological change. In the case of LBD and AEEI, the simple progress of time or the normal accumulation of experience is all that is required for progress to occur. With AEEI, just the passage of time reduces energy input requirements. With LBD, the simple accumulation of production capacity lowers the cost and resources required for production. These models specify that no additional resources have to be sacrificed to achieve these changes, so society does not have to give up anything.

On the other hand, both R&D and technology replacement entail considerable societal costs that may partially offset the benefits of technology innovation and diffusion. R&D requires expensive facilities and personnel. The R&D investment may pay off in terms of future technological breakthroughs, but it may not. Technology replacement can be costly because it may involve the premature retirement of useful equipment. For example, the owner of a factory might have made an investment in energy equipment which was expected to last ten years. If carbon control policies were implemented, that equipment may have to be replaced with new and more efficient technology. If the policies were imposed less than ten years after the factory owner made his investment, money would be lost. Thus the form of technological change that the model assumes will affect the costs of innovation and diffusion, and thus mitigation costs.

E. Modeling Endogenous Technological Change is Important, but Difficult

Incorporating endogenous technological change into economic climate change models is important, but the real-world processes that give rise to technological change are so complex that no model currently captures them well. There are three ways that endogenous technological change (ETC) is introduced into economic models of climate change. The first is to alter the rate of efficiency improvement in energy use by converting the AEEI to a variable determined by the model (rather than an assumption of the model). One way to endogenize the energy efficiency improvement factor is to make it a function of energy prices. A second approach introduces an explicit R&D activity that leads to new technologies that affect the efficiency of energy use. The third way is to allow improvement in energy efficiency (or abatement activities) as experience is gained in the production of energy-intensive goods. This modeling of LBD usually allows energy efficiency to improve based on cumulative production, i.e., how much is produced over a span of time.

Numerous models have attempted to “endogenize” technical change using one or more of the three methods (price effects, explicit R&D, or LBD). Grubb *et al.* were among the first to explicitly model how ETC might affect abatement costs by using a simple aggregate model with two forms of ETC R&D

investment and LBD.[49] They found that much greater abatement takes place when ETC is taken into account than when it is not.

Another study by Dowlatabadi and Oravetz[50] modeled ETC through price effects. A price-dependent energy efficiency improvement (EEI) parameter was integrated into their Integrated Climate Assessment Model (ICAM-3). Price-induced efficiency improvements significantly lowered emissions for the United States and reduced the cost of limiting CO_2 concentrations. This occurred because as energy prices increased, technological change occurred more rapidly, energy use declined, and carbon emissions per unit of energy used declined. In a 1998 article, Dowlatabadi elaborated on these findings[51] by adding LBD and allowing for the discovery of new fossil fuel reserves through productivity improvements in mining and exploration. Mitigation costs were at their lowest when prices induced energy efficiency improvements and when LBD was effective. Reducing the costs of supplying fossil energy slowed efficiency improvements and made mitigation costs higher. Costs of energy efficiency improvements were highest when fossil energy prices were low and when new fossil reserves were added. This article provided a new and interesting dimension to modeling ETC. However the results still remain far removed from events in the real world.

Goulder and Mathai took a very different approach to the above analysis.[52] Their analysis incorporates LBD and an explicit R&D sector in solving for two objectives. One objective is to find the optimal path of abatement that minimizes the cost of achieving a specified atmospheric concentration target (the *optimal path* case). The second objective is to find the minimum combined costs of abatement, investment costs, and damages from emissions (the *minimum cost* case). The three cases in the study were: (1) LBD-induced technological change; (2) R&D-induced technological change; and (3) no ETC. In all cases the objectives are achieved through the imposition of a carbon tax. In the R&D variant, costs are affected by R&D investment. In the LBD variant, the costs are influenced by abatement experience.

The results show that meeting the *optimal path* objective is less expensive with R&D-induced technological change than without it. Overall costs are lower and the required carbon tax is reduced. Initial abatement costs fall, and later abatement costs rise — i.e., some abatement is shifted from the present to the future. LBD-induced technological change also reduces overall costs and the carbon tax, but the effect on the time profile of abatement costs is ambiguous.[53] In meeting the *minimum cost* objective, R&D lowers net costs and lowers the required carbon tax at all points in time. Thus either version of ETC lowers costs. However, unlike LBD, R&D is not "free," so R&D costs must be included in the overall cost of mitigation.

Another promising study of ETC was recently published by Goulder and Schneider[54] introducing two types of R&D activity[55] — “sector-specific” and “spillovers.” In their model, sector-specific knowledge is derived from R&D expenditures paid by that industry or sector, and only benefits that sector. R&D that has economy-wide benefits (“spillovers”) can be financed by government subsidies. Their model forecasted that a carbon tax would reduce the initial use of both carbon and alternative fuels, but that R&D would later become more attractive in the non-carbon energy industry. The introduction of a carbon tax caused a decline in GDP, more so with ETC than without it. This occurred because ETC encourages R&D, and there is a cost to R&D investment. However, ETC also resulted in greater abatement, and therefore greater environmental benefits. Thus the net benefits from a given carbon tax were higher in the presence of ETC. Subsidies to R&D had either positive or negative consequences. Industry-specific R&D subsidies led to over-investment in R&D, but R&D subsidies of knowledge spillovers reduced the costs of achieving emissions reductions. Both the Goulder and Schneider and the Goulder and Matthai analyses constitute progress in the sense that additional complexities were added and the trade-offs were identified. Still, they include only a highly simplified, unrealistic connection between R&D expenditures and future technological change.

A number of bottom-up modelers have integrated ETC with technology snapshot models in interesting ways. For example, Messner has introduced ETC into the MESSAGE model,[56] which includes cost and performance information about a variety of advanced technologies, including advanced coal, new nuclear, wind, solar thermal and solar PV technologies. A base or static case assumes that the costs of new technologies stay at their 1990 levels. In the LBD case, these costs are forecast to decline over time as the level of investment in the technology increases. Each doubling of the number of units reduces costs by 7 to 28 percent, depending on the technology. For example, in the LBD case, solar PV costs decline by a factor of five by the year 2050. In the static case, standard coal and nuclear power are still the dominant technologies in 2050. When LBD is built into the cost adjustments, the optimal technology mix changes considerably — i.e., advanced coal, new nuclear, and solar technologies dominate the mix. Investment costs also become much lower in the LBD case compared to the base case (i.e., about 20 percent lower by 2050).

Another study by Grübler and Gritsevskii[57] used a bottom-up model to explore delays in the adoption of a technology as learning occurs, or as uncertainty arises. They constructed a simple model with three technologies (existing, incremental, and revolutionary) that satisfy all of the economy's demand for products and services. Each technology uses a single resource, the price of which increases as it is depleted. These three technologies have different associated investment costs (including R&D) and very different associated efficiencies. If the modeler exogenously specifies improvement in the incremental technology, it immediately replaces the existing technology. If LBD is introduced (i.e., it takes time for the incremental technology to improve), the incremental technology penetrates rapidly, replacing the existing technology within about 10 years. But if this learning is uncertain, then penetration is delayed until about 2015. The revolutionary technology becomes dominant much later, by about 2070, unless it too is subject to uncertainty, in which case it penetrates by about 2090. Other simulations indicate that the revolutionary technology will penetrate much more rapidly if learning rates are increased, or if taxes are imposed on resource use.

These, and other, approaches to ETC from the top-down and bottom-up communities add to the set of models that can be used to explore technological change and its effect on mitigation costs.[58] However, a gap still exists between how economic models depict the process of technological change, and what happens in reality.

V. Conclusions

Technological change in the use of energy and in the development of backstop technologies both work to reduce GHG emissions and lower the cost of mitigation over time. Technological changes that reduce the cost of fossil energy or raise the productivity of labor will likely increase emissions and raise the costs of mitigation.

Technological change that improves energy efficiency for the economy as a whole will tend to lower mitigation costs. The literature on this point is unanimous and unambiguous.[59] Carbon efficiency improvements, that is, the development of low- and non-carbon technology options, and improvements in efficiency of the use of energy will both tend to reduce mitigation costs. The magnitude of these changes over centuries is great. Indeed, these changes can be so great that a number of studies argue for "when flexibility"[60] to take full advantage of these technologies as they are developed.

Modeling the rate of technological change is in its infancy. While relatively simple models can be built that illustrate the effects of inducing technological change through R&D expenditures, through LBD, and through price, these models fall far short of the complexity of the real world. Moreover, ETC models substitute assumptions about what factors affect the rate of technological change for assumptions about technological change itself. While these models provide some insights, they do not fully explain the process of technological change, nor do they relieve the modeler of having to make assumptions about the process.

The value to a policy-maker of using economic models of climate change to assess the cost of mitigating GHG emissions will depend on the specific question being asked and the design of the model used. If the question is how specific technologies may reduce emissions or mitigation costs, then the model must be capable of allowing that technology to affect the outcome of the model simulation. A general understanding of the model and how technological change is treated in the model will serve the policy-maker well. The questions below provide insight into the value of the model for answering specific policy questions. In some cases, the answers to the questions need to differentiate between cause and effect in the real world and how models depict the cause and effect relationship.

What determines the rate of technological change in models?

In bottom-up models, the *rate* of technological change depends on how different the snapshots are, and how quickly they substitute for one another. In ETC versions of these models, the rate of technological change also depends on LBD. For top-down models with exogenous technological change, the rate of change is determined by assumption about the AEEI or elasticities. For top-down models in which technological change is endogenous, the rate of change depends on the rate of past production, the amount of past R&D, or the extent of energy price changes.

How do energy prices affect technological change?

When energy prices increase, the costs of production increase for nearly all goods and services. Costs increase more for those goods and services that require larger amounts or more expensive kinds of energy. As these costs flow through the economy, both producers and consumers will search for alternatives to these goods and services. This search leads to innovation and technological change that reduces the need for energy. This phenomenon is captured in models in a variety of ways. Endogenous models of technological change can capture this directly by having technological change accelerate when prices increase. In technology snapshot models, energy price increases may improve the cost advantage of new technologies so they penetrate faster. Top-down models capture the effect of higher energy prices through the elasticity of substitution between energy and other inputs.

How does R&D affect technological change?

R&D affects technological change in three basic ways. First, R&D contributes to knowledge generally, and leads to future developments that may (or may not) directly improve the efficiency of energy use. Second, R&D can lead directly to changes in the efficiency of energy-using equipment (for example, the research on high-efficiency lighting done by the U.S. Department of Energy). Third, R&D can lead to improvements in the efficiency of extraction of fossil fuel and thus encourage, through lower prices, further consumption of fossil fuels. Indirectly, contributions to knowledge are integrated into production techniques that lower the costs of production and may reduce energy use. The complex chain of events that leads from R&D expenditures to increases in knowledge and hence to improvements in energy efficiency is important, but is neither well understood, nor the topic of this paper. In models of endogenous technological change, the models assume that R&D at one point in time will lead to improved energy efficiency at a later point in time.

While economic models can explore what might happen, they cannot forecast what *will* happen. How these events unfold in the future will depend not only on how technology affects mitigation costs, but also on what decision-makers do in response to the threat of global warming: from R&D investments, to the timing of policy, to the international climate change negotiations. Economic models can help to inform those actions. A better understanding of what the models say should lead to better decisions, and to reduced costs of GHG emissions mitigation.

Endnotes

1. Atmospheric CO_2 has risen from preindustrial levels of approximately 275 parts per million volume (ppmv, a measure of concentration in the atmosphere) to more than 365 ppmv.

2. Biomass also contains carbon and therefore releases CO_2 to the atmosphere. However, because the carbon was taken out of the atmosphere in the growing process, the use of biomass fuels has no net effect on CO_2 concentrations in the atmosphere. In fact, crops such as switch grass may actually remove more carbon from the atmosphere than the harvested portion releases, because the residual builds up in the soils.

3. To produce a given amount of energy, natural gas yields approximately half the carbon emissions of coal. Oil emissions lie between those produced by the use of coal and natural gas.

4. Hydrogen combustion produces water vapor as a byproduct. While water vapor is itself a GHG, the scale of potential human injection appears to be insufficient to affect climate. Carbon capture still leaves the problems of transport and disposal, which present technological, social, and environmental challenges of their own.

5. Grübler, A. 1998. *Technology and Global Change.* Cambridge University Press. Cambridge, United Kingdom.

6. Simon Kuznets received the Bank of Sweden Prize in Economic Sciences in Memory of Alfred Nobel in 1971, partly on the basis of *Economic Growth of Nations*, Harvard University Press, 1971. Robert Solow received the same prize in 1987 for his contributions to the theory of economic growth.

7. Mokyr, J. 1990. *Twenty-Five Centuries of Technological Change: A Historical Survey.* Harwood Academic Publishers, New York.

8. Edmonds, J., M.J. Scott, J.M. Roop, and C.N. MacCracken. 1999. *International Emissions Trading and Global Climate Change.* The Pew Center on Global Climate Change, Arlington, VA.

9. Goulder, L.H. and S.H. Schneider. 1999. "Induced Technological Change and the Attractiveness of CO_2 Abatement Policies," *Resource and Energy Economics* **21**: 211-53.

10. If scale effects were possible in competitive models (i.e., if costs continued to decline as the size of plants increased), the model would move to a solution with only one producer for each such good, eliminating competition.

11. See especially the section, "The cumulative impact of small improvements," in Rosenburg, N. 1982. "Technology Interdependence in the American Economy," Chapter 3 in *Inside the black box: Technology and economics.* Cambridge University Press, New York. pp. 62-70. The article was originally published in *Technology and Culture*, January, 1979.

12. Mokyr. *op. cit.* p. 103.

13. Denison, E.F. 1974. *Accounting for United States Economic Growth, 1929-1969.* The Brookings Institution. Table 9.7. Washington, D.C.

14. One of the first economic studies to document this market penetration is by Griliches. The Griliches citation and others are given in Jaffe, A.B. and R.N. Stavins, 1994. "The energy-efficiency gap: What does it mean?" *Energy Policy* **22**(10): 804-810.

15. While this improvement has been dramatic (see, for example, M.N. Fagan. 1995. "Resource Depletion and Technological change: Effects on U.S. Crude Oil Finding Costs from 1977 to 1994," *Energy Journal* **18**(4): 91-105, who suggests that the rate of technological change in refining has increased over time, reaching 15 percent per year in cost reductions in 1994) and is important to carbon emissions, there is very little mention of this type of technological change in the literature. Accordingly, there is no further emphasis on this point.

16. Labor productivity directly affects economic growth, in both models and reality. The rate of productivity growth for the economy as a whole can be associated with improvements in inputs (e.g., a more educated labor force), or changes in the ratio of one input to another, (e.g., capital deepening). The work of Denison decomposes the sources of productivity change into about 20 different such improvements (Denison, *op. cit.*). As used in climate change models, this component of technological change usually shows up as changes in labor productivity (that is, output per hour of labor), and is determined or assumed. Improvements in labor productivity may cause the economy to grow more rapidly, and increase the use of carbon-based fuels, so the likely effect of an increase in labor productivity would be an increase in carbon emissions. Because the focus of this paper is on how models depict technological change that reduces carbon emissions, there is little further emphasis on this point.

17. There is a fifth way that models depict the rate of technological change that is indirect and therefore not highlighted in the literature. That is through the responsiveness of changes in demand to energy prices. As energy price increases become embedded in both goods used to produce other goods and final consumption goods, firms and consumers will economize on these now more expensive goods and services. These shifts in both final consumption and production will alter the structure of the economy over time, and bring about technological change that would otherwise not have occurred. These shifts are additional to the two mechanisms discussed in the text below.

18. Energy intensity is defined as energy use divided by output, where output may be denominated in dollars. Energy efficiency is physical output per unit of energy input — e.g., tons of steel per million Btu. For examples of intensity measures, see: Belzer, D.B., J.M. Roop, R.J. Sands, and D.L. Greene. 1995. *Energy Conservation Trends: Understanding the Factors Affecting Energy Conservation Gains and Their Implications for Policy Development.* DOE/PO-0034, U.S. Department of Energy. Washington, D.C.

19. The wind and PV cost numbers do not include back-up systems to cover down periods. While this is not a problem for marginal deployment, it becomes an important issue when significant displacement of conventional capacity is addressed.

20. The cost of electricity is measured in the European Currency Unit (ECU), which was an artificial "basket" currency used by the member states of the European Union (EU) as their internal accounting unit. The ECU was conceived on March 13, 1979, by the European Economic Community (EEC), the predecessor of the EU, as a unit of account for the currency area called the European Monetary System (EMS). The ECU was also the precursor of the new single European currency, the euro, which was introduced on January 1, 1999. The ECU is used here instead of the euro since the figures do not equal the euro conversion of 1999.

21. The Economist, March 6, 1999. p.72. This quotation originally appeared in Arora, A., R. Landau, and N. Rosenberg, eds. 1999. *Chemicals and long-term economic growth.* Economic Focus. Wiley Interscience. New York.

22. Ausubel, J.H. "Technical progress and climate change." *Energy Policy* **23**(4/5): 411-416. For contrary evidence, see the Memorandum to Deputy Secretary L. Summers from J. Gruber. Subject: Do we always overestimate environmental control costs? October 15, 1997, U.S. Department of the Treasury.

23. For example, finding a set of prices such that all markets are in equilibrium.

24. Barriers to energy efficiency were the topic for an entire issue of *Energy Policy* **22**(10), 1994. See especially Jaffe and Stavins, *op. cit.*, Reference 14; Sanstad, A.H. and R.B. Howarth "Normal markets, market imperfections, and energy efficiency," pp. 811-818; and H.G. Huntington, "Been Top Down So Long It Looks Like Bottom Up To Me," pp. 833-839.

25. That is, the cost of forgone opportunities.

26. Hourcade, J.C. and J. Robinson. 1996. "Mitigating factors: Assessing the costs of reducing GHG emissions." *Energy Policy* **24**(10/11): 863-873.

27. To see this, consider the impacts from the recent Hurricane Hugo. Rebuilding afterwards clearly cost society in foregone wealth and current and future consumption, but added to current economic output as measured by GDP.

28. A measure of cumulative costs over time that takes into account individuals' preferences for incurring benefits sooner and costs later.

29. A constant annual cost that is equivalent, when accumulated over time, to the net present value. Actual costs will vary from year to year. Levelized costs smooth this variation.

30. Hourcade, J.C., K. Halsnaes, M. Maccard, W.E. Montgomery, R. Richels, J. Robinson, P.R. Shukla, and P. Sturm. 1996. "A Review of Mitigation Cost Studies," Chapter 9 in *Climate Change 1995: Economic and Social Dimensions of Climate Change*, J.P. Bruce, H. Lee, and E.F. Haites, eds. Cambridge University Press, Cambridge, UK, pp. 297-366. Hourcade, J.C., R. Richels, and J. Robinson. 1996. "Estimating the Costs of Mitigating Greenhouse Gases," Chapter 8, ibid., pp. 263-296. More condensed reviews are available in the 1996 *Energy Policy* **24**(10/11): Hourcade, J.C. and J. Robinson, "Mitigating factors: Assessing the costs of reducing GHG emissions," pp. 863-873; Richels, R. and P. Sturm, "The costs of CO_2 emissions reductions: Some insights from global analyses," pp. 875-887.

31. See especially three articles in *Energy Policy* **24**(10/11): Hourcade, J.C. and J. Robinson, "Mitigating factors: Assessing the costs of reducing GHG emissions," pp. 863-873; Richels, R. and P. Sturm, "The costs of CO_2 emissions reduction: Some insights from global analysis," pp. 875-887; and Weyant, J.P., "Commentary: The IPCC energy assessment," pp. 1005-1008.

32. Weyant, J.P. 2000. *The Economy and Global Climate Change: An Introduction to the Economics of Climate Change Policy.* The Pew Center on Global Climate Change, Arlington, VA. This paper shows how five key determinants provide a framework for interpreting the vast array of available GHG emissions reduction cost and benefit estimates. The determinants include three factors external to models: (1) baseline emissions projections; (2) the policy regime considered; and (3) whether emissions reduction benefits are considered – and two major model features: (4) the way substitution — among inputs into the production of goods and services and among goods and services purchased by consumers — is represented; and (5) how technological change provides new products to consumers, or allows existing goods and services to be produced with fewer inputs.

33. Hourcade, J.C. *et al., op cit.* p. 322.

34. The references for the table are as follows:

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Messner, S. 1997. "Endogenized Technological Learning in an Energy Systems Model." *Journal of Evolutionary Economics,* **7**(3): 291-313.

Peck, S.C. and T.J. Teisberg. 1992. "CETA: A Model for Carbon Emissions Trajectory Assessment," *Energy Journal* **13**(1): 55-77.

Rutherford, T. 1992. "The welfare effects of fossil carbon reductions: Results from a recursive dynamic trade model." Working Paper 112, OECD/GD(92)89, OECD, Paris.

The AES Corporation and Energy and Environmental Analysis, Inc. 1991. *Fossil-2 Energy Policy Model Documented Listing* (6 volumes), Arlington, VA.

35. Barns, D.W. *et al.* 1992. The Edmonds-Reilly model is found in Edmonds, J.A. and J.M. Reilly. 1985. *Global Energy: Assessing the Future*. Oxford University Press, New York.

36. Fossil-2 is a systems dynamics model originally developed at Dartmouth, then revised as Fossil-2 for forecasting

and policy analysis at the Department of Energy's Office of Policy, Planning and Evaluation. After modification to the transportation and utility sectors, it was renamed IDEAS, and is currently available through OnLocation, Inc., located in Washington, D.C. (http://www.onlocationinc.com).

37. Global 2100 is documented in Manne, A.S. and R.G. Richels. 1992. *Buying Greenhouse Insurance*, MIT Press, Cambridge, MA.

38. The Canadian Recursive Trade Model (CRTM) is reported in Rutherford, T. 1992. "The Welfare Effects of Fossil Carbon Reductions: Results from a Recursive Dynamic Trade Model." Working Paper No. 112, OECD/GD(92)89, OECD, Paris.

39. Hourcade *et al.*, *op. cit.* p. 308.

40. See, for example, the following three papers: Edmonds, J. and M. Wise, 1998. "Exploring a Technology Strategy for Stabilizing Atmospheric CO_2," Nota di Lavoro Della Fondazione Eni Enrico Mattes, Foundazione Eni Enrico Mattei, Working Paper Series, Milan, Italy; Edmonds, J. and M. Wise. 1998. "Building Backstop Technologies and Policies to Implement the Framework Convention on Climate Change" *Energy & Environment*, **9**(4): 383-397; and MacCracken, C.N., S.L. Legro, J.A. Edmonds, and W.U. Chandler. 1998. "Climate Change Mitigation Costs: The Roles of Research and Economic Reform," Pacific Northwest National Laboratory, Washington, D.C.

41. Hourcade, J.C. *et al., op. cit.* p. 322.

42. Edmonds, J., M. Wise, and J. Dooley. 1997. "Atmospheric Stabilization and the Role of Energy Technology." in Walker, C.E., M.A. Bloomfield and M. Thorning, eds. *Climate Change Policy, Risk Prioritization and U.S. Economic Growth*, American Council for Capital Formation. Washington, D.C. pp. 71-94.

43. MiniCAM combines ERB with a model of global atmospheric response to emissions and a damage assessment model. See Scott, M.J., R.D. Sands, J. Edmonds, A. Liebentrau, and D. Engel. 1999. "Uncertainty in Integrated Assessment Models: Modeling with MiniCam 1.0," *Energy Policy,* **27**(11): 855-879.

44. Houghton, J.T., G.J. Jenkins, and J.J. Ephraums, eds. 1996. *Climate Change: The IPCC Scientific Assessment*, Cambridge University Press. Cambridge, United Kingdom.

45. The IPCC technology suite includes improvements in power production of 1.0 percent per year from 1990 to 2050, end-use energy intensity improvements of 0.5 percent per year, and non-fossil fuel power generation efficiency improvements of 4.5 percent per year to 2025, then declining to 1.5 percent per year to 2100. Biomass energy prices range from $2.50/GJ to $4.40/GJ, depending on the location and scale of production. Labor productivity also increases at a rate of 2.3 percent per year between 1990 and 2100. These assumptions in combination decrease energy intensity by 1.0 percent per year. The advanced technology scenario included advanced liquefied hydrogen fuel cells; hydrogen transformation from natural gas, biomass, or electrolysis; and the introduction of advanced electric generating facilities such as solar PV and nuclear fusion. Non-carbon electric costs are presumed to reach $0.04/kWh by 2020 and decline by 0.5 percent per year thereafter. Biomass is available in the advanced technology scenario at costs ranging from $1.40/GJ to $2.40/GJ.

46. Weyant, J.P. 1997. "Preliminary Results from EMF-14 on Integrated Assessment of Climate Change." Energy Modeling Forum. Stanford University, Stanford, CA.

47. MacCracken *et al., op.cit*. The technology cases are described on pages 2-5, the global costs on pages 5-12.

48. There are six advanced technology cases: (1) advanced fossil fuel technologies reach 66 percent efficiency in 2050; (2) low-cost biomass, 20 percent of which is available at $1.40/GJ, the rest at $2.40/GJ (the reference case is $2.40/GJ and $4.40/GJ); (3) Case 2 with advanced hydrogen fuel cells used in transportation; (4) Case 3 with additional

costs for liquefaction; (5) solar electric costs reach $0.04/kWh by 2020 and decrease 0.5 percent per year thereafter; and (6) a combination of Cases 1 and 4.

49. Grubb *et al., op. cit.* 1995. Manne and Richels in 1992 were the first to attempt to model the decline of energy costs over time, but they did so by assumption, not by endogenous technological change.

50. Dowlatabadi, H. and M.A. Oravetz. "Understanding Trends in Energy Intensity: a Simple Model of Technological Change." *Energy Policy* in press.

51. Dowlatabadi, H. *op. cit.* pp. 472-492.

52. Goulder, L.H. and K. Mathai. *op.cit.* 1998.

53. These analytical results are then buttressed by numerical simulations using initial values and parameters that follow closely results found in the literature. The numerical results are much in line with the analytical results. The effect on the optimal abatement path with induced (i.e., endogenous) technological change (ITC) is very small, but it lowers the optimal carbon tax path by about 35 percent up to the year 2200. With LBD, the effect on the optimal abatement path is even smaller, but the optimal tax path is lowered by about 40 percent. The fact that LBD has more effect on the optimal tax path "reflects the fact that under LBD-based ITC, technological progress comes about as a 'free' by-product of abatement, rather than as a result of costly expenditures on R&D." Under the *minimum cost case*, which uses a benefit-cost criterion, the optimal concentration is at 800 ppmv, rather than the 550 ppmv imposed in the optimal path case, which uses a cost-effectiveness criterion. This implies that the lower target is too stringent from an efficiency point of view. In sharp contrast to the cost-effective simulations, the benefit-cost simulations show no perceptible difference between the simulation with no ITC and the simulations with ITC, whether as a result of R&D or LBD.

54. Goulder L. and S. Schneider, *op. cit.* 1998.

55. This model is a computable general equilibrium model in which economic output is derived from knowledge capital, regular capital, labor, two forms of energy (carbon emitting and alternative energy), and two intermediate goods (energy intensive and not energy intensive). Knowledge capital can be either specific to the industry (and thus the industry can appropriate R&D benefits) or "spillover" knowledge that benefits other industries as well. The only policy instruments are taxes on output and subsidies for R&D. The model is run to generate base case simulations both with and without induced technological change, and observe the effects of a carbon tax by comparing tax simulations to each of these base cases. Simulations are also undertaken to explore the impact of spillover knowledge and R&D subsidies in various industries. Generally, there are different effects on different industries, both in terms of output and in terms of investment in R&D.

56. Messner, S., *op. cit.* 1997.

57. Grübler, A. and A. Gritsevski, *op. cit.* 1997.

58. Along with IIASA, the Netherlands Energy Research Foundation (ECN) and the Paul Scherrer Institute (PSI) are actively involved in this research. See, for example, Seebregts, A.J. *et al.* 1999 "Endogenous Technological Change in Energy Systems Models," ECN-C—99-025, with authors from all three institutes; Kypreos, S. and L. Barreto, "A Simple Global Electricity MARKAL-Macro Model with Endogenous Learning," PSI (available as ECNws6-kyp2.pdf through the ECN web site: http://www.ecn.nl/main.html, updated 9 March 2000); and Seebregts, A.J., T. Kram, G.J. Schaeffed and A.J.M. Bos, "Modeling technological progress in a MARKAL model for Western Europe including clusters of technologies," ECN-RX—99-028.

59. On the other hand, technological change in the discovery and extraction of fossil energy can raise mitigation costs.

60. "When flexibility" means that emissions reduction deadlines are flexible. This could be implemented through a multi-year averaging period for measuring compliance, or through tying control obligations to capital investments.

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