economics

Induced technological change and climate policy

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

Over the upcoming decades, large-scale reductions in emissions of carbon dioxide (CO_2) and other greenhouse gases (GHGs) will be required to reduce the risks of global climate change. In order to achieve this transformation, the development and diffusion of new technologies to reduce GHG emissions will be critical. As the world's largest and most inventive economy, the United States must play a decisive role in the discovery, innovation, and marketing of these new technologies, and climate policies can be influential drivers in this process.

Technological change occurs for a variety of reasons as firms compete in existing and new markets. However, climate policies can spur *additional* or "induced" technological change (ITC). This can be achieved through technology "push" policies that boost the invention and innovation processes (such as funding for R&D), and through direct emissions control policies that "pull" new technologies into the market (such as a GHG cap-and-trade program).

In this report, Lawrence Goulder of Stanford University explores the role of induced technological change (ITC), and examines the implications of ITC for the effective design of climate policy. These implications fall into four main categories: (1) how much ITC can lower the costs of climate policies, (2) what this means for the timing of policies, (3) the value of announcing policies well in advance of enactment, and (4) the most appropriate use of various policy instruments to boost technological change. Until recently, economic models of climate change could not address these issues. However, state-of-the-art modeling now treats ITC as an integral or "endogenous" component in calculations, thus providing new insights into this critical topic.

This report finds that ITC lowers the cost of achieving GHG reductions, and that the impact of ITC is especially pronounced when policies are announced in advanced. Goulder also concludes that in order to reduce GHG emissions most cost-effectively, both technology-push and emissions reduction policies are required. In addition, although studies show different implications of ITC on the overall timing of climate policy, all find that some abatement must begin now in order to jump-start the critical process of technological change.

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Executive Summary

A central goal of climate policy is to avoid potential changes in climate and associated adverse biophysical impacts by slowing or avoiding the atmospheric build-up of greenhouse gases (GHGs). Technological change will crucially influence the extent to which nations achieve this goal. The direction and extent of technological change over the next century have profound implications for emissions and atmospheric concentrations of GHGs over time, the extent of future climate change, and associated impacts on human welfare.

Climate policy can alter the future by influencing the rate and direction of technological change. "Induced technological change" (ITC) here refers to the additional technological change that is brought about by policy. This report explores how climate policy can induce technological change and examines the implications of ITC for the effective design of climate policy.

Some of the main findings are:

1) The presence of ITC lowers the costs of achieving emissions reductions. By stimulating additional technological change, climate policy can reduce the costs of meeting a given target for reductions in GHG emissions or concentrations. Until recently, most economy-wide climate change policy studies ignored ITC. Models that disregard policy-induced technological advances will tend to overestimate policy costs.

2) The presence of ITC justifies more extensive reductions in GHGs than would otherwise be called for. Because ITC lowers the costs of achieving emissions reductions, the optimal extent of GHG reduction is greater than would be predicted by models that ignore ITC. The net benefits from climate policy are larger as well.

3) The presence of ITC alters the optimal timing of emissions abatement. Although considerable technological change occurs in the absence of policy intervention, climate policy can induce additional technological change by providing incentives for additional research and development (R&D) and by stimulating additional experience with alternative technologies or processes, thereby generating "learning-by-doing." Analysts offer contrasting views as to how ITC alters the optimal timing of emissions abatement compared to a case where climate policy does not affect the rate of technological change (that is, the case with no ITC). Does ITC justify more extensive near-term emissions reductions, or does it justify postponing reductions? Recent analyses indicate that insofar as technological change results from R&D, the presence of ITC justifies somewhat less abatement in the near-term, and more abatement in the future (when technological change has lowered the costs of abatement). On the other hand, if ITC primarily results from learning-by-doing, greater emphasis on abatement in the short term may be called for, since early abatement efforts accelerate the learning process and can thereby lower costs.

4) In the presence of ITC, announcing climate policies in advance can reduce policy costs. Announcing policies in advance can lower the cost of meeting given targets for cumulative abatement or reductions in GHG concentrations. Illustrative results indicate that announcing a $25 per ton carbon tax 10 years in advance can reduce discounted economic costs (as measured by changes in gross domestic product or GDP) by about a third, compared to the same climate policy imposed with no prior notice.

5) Economic analysis offers a justification for public policies to induce technological change, even when the returns are highly uncertain. Uncertainties surround many aspects of ITC. Neither the returns to a given investment in R&D nor the extent of future learning-by-doing can be precisely predicted. As a result, one cannot estimate with precision the cost savings from ITC or pinpoint the optimal timing of abatement. Moreover, while prior announcements of climate policies will yield cost-savings, uncertainties about costs of adjustment make it impossible to accurately forecast these savings. Despite these uncertainties, two key market failures provide a strong rationale for public policy to stimulate ITC. These are: (1) the "spillover benefits" to society as a result of R&D investments by individual firms and (2) the presence of negative "externalities" – adverse impacts that are not accounted for in the market prices of carbon based fuels.

6) To promote ITC and reduce GHG emissions most cost-effectively, two types of policies are required: policies to reduce emissions and incentives for technological innovation. This study emphasizes that two types of policies are necessary to address the two market failures noted above and to achieve, at least-cost to society, a given target for cumulative reductions in emissions or GHG concentrations. Technology incentives can deal with the market failure created by firms' inabilities to capture all the returns on their R&D investments. Direct emissions policies (such as carbon caps or carbon taxes) can deal with the market failure created by climate-related externalities. Attempting to address the climate change problem with only one of these policy approaches cannot fully correct both market failures. As a result, adopting one approach is likely to involve higher costs than utilizing the two approaches in tandem. To date, direct GHG emissions policies have had little political success at the federal level. But there is a strong need for these policies, along with technology incentives, to deal with the prospect of climate change in a cost-effective manner.

I. Introduction

A. The Climate Change Problem

Of all the environmental problems currently faced by mankind, global climate change is potentially one of the most significant. It is also one of the most controversial. Human activities have led to significant increases in atmospheric concentrations of heat-trapping "greenhouse gases" since the pre-industrial era. Concentrations of carbon dioxide (CO_2), in particular, have risen by over 30 percent since 1775, primarily as a result of the combustion of fossil fuels.[1] Although there is still some uncertainty as to the precise implications of higher greenhouse gas (GHG) concentrations for the Earth's climate, atmospheric scientists are moving toward general consensus on the issue. The Intergovernmental Panel on Climate Change (IPCC), an international body of leading scientists studying climate change, asserted in its 2001 *Summary for Policymakers* that "[in the last six years] there is new and stronger evidence [since the IPCC's 1995 report] that most of the warming observed over the last 50 years is attributable to human activities," and that "human influences will continue to change atmospheric composition [of GHGs] throughout the 21st century" (IPCC, 2001). The IPCC also indicated that under "business-as-usual" (BAU) assumptions (that is, in the absence of public action to slow the increase in GHG concentrations), "the global average surface temperature is projected to increase by 1.4 to 5.8 degrees Celsius [2.5 to 10.4 degrees Fahrenheit] over the period 1990 to 2100."

For policy-makers, the fundamental concern is not global warming *per se* but the various biophysical impacts associated with it and the ultimate implications for the well-being of humans and other living things. Gaining political support for climate policies is difficult because the extent of future climate change is highly uncertain: politicians are reluctant to support near-term costs for uncertain benefits in the future. An additional complication is that impacts of climate change are likely to vary significantly across regions of the globe.[2] Some areas might experience significant negative impacts such as sea-level rise, increased prevalence of tropical diseases, reductions in agricultural productivity, and disruptions to ecosystems. On the other hand, other geographical areas or sectors may benefit, at least under moderate temperature increases, although any transition to a substantially different temperature profile will impose significant stresses on natural and human infrastructures.

B. The Importance of Technological Change for Climate Policy

A central goal of climate policy is to avoid potential climate change damages by slowing or avoiding the atmospheric build-up of GHGs. Technological change will crucially influence how successfully nations will achieve this goal. The direction and extent of technological change over the next century have profound implications for BAU emissions of GHGs. In addition, technological change substantially affects the costs of reducing emissions from the BAU trajectory.

Technological change occurs when producers discover and utilize new production methods—methods that enable them to produce goods and services in ways that were previously unknown. Beneficial technological change enables manufacturers to produce the same goods or services using fewer inputs, or better goods and services with the same inputs. The phenomenon of discovery distinguishes technological *change* from technological *substitution,* which usually refers to switching from one known production method to another, already known method.[3]

In the context of climate policy, technological change might allow the economy to reduce its reliance on carbon-based fuels such as coal, oil, and natural gas—thereby reducing emissions of CO_2, the principal greenhouse gas. Consider, for example, the potential significance of technological change in the transportation sector. About 20 percent of CO_2 emissions in the United States derive from the combustion of gasoline (a refined oil product) to power motor vehicles.[4] Considerable research is now underway to develop alternatives to the internal combustion engine, including fuel-cell technology. At present, a car utilizing fuel-cell technology would be considerably more costly to produce than a car utilizing the internal combustion engine. But with sufficient technological change, a fuel-cell car could become competitive. This development in turn could make a substantial difference in terms of the nation's future dependence on fossil fuels and associated CO_2 emissions. Similar possibilities apply in other parts of the economy: ongoing innovations in propeller design continue to reduce the cost of wind-generated electricity considerably, and recent improvements in motor design continue to yield substantial cost reductions in many industrial settings.

This report focuses on the particular implications of induced technological change for emissions and concentrations of CO_2. Carbon dioxide is the major contributor to overall U.S. GHG emissions. It is the primary GHG generated by the energy sector—a sector that could require considerable technological change to achieve substantial reductions in GHGs without large cost increases. However, it should be noted that other GHGs account for nearly 20 percent of U.S. emissions. These gases—which include methane (CH_4), nitrous oxide (N_2O), and a group of industrial gases including perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulfur hexafluoride (SF_6)—are emitted across a wide range of energy, industrial and agricultural sectors. Thus far, public policy provides virtually no incentives for technological innovation to reduce emissions of these other gases. However, there may be considerable potential for ITC to produce cost-effective abatement opportunities for these gases. For a study of how non-CO_2 GHGs could be incorporated in climate policy, see Reilly, Jacoby, and Prinn (2003). Several insights from this report should be applicable to non-CO_2 GHGs as well.

C. Policies That Induce Technological Change

Much technological change occurs without policy intervention. The free enterprise system encourages technological change by offering significant rewards to inventions that yield a competitive advantage in the marketplace. Moreover, many individuals actively strive to invent and expand the knowledge base even without the promise of financial gain. However, in the past two decades policy analysts have become increasingly interested in the potential to stimulate additional technological change through public policies. The technological change that results from policy is often called *induced* technological change (ITC). Through taxes, subsidies, mandated technologies, or other measures, government policies can alter economic incentives and thereby change the course of technological progress.[5] Given the potential importance of technological change for dealing with climate change, policy-makers have become keenly interested in whether the pace of such change can be significantly increased through public policies.[6]

A variety of climate policies can induce technological change. These include taxes on fossil fuels, caps on CO_2 emissions, and subsidies to research and development (R&D) in low-carbon technologies. These policies can be grouped into two main categories. *Direct emissions policies* include taxes on fossil fuels and CO_2 emissions caps. These policies raise the prices of carbon-based fuels, either by taxing such fuels or by restricting their supply by way of limits on the emissions associated with their use. This in turn stimulates technological change by increasing the reward (cost savings) for discovering a process that allows reduced consumption of such fuels, which are now more expensive.[7] *Technology-push policies* include subsidies to R&D in low-carbon technologies, government performance requirements, and strengthened patent protections.[8] R&D subsidies, in particular, lower the cost to firms of investing in knowledge, and thereby expand private incentives to engage in R&D.

Box 1

Alternative Climate-Policy Approaches

Direct Emissions Policies

- carbon taxes
- carbon quotas
- tradable CO_2 (or more generally, GHG) emission permits (cap-and-trade)
- subsidies to CO_2 emissions abatement

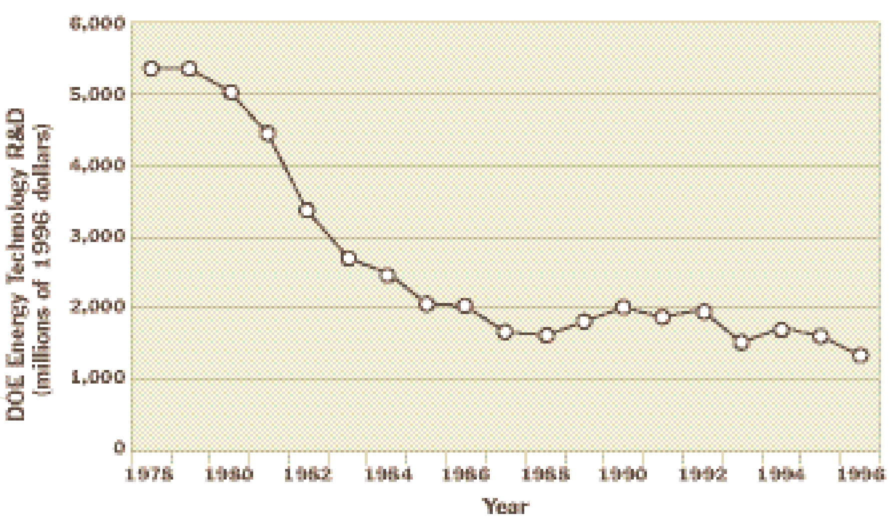
Technology-Push Policies

- subsidies to R&D in low-carbon technologies
- public-sector R&D in low-carbon technologies
- government-financed technology competitions (with awards)
- strengthened patent rules

In the United States at the federal level, only technology-push policies—most prevalently in the form of subsidies to R&D—have enjoyed political success thus far.[9] Under the Clinton Administration, grants to R&D to reduce GHG emissions or oil consumption averaged about $800 million per year, but no direct emissions policies were introduced. More recently, the Bush Administration's climate change plan, announced in February 2002, included $1.3 billion for fiscal year 2003 in R&D subsidies for energy conservation technologies and renewable energy, and $1.7 billion to fund basic scientific research on climate change (Executive Office of the President, 2002). But the plan did not include any caps or taxes on emissions or the fuels that produce them. A likely reason for the appeal of subsidy approaches is that they reward fossil energy industries that have a large economic stake in climate policies and

Figure 1

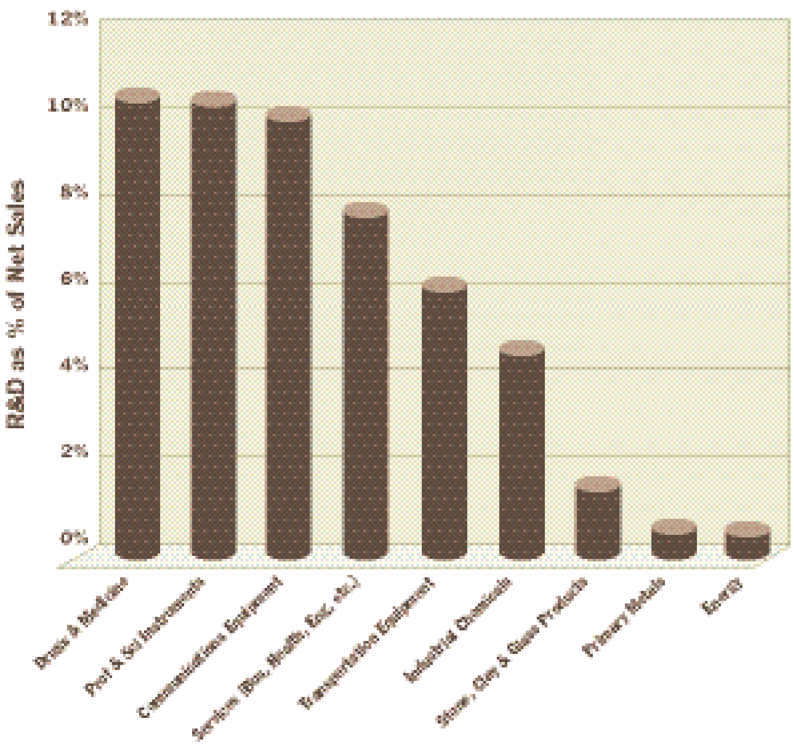
Total U.S. DOE **Energy Technology R&D**



Source: Margolis and Kammen (1999)

Figure 2

R&D as Percent of Net Sales for Selected Sectors in the U.S. in 1995



Source: Margolis and Kammen (1999)

are highly mobilized politically. In contrast, direct emissions policies usually impose costs on these same industries. Thus the carrot (technology subsidies) has proved to be more politically acceptable than the stick (direct emissions policies).[10]

Although several technology-push policies have emerged, overall U.S. energy R&D has declined more or less steadily over the past three decades. Figure 1 illustrates this decline in terms of energy technology R&D expenditures by the U.S. Department of Energy. Figure 2 further indicates that the ratio of R&D investments to the value of net sales is relatively low in the energy sector compared to other sectors. To many, these findings suggest that U.S. policy is not doing enough to encourage energy-related R&D.

D. Promoting Technological Change through Public Policy: Is It Justified?

The question of whether the United States is doing enough to promote R&D—in the energy sector generally or in the specific context of climate policy—should be approached carefully. It is one thing to point out that public policy can influence the rate of technological change. It is another to claim that public intervention of this sort is beneficial to society overall.

Economic theory indicates that public policy has a legitimate role in promoting technological change in the sense that the benefits of intervention can exceed its cost to society. The justification stems from two "market failures." One of these failures reflects the inability of investors in R&D to appropriate all of the knowledge stemming from this investment. Some of the knowledge associated with R&D "spills over" and benefits firms other than the investing firm. Hence the total social return to R&D (which includes these spillover benefits) exceeds the investing firm's private return. As a result, absent public intervention, investments in R&D tend to fall short of the efficient amount—that is, the amount which maximizes social net benefits. This market failure provides a major justification for technology-push policies.[11]

A second market failure stems from the fact that, absent public policy, climate-related costs imposed by the combustion of fossil fuels and by other GHG-producing activities are not reflected in market prices.[12] As long as these environmental costs remain "external" to the marketplace, society will tend to consume fossil fuels at a level that is excessive in terms of economic efficiency: at the margin, the value of fossil fuels consumed is below the true cost to society, which includes both private and external costs. The presence of this externality can justify direct emissions policies (such as carbon taxes or caps on CO_2 emissions) that help bring the price of carbon-based fuels closer to their true social cost.

The above considerations suggest that there is a legitimate role for policy intervention to promote climate-friendly technological change. However, this conclusion itself raises further questions: *How much* intervention is appropriate? And *when* should such intervention take place? These issues are the focus of the discussion that follows.

E. Policy Issues Examined Here

The remainder of this report considers four main issues relating to ITC and climate-change policy.[13] First, it examines the implications of ITC for the costs of climate policies. When does ITC lower the costs of climate policies? Under what circumstances might it eliminate the costs altogether?

Second, it explores the implications of ITC for the timing of emissions abatement. Does the presence of ITC mean that nations should move more quickly to reduce GHG emissions, relative to what they would do if policies did not induce technological change? Since ITC tends to reduce costs, more aggressive near-term action might seem to be justified. On the other hand, if ITC tends to reduce costs mainly in the future, postponing significant emissions abatement to the future might allow resulting cost reductions to be exploited more fully. Which of these opposing viewpoints is correct?

A third issue is whether the presence of ITC implies a dividend from announcing policies in advance. Given that R&D investment by firms represents an important channel for ITC, advance announcements could facilitate a smoother transition to a new policy environment. If so, does this lead to significantly lower policy costs, compared with the case where producers have relatively little advance notice?

A final issue is the choice of policy instruments for stimulating ITC. As noted previously, technological change can be induced through both direct emissions policies and technology-push policies, such as subsidies to R&D. Which of these policies can enable nations to achieve emissions reductions at lower cost? Is a combination of both policies desirable?

II. ITC and the Costs of Emissions Abatement

One reason for the keen interest in ITC is the possibility that it will significantly lower the costs of climate policy initiatives, perhaps even reducing costs to zero. To what extent can ITC lower the costs of climate policies?

A. Two Channels for ITC

Over the last decade, there has been substantial progress in the use of models to evaluate alternative climate change policies. Some models consider individual sectors. Others have a broader focus, examining impacts at a regional, national, or even global level. Until recently, nearly all of the national or multi-nation models treated the rate of technological change as exogenous—that is, unaffected by policy.[14] Clearly, this assumption is unrealistic. Both direct emissions policies and technology-push policies can be expected to have some effect on the rate of technological change.

These effects can occur through two main channels. The first is R&D. Direct emissions policies like carbon taxes or caps on CO_2 emissions would raise prices of fossil fuels and of energy sources derived from them, such as electricity. Firms that utilize these fuels might find it worthwhile to invest more R&D aimed at developing alternative production processes that reduce fossil fuel consumption, since discovery of such processes could now yield significant cost savings. To the extent that R&D investment increases and this leads to increased knowledge, direct emissions policies induce technological change. Technology-push policies such as subsidy programs can also induce technological change by stimulating additional R&D.

The second main channel for ITC is learning-by-doing.[15] Climate policy can encourage firms to adopt production processes that they otherwise might not implement, or to expand their output of certain (low-carbon) products. As firms gain familiarity with these processes, or acquire experience through expanded production, they can discover ways to bring costs down. Such experience-based technological change is called learning-by-doing.

Numerous studies attest to the importance of both R&D and learning-by-doing in reducing costs. Cost reductions may stem from the discovery of new products, new processes, or new forms of management organization. R&D clearly has led to large cost reductions in many important energy-related areas. The National Research Council (NRC) recently studied 39 R&D programs in energy efficiency and fossil energy sponsored by the U.S. Department of Energy, and concluded that these programs taken together yielded an annual rate of return of over 100 percent (NRC, 2001).

Two of the most successful public and private R&D efforts to date have involved wind power and photovoltaic panels. Since 1977, the cost of wind power has dropped by a factor of eight (to about 5 cents per kilowatt-hour (kWh)), while the cost of photovoltaic panels has dropped by more than a factor of three (to 25-30 cents per kWh in regions with the best insolation). Like R&D, learning-by-doing has also yielded significant cost reductions. A typical estimate is that, for relatively new technologies, costs fall by 20 percent for every doubling of cumulative experience.[16] Here the distinction between overall technological change and the policy-*induced* component of technological change should be kept in mind. A considerable amount of R&D and learning-by-doing occurs in the absence of public policy. Our focus here is on the *additional* technological change and cost reductions induced by climate policy, either through policy-induced increases in R&D or policy-induced additional learning-by-doing.

B. Determinants of Cost Reductions from ITC

While identifying the channels through which ITC occurs is relatively straightforward, determining the cost implications is less so. This section considers the cost of reducing national GHG emissions by some given amount. How does ITC affect this cost? Both R&D and learning-by-doing can contribute to cost-reductions in several ways. Some major pathways are shown in Table 1.

R&D-Based Technological Change

The Net Internal R&D Effect

Consider the case where technological change is induced through expanded R&D. If the additional R&D is productive, it will yield new knowledge that reveals lower-cost production methods. The *net internal R&D effect* is the cost reduction (in present value terms) that firms experience as a result of their own R&D commitments, net of the social cost of these commitments.[17]

Table 1

Components of Cost Savings
from Induced Technological Change

R&D-Based Technological Change	Learning-by-Doing-Based Technological Change
Net Internal R&D Effect present value of cost reductions from policy-induced *net* increases in R&D *less* social cost of this R&D	*Net Internal Learning-by-Doing Effect* present value of cost reductions from policy-induced *net* increases in experience and associated learning-by-doing
Net R&D Spillover Effect present value of cost reductions from net spillovers associated with policy-induced net increases in R&D	*Net Learning-by-Doing Spillover Effect* present value of cost reductions from net spillovers associated with policy-induced net increases in experience

The word "net" is included in the name of this effect to acknowledge the possibility that additional inducements to R&D in one sector of the economy may be accompanied by offsetting R&D-related cost impacts in other sectors of the economy. For example, climate policies will tend to induce additional R&D investment by industries that supply fossil fuel alternatives or that use fossil fuels intensively. The same policies, however, can also *discourage* R&D investments by other industries. Incentives for R&D in traditional coal extraction and conversion,[18] for example, might well be diminished by a climate policy. At the same time, other seemingly unrelated industries—such as textiles, civil engineering or computer software—might also lower their R&D expenditures to the extent that climate policy reduces consumer incomes and demands for their output.[19] In addition, increased R&D investment in certain sectors can bid up the prices of key research inputs (e.g., highly qualified engineers and scientists, specialized research equipment, etc.) and thereby discourage R&D by other sectors. In those industries where R&D is reduced (relative to the no-climate-policy or BAU case), there is a smaller contribution to knowledge than would otherwise occur. In such industries, production costs will be higher than in the absence of climate policy. This offsetting effect needs to be considered to arrive at the overall (net) R&D impact.

There is no way to predict with precision the size of the net internal R&D effect: returns on investment in new knowledge are fundamentally uncertain. It is conceivable that the additional R&D investment stimulated by a carbon tax, say, would be just enough to produce a major technological breakthrough that yields a fundamentally lower-cost substitute for fossil fuels. Yet it is also possible that the additional investments in R&D sparked by such a policy would have disappointingly low payoffs. Subsection C below describes results from simulation model experiments aimed at assessing the impact of ITC. The approach taken in these models is to assume that the private return to R&D is comparable to returns from other investments and that the social return (private return plus additional benefits from knowledge spillovers) is comparable to that which has been observed historically. Thus, the models tend to assume that future policy-induced R&D will be about as productive as it has been, on average, in the past.

In this connection, it is important to distinguish policy-induced technological change from policy-induced technological *substitution*. Several studies indicate that, in many circumstances, firms fail to minimize their private costs by overlooking *pre-existing* zero or negative-cost opportunities for emissions reductions.[20] This might reflect characteristics of individual firms, bureaucratic inertia, or an imperfectly competitive market structure. Under these circumstances, a public policy intervention can stimulate the "discovery" of costless emissions reduction opportunities that, in a sense, were already there for the taking. In these instances, a policy stimulus can produce significant emissions reductions at little or no cost to firms.

The phenomenon just described—where policy interventions induce firms to discover existing inefficiencies—is distinct from what usually falls under the concept of R&D-based technological change. Since little or no expenditure on research may be involved, it may be better characterized as a case of technological substitution (that is, a switch to an existing production option) than as the invention or initial discovery of a new production method. No matter what term is applied, however, the result is a policy-induced change in firms' behavior that yields significant emissions reductions at relatively low cost. There is considerable empirical evidence showing that firms sometimes fail to minimize costs, and that zero-cost opportunities exist in specific circumstances involving particular processes or pollutants of specific firms. For example, BP and DuPont have achieved self-imposed targets for GHG emissions reductions years ahead of schedule. Moreover, both companies claim that these efforts actually led to cost-savings.[21] On the other hand, while few researchers question the existence of some no-cost abatement opportunities, many would question whether such opportunities exist on a broad enough scale to allow deep cuts in GHG emissions.[22]

The Net R&D Spillover Effect

A second R&D-based mechanism for technological change is the *net R&D spillover effect.* When firms invest in R&D, not all of the knowledge produced by such investments can be excluded from other firms: in other words, it is difficult to appropriate all of the R&D-generated knowledge. Thus, some firms can benefit from other firms' R&D to the extent that the knowledge spills over from the investing firms to them.

From a social perspective, the cost savings that follow from such spillovers are additional to the direct cost savings achieved by the investing firm. Some firms might experience cost savings both from their own R&D efforts *and* by receiving beneficial knowledge spillovers from the R&D efforts of competing firms. Other firms might simply be free-riders, enjoying positive knowledge spillovers even though they themselves have not increased their R&D.

The *net* spillover effect is large when knowledge spillovers from industries that expand their R&D investments in response to climate policy are big compared with the foregone spillovers from industries that reduce their R&D efforts in response to such policies. This would occur, for example, if the potential spillovers from R&D investments in alternative energy industries far exceeded the foregone potential spillovers from reduced R&D in fossil fuel industries and other industries. Unfortunately, current understanding of the relative magnitude of likely R&D spillover effects is fairly limited. One of the few empirical studies of this phenomenon, by Sakurai, Ioannidis, and Papaconstantinou (1996), suggests that spillover effects are especially important in the information and computer technology sectors, and less important in manufacturing. To the extent that R&D investment by alternative energy industries is likely to produce greater spillover benefits than R&D investment by conventional energy industries—or to utilize inputs (such as computer technology) that involve relatively large spillovers—the net effect will be larger.[23]

Learning-by-Doing-Based Technological Change

The Net Internal Learning-by-Doing Effect

As mentioned, climate policies can cause firms to introduce new or different production methods in order to conserve higher-priced carbon-based fuels. As firms gain experience with these processes, they may learn how to employ them more cheaply. In this way, learning-by-doing reduces the cost of emissions abatement.

Again the word "net" is used here to acknowledge the fact that climate policies can have contrasting impacts on firms' output: while some industries might expand their output relative to a BAU under such policies, others might contract their operations. For those industries that reduce their output, cumulative output or "experience" is reduced and there is less learning than would otherwise have been the case. This reduced learning has an offsetting impact on the overall knowledge generated by the policy.

The Net Learning-by-Doing Spillover Effect

As with knowledge from R&D, knowledge generated through learning-by-doing can spill over to other firms. The net effect will be large if the learning spillovers from industries that expand their output as a result of climate policy are large compared to the foregone learning spillovers associated with other industries' reductions in output.

The foregoing discussion points to a need for better information on the different components of ITC under a climate policy. Additional empirical work on these issues might have significant payoffs. In particular, it would be useful to get better information, at the level of individual sectors or industries, about historic private and social returns to R&D, past patterns of learning-by-doing, the extent to which existing cost-cutting options are overlooked (and the costs of recognizing them), the magnitudes of knowledge spillovers (from both R&D and learning-by-doing), and any offsetting reductions of R&D or learning-by-doing in other sectors.

C. Some Simulation Results with ITC

This section presents results from simulation experiments using several different models to explore the effects of technological change; the findings illustrate a wide range of possible outcomes. Two types of experiments are discussed.[24] In the first, the policy objective is to minimize the cost of meeting a given target for cumulative reductions in GHG emissions or concentrations. These are termed *cost-effectiveness analyses.* In the second type of experiment, the objective is to maximize the net benefits (avoided damages minus costs of abatement) from GHG reductions. These are termed *net-benefit-maximization analyses.* Modeling results for the two types of experiments are described below, followed by discussion of general insights.

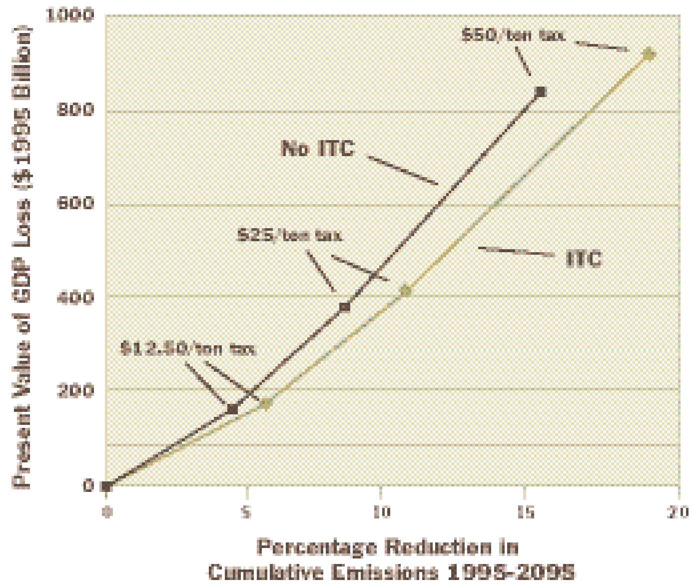
Cost-Effectiveness Analyses

Goulder and Schneider (1999) apply a general equilibrium simulation model to illustrate how the presence of ITC might lower the costs of meeting a given target for cumulative reductions in U.S. carbon emissions. This model treats technological change as a function of R&D only (i.e., there is no learning-by-doing). Firms pursue the amount of R&D consistent with maximizing the present value of after-tax profits. Policy changes, such as constraints on emissions, lead to changes in relative prices that cause firms to alter their R&D expenditures. This in turn affects the path of technological change.

The Goulder-Schneider model assumes that the private return to R&D investment is "normal" — that is, there are no unusually profitable investments, nor any big losers. In the first set of experiments considered by Goulder and Schneider, no potential spillovers are considered: only the net *internal* R&D effect is captured. The authors consider cumulative reductions in CO_2 emissions of about 20, 40, and 60 billion metric tons (or about 6, 12, and 18 percent of total national emissions, respectively) over the interval 1995-2095. Figure 3 displays the results. As the figure indicates, at any given level of abatement ITC reduces the GDP costs by about 10-15 percent.[25]

Figure 3

Implications of ITC for Cost of CO_2 Abatement



Source: Goulder and Schneider (1999)

Goulder and Mathai (2000) also consider the impact of ITC on the costs of a global climate policy. They apply a model in which global costs of abatement depend on the extent of abatement and the stock of knowledge (or level of technology). Increases in the stock of knowledge constitute technological change. This model considers both R&D and learning-by-doing as sources of ITC.[26] Specifically, Goulder and Mathai explore the implications of ITC for the costs of limiting global *concentrations* of CO_2 to 550 parts per million (ppm) by the year 2200.[27]

Assuming "central" or middle-case values for key parameters or inputs, this model predicts that ITC will lower abatement costs by about 30 percent—approximately twice the impact predicted by the Goulder-Schneider analysis. It is difficult to pinpoint the source of discrepancy in these results, since the two models differ in many ways. However, one apparent factor is that, for a given level of knowledge, producers' marginal abatement cost functions in Goulder-Schneider are somewhat more convex (that is, marginal costs increase more rapidly with rising levels of abatement) than in Goulder-Mathai.[28] A second factor seems to be that the policy objective is more aggressive—and marginal abatement costs are therefore higher—in the Goulder-Mathai central case. When a less stringent target of 838 ppm is imposed in the Goulder-Mathai model, the presence of ITC reduces costs by only 7 percent.[29] Likewise, when a more stringent target of 350 ppm is imposed, ITC reduces costs by 51 percent.

Manne and Richels (2002) examine the impact of learning-by-doing on the costs of stabilizing atmospheric CO_2 concentrations at 550 ppm by the year 2100. Their model considers global costs under an international climate policy. The authors compare the costs of meeting this target in the presence and absence of learning-by-doing in the electricity sector. Specifically, they assume that technological progress lowers electricity production costs by 20 percent for every doubling of cumulative experience. In their "high cost" learning-by-doing scenario, the costs of electricity cannot fall below a floor of 55 mills/kWh;[30] in their "low cost" learning-by-doing scenario, the floor is 35 mills/kWh. This compares with initial costs of 96 mills/kWh.

Manne and Richels find that learning-by-doing substantially reduces the cost of the climate policy analyzed. Such learning reduces the cost of meeting the 550 ppm abatement target by 42 percent under the high-cost scenario and by 72 percent under the low-cost scenario.[31] The main reason for the cost reduction is that learning-by-doing implies a much lower emissions baseline. That is, projected BAU carbon emissions are much lower when the effects of learning-by-doing are incorporated than when learning-by-doing is absent. The difference between the no-learning and learning-by-doing baselines is especially significant starting about 2060. Because baseline emissions are much lower under learning-by-doing, the additional abatement required to reach the CO_2 concentration target is considerably lower.

It is important to recognize that Manne and Richels do not directly examine the importance of the policy-induced component of learning-by-doing. In their policy experiments, the costs of meeting the concentration target reflect both the learning that occurs as part of the baseline as well as the additional learning that results from the policy being imposed (in this case, the requirement to reduce atmospheric concentrations to 550 ppm). To isolate the effect of policy-induced learning, one would need to compare costs under two scenarios: (1) the scenario actually performed by Manne and Richels (which incorporates both baseline learning and additional policy-induced learning) and (2) an additional scenario which does not allow for any additional learning-by-doing beyond that which occurs in the baseline. Since Manne and Richels do not consider the second scenario, one cannot identify the effect of policy-induced learning-by-doing in their analysis. Nevertheless, their results suggest that learning-by-doing generally has a very important impact on costs, particularly to the extent that it changes baseline conditions.

Net-Benefit-Maximization Analyses

A number of studies have examined how the presence of ITC affects net benefits from climate policy when the timing and overall level of abatement are chosen to maximize such benefits. In these models, the extent of abatement is therefore chosen optimally, rather than imposed as an arbitrary target or constraint as in the cost-effectiveness studies discussed earlier. This type of experiment has been performed both by Goulder and Mathai and by Nordhaus (1997), who considers the importance of ITC in the "R&DICE" model, an extended version of the Dynamic Integrated Climate Economy (DICE) model. The R&DICE model expresses the aggregate output of the economy as a function of capital, labor, and energy.[32] In the model, R&D expenditures entail costs, as output needs to be devoted to this activity rather than producing other goods and services (capital and consumption goods). However, such expenditures also yield benefits by reducing the ratio of emissions per unit of output through the discovery and use of cleaner technologies. This implies reduced emissions and lower damages from climate change. Along the optimal abatement path, rates of investment in R&D and corresponding emissions reductions are calculated to maximize well-being.

When key parameters or inputs are at "central" (middle case) values in the Nordhaus and Goulder-Mathai net-benefit-maximization analyses, these models estimate fairly small net benefits from ITC. For example, in the Goulder-Mathai model, R&D-based ITC lowers abatement costs by only 2.3 percent and raises the net benefits of the climate policy by only 0.7 percent. These modest impacts contrast with the results from the cost-effectiveness studies described above, where cost impacts from ITC are significant. The discrepancy is partly due to differences in the shape of firms' abatement cost functions in the two models.[33] ITC has a larger effect when abatement costs increase rapidly as more reductions are required.

D. General Insights

A number of general conclusions about the impact of ITC can be derived from the theory and model simulations described above. First, ITC lowers the cost of climate policies. The specific cost impacts estimated by different simulation studies vary from very small to quite significant. In the cost-effectiveness studies, cost savings from ITC are large when the constraints on GHG emissions or concentrations are stringent. In addition, in both cost-effectiveness and net-benefit-maximization studies, the extent of the cost savings is sensitive to the specification of how quickly firms' marginal abatement cost functions rise with deeper emissions reductions. These results indicate that economic models that disregard ITC will be biased toward overestimating the costs of climate policies. They will also understate the optimal amount of emissions abatement.

The BAU component of technological change (i.e., the portion that is *not* induced by a policy change) is important as well. Business-as-usual R&D and learning-by-doing can imply significantly lower *baseline* levels of GHG emissions. This in turn can imply lower policy costs since much less abatement would be necessary to reach a given GHG concentration target.

Some major uncertainties deserve recognition. Key information that could help refine predictions of cost savings from ITC is currently lacking. However, even with better information it may be quite some time before researchers can precisely estimate return from investments in any technology portfolio or the scope of cost savings from learning-by-doing.

This leads to a key point regarding climate policy. While it is impossible to know in advance whether ITC will lead to large versus small cost reductions, even without this knowledge one can identify what types of climate policies are justified. The introduction to this study contrasted two main climate policy approaches: *direct emissions policies* and *technology-push policies.* As discussed in Section V below, there is a strong economic rationale for employing both types of strategies in parallel—even when associated cost-reductions from ITC are uncertain. The rationale stems from the two market failures mentioned in the Introduction: (1) that private investment in R&D tends to be suboptimal as a result of the inability of private investors to appropriate all of the returns to R&D, and (2) that reliance on carbon-based fuels generally exceeds socially efficient levels because market prices of these fuels fail to capture climate-related externalities. Notwithstanding the uncertainties, the presence of these market failures implies a role for direct emissions policies and technology policies. Economic theory unambiguously indicates that, provided they are not too stringent, these two policies will produce net benefits: the aggregate benefits from avoided climate damages will exceed policy costs.

III. ITC and the Timing of Emissions Abatement

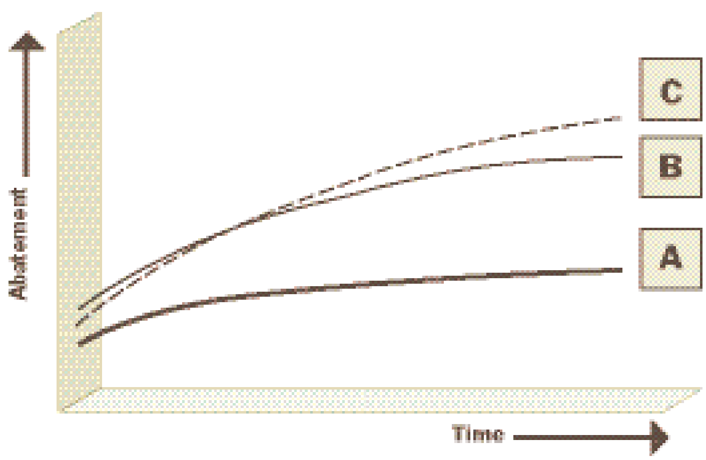
A. Clarifying the Issues

What does ITC imply about the timing of emissions abatement? As mentioned in the introduction, there has been considerable debate on this issue.[34] Some researchers, such as Wigley, Richels, and Edmonds (1996), have argued that the prospect of technological change justifies relatively modest abatement efforts in the near-term: they conclude it is better to wait until additional knowledge makes abatement less costly. Others, such as Ha-Duong, Grubb, and Hourcade (1996), have maintained that the potential for ITC justifies relatively *more* near-term abatement, in light of the ability of early efforts to contribute to learning-by-doing.

To deal with these issues successfully, it is again important to distinguish the BAU and *induced* components of technological change. As indicated previously, the former is that which occurs under the baseline—that is, in the absence of a policy change—whereas the latter occurs as a result of policy change.[35] These different concepts enable us to distinguish two issues that often are confused: (1) the impact of *all* technological change (both the BAU and induced components) on the timing of abatement, and (2) the impact of induced technological change on the timing of abatement. The latter effect is the impact over and above the technological change that would occur anyway.

Figure 4

Illustrative Time Paths for Abatement Under Different Technological Change Assumptions



Note: Paths in the figures are optimal time-profiles for greenhouse gas abatement:

in absence of technological change (Path A)
in presence of business-as-usual technological change (Path B)
in presence of business-as-usual and induced technological change (Path C)

The two effects are contrasted in Figure 4, which displays hypothetical optimal abatement paths under different scenarios. The paths are arbitrary and used here just for purposes of illustration. Path A assumes no technological change. Path B assumes the presence of BAU technological change. Path C is the path that applies in the presence of both BAU and induced technological change. The difference between Path B and Path A represents the impact of BAU technological change for the timing of abatement. The difference between Path C and Path B is the impact of ITC. The difference between Path C and Path A is the impact of all technological change. As drawn, both BAU and induced technological change work toward steepening the abatement profile, implying an increase in the relative contribution of future abatement efforts. However, as will be discussed below, induced technological change could, in theory, imply either a steeper or a flatter optimal abatement profile than would be the case absent ITC. Figure 4 also indicates that overall abatement tends to be higher in the presence of technological change, compared to a case with no technological change. This result gains support from both theory and simulation exercises.

B. Some Results on ITC's Implications for the Timing of Abatement

Wigley, Richels, and Edmonds (1996) consider the optimal time path of abatement that satisfies the requirement of meeting a given GHG concentration target by 2100. They focus on the impact of BAU technological change—their analysis does not consider ITC. The relatively informal analysis by Wigley, Richels, and Edmonds, along with a more rigorous optimization analysis by Manne and Richels (1997), indicates that the optimal abatement path involves relatively modest efforts in the short term and increasing amounts of abatement as time progresses.

These authors point to several factors that favor greater abatement in the future relative to the present. One is discounting: it pays to defer some abatement costs to the future so that they can be discounted. A second factor is technological change. Even without discounting, there is an advantage to postponing some abatement effort to the future, after technological change has made it cheaper to undertake given amounts of abatement. As a result, the optimal abatement profile is an increasing function of time. A third factor is the durability of the existing capital stock and the cost of capital turnover. To a large extent, reducing GHG emissions requires investments in new infrastructures and equipment. In some cases it is cheaper to allow existing capital to serve out much of its productive life before making these investments, particularly if there is no alternative use and resale value for these assets. Withdrawing capital before the end of its productive life and before its potential services are utilized can imply significant economic losses.

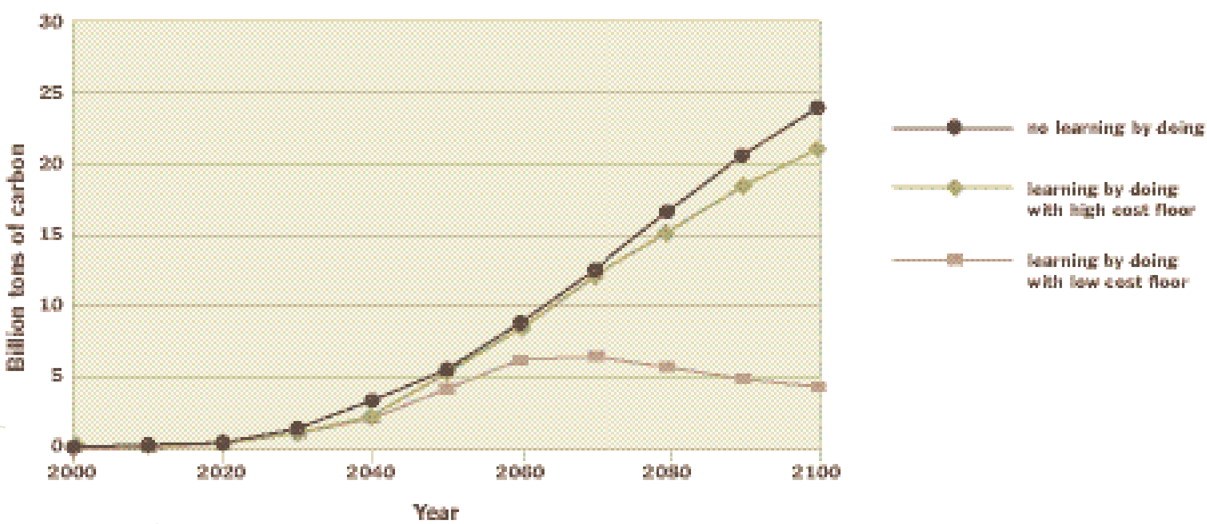
In the case where technological change (whether BAU or induced) results from learning-by-doing, there is another factor that works in the opposite direction. With learning-by-doing, there is a virtue in undertaking abatement in the near-term: such abatement generates experience and helps promote learning and lower future costs. This benefit from near-term abatement must be weighed against the three previously mentioned factors that support undertaking more abatement in the longer term. Goulder and Mathai (2000) show that, because of these competing factors, it cannot be determined from theory alone whether the presence of learning-by-doing justifies more extensive abatement in the short term than would be warranted if such learning did not occur. Indeed, it is not clear from theory whether abatement should increase or decrease over time.

Although theory allows for several possibilities, the results from available simulation studies tend to paint a fairly consistent picture in which the optimal level of abatement increases over time. Because most of these studies do not consider learning-by-doing, this result is not surprising. However, as indicated below, even in studies that do consider learning-by-doing, the optimal abatement trajectory rises with time, at least for the next 70 years.[36]

Figures 5 and 6 display the optimal abatement paths from two recent studies. Figure 5 is from Manne and Richels (2002) discussed previously. Manne and Richels perform the cost-effectiveness

Figure 5

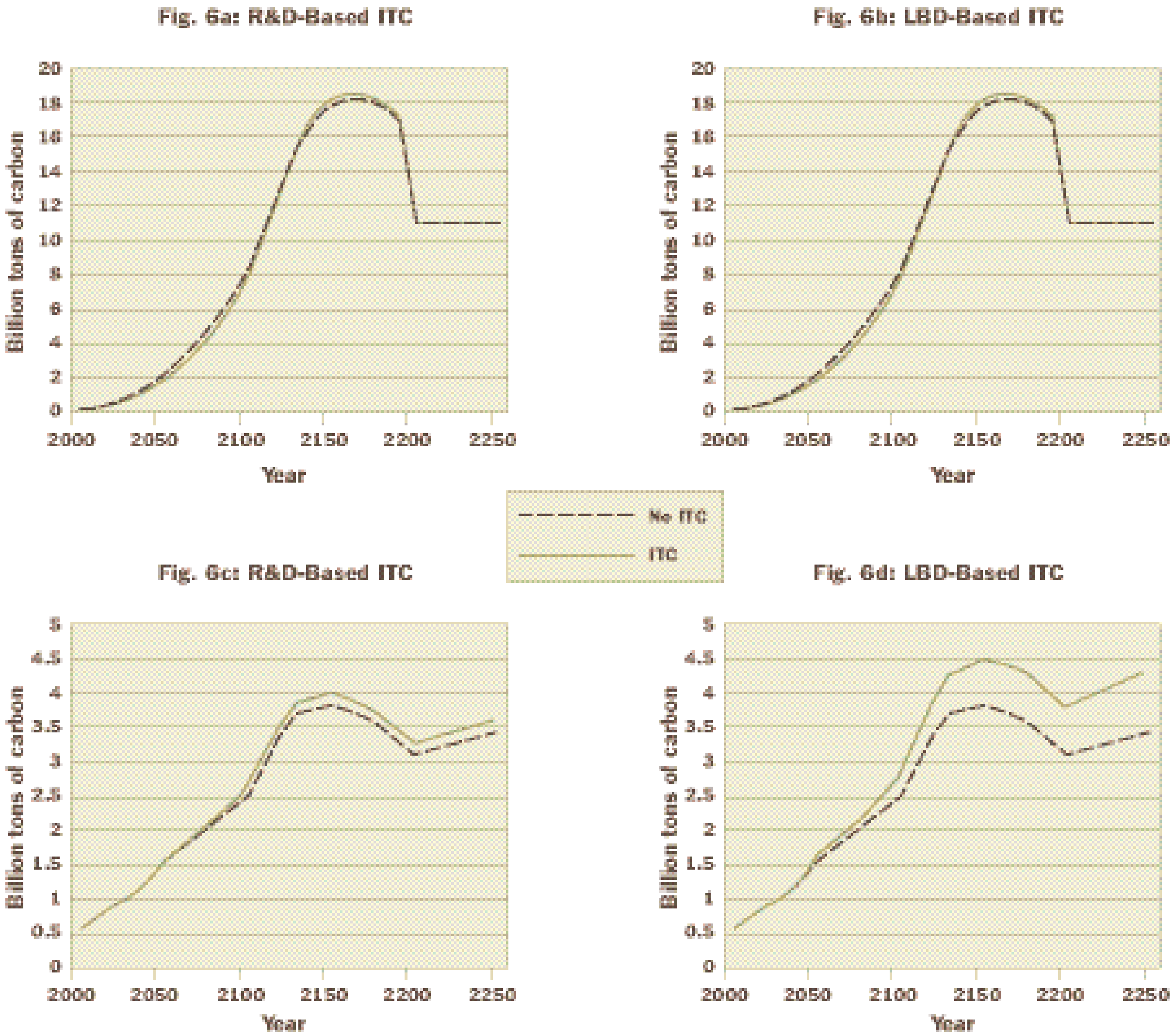
Optimal Time-Profile for Global Emission Reductions



Source: Manne and Richels (2002)

Figure 6

Optimal Time-Profiles for CO_2 Abatement



Note: Figs. 6a and 6b are from cost-effective model runs. Figs. 6c and 6d are from net-benefit-maximization model runs.

Source: Goulder and Mathai (2000)

exercise of determining the abatement path that minimizes the cost of meeting a given atmospheric CO_2 concentration target by the year 2100. Figure 5 shows results for the central experiment in the Manne and Richels analysis, where the target concentration is 550 ppm. The top path in the figure represents the case in which all technological change is exogenous. The middle and lower paths represent cases where technological change occurs both exogenously and as a result of learning-by-doing.[37] The middle path is Manne-Richels's "high cost learning-by-doing" case; the lower path is their "low cost" case. Note that in all of these cases, there is considerably more abatement after 2030 than in the first three decades.

Figures 6a-6d display abatement paths from Goulder and Mathai (2000). The dashed brown lines in each figure are optimal abatement paths in the absence of ITC; the solid green lines indicate optimal abatement paths when ITC is present. The top two figures (6a and 6b) are from cost-effectiveness exercises; the bottom two (6c and 6d) are from net-benefit-maximization exercises. In all cases, the optimal amount of abatement increases as a function of time. In the cost-effectiveness cases, the presence of ITC justifies concentrating a bit more abatement in the future relative to the nearer term, although the effect is almost imperceptible. In the net-benefit-maximization cases, ITC justifies more total abatement and the ITC-based increment to optimal abatement levels increases with time.

To summarize, theory indicates that the optimal abatement path involves increasing abatement through time when technological change stems from R&D, but allows for rising or falling abatement through time when technological change stems from learning-by-doing. Empirically based simulation models consistently yield rising abatement through time for both R&D based and learning-by-doing based technological change. This finding of increasing abatement though time is robust in other respects. It applies both when the government must meet a given concentration (cumulative abatement) target, and when the government aims to maximize net benefits from emissions reductions. And it applies whether or not ITC is present. Finally, Goulder and Mathai's study suggests that, in the cost-effectiveness case, the *differential* impact of ITC on the optimal timing of abatement is fairly small.

For many policy analysts, an issue as important as whether the abatement path is rising or falling through time is whether the economy should be commencing abatement efforts now (that is, in the near-term) and, if so, whether the amount of abatement should be "significant." In this connection, it may be noted that all of the simulation studies examined in this report call for at least some immediate abatement. Abatement efforts may be weighted toward the future, but *some* abatement must start now.[38]

Should required near-term abatement efforts be "significant"? In the Manne-Richels analysis, abatement in the 10-year period following policy implementation totals about one percent of global emissions, or roughly 100 million tons of carbon. The Goulder-Mathai analysis calls for first-year emissions reductions of about 0.8 percent in the cost-effectiveness experiments and about 0.48 percent in the net-benefit-maximization experiments, relative to baseline global emissions of about 7 billion tons.[39] These are not trivial reductions. Thus, although simulation experiments tend to call for greater abatement efforts in the future, their results should not be interpreted as justifying inaction in the near-term.

IV. The Value of Prior Announcements in the Presence of ITC

Policies can be, and often are, announced prior to their implementation. Suppose the implementation date for a policy is some time in the future. If government policy can affect innovation, how helpful is it to announce the policy early (i.e., before implementation)?

To address this question, the Goulder-Schneider U.S. model was employed to compare the following two policy scenarios. In the first, a $25 per ton carbon tax is introduced in 2010 (10 years from the benchmark year of 2000) with no prior announcement. It is assumed that the policy is unanticipated. The second scenario involves a carbon tax that is announced 10 years in advance (that is, in the benchmark year). An announced carbon tax of $25 per ton actually would lead to greater reductions in emissions than a $25 per ton tax that comes as a surprise. To make the policies comparable, the carbon tax rate in the announced-policy scenario is "normalized" (that is, lowered) so that the cumulative reduction in emissions is the same as in the surprise-policy case. (Note that in the Goulder-Schneider model, a carbon tax has the same economic impact as a system of tradable emissions permits, where the quantity of available permits is set such that it yields a permit price equal to the assumed carbon tax rate. Hence, the findings apply equally to potential cost savings from prior announcements of a carbon permits program.)

Figures 7 and 8 display results from this set of simulations. Figure 7a shows the implications for R&D investment by the "alternative energy" (non-carbon-based energy) sector. Introducing a carbon tax is an inducement to additional R&D in this sector, since the tax makes alternative energy relatively cheaper and increases its market potential. When there is no prior announcement, the increase in R&D does not begin until the policy is implemented. By contrast, prior announcement of the policy causes R&D in this sector to expand immediately—that is, at the time of the announcement.

The Goulder-Schneider model assumes that producers make investment decisions to maximize the value of their firms, which is roughly equal to the present value of after-tax profits.[40] Profit-maximizing producers of alternative energy find it advantageous to get a head start in ramping up their R&D and their capital stocks because this allows them to spread the costs of hiring new researchers and installing

Figure 7

Percentage Changes in R&D – Announced vs. Surprise Policies

Fig. 7a. Alternative Energy Sector

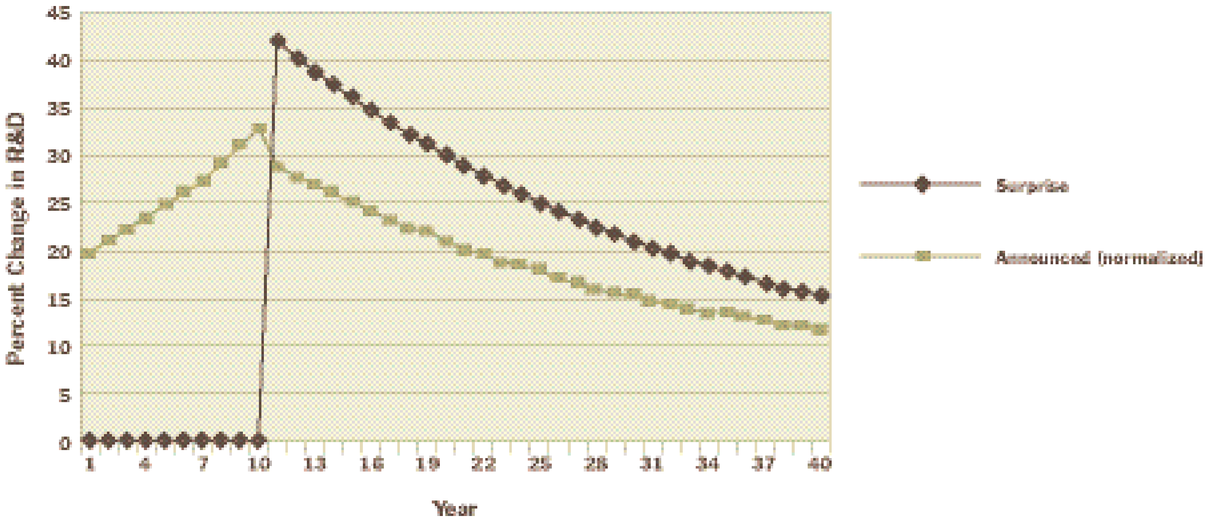
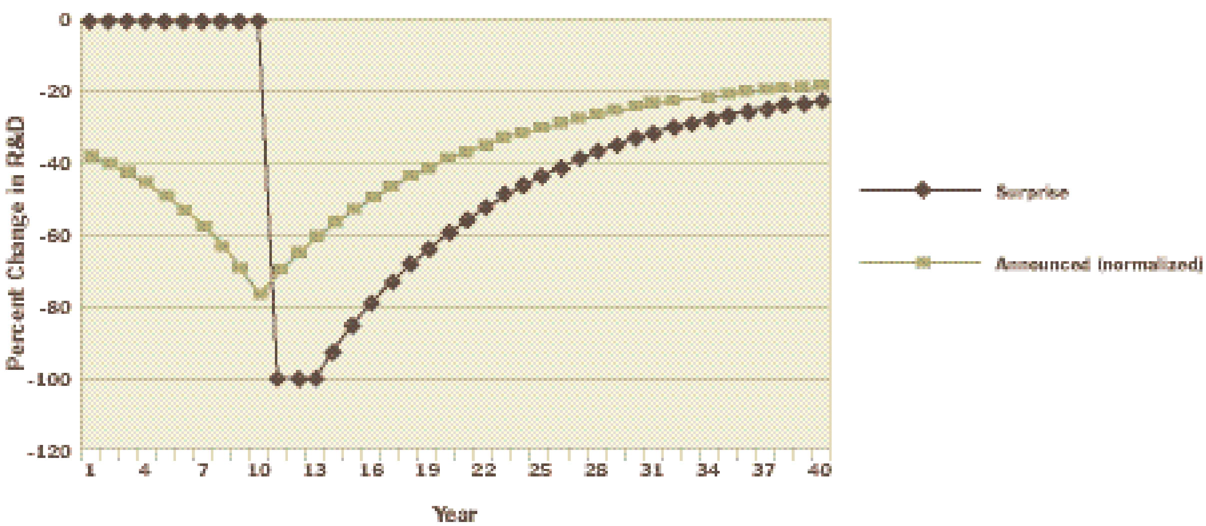


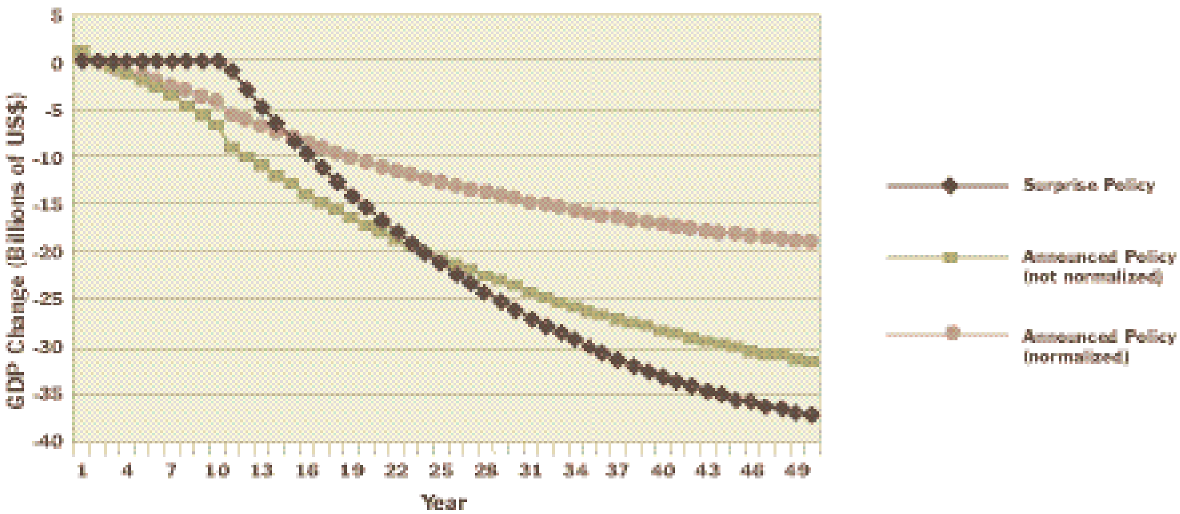
Fig. 7b. Conventional Energy Sector



new equipment over a longer time interval. In the model, expanding the stock of researchers or equipment can be very costly if it is done all at once. For example, doubling the amount of new equipment requires more than a doubling of expenditures. Thus, firms can keep costs down by implementing the expansion over a longer period of time.[41]

Figure 8

Changes in Real GDP – Announced vs. Surprise Policies



Note: The normalized announced policy case involves the same cumulative emissions reductions as in the surprise case. The other announced policy case involves higher cumulative reductions.

Figure 7b shows R&D impacts in the "conventional energy" (fossil-fuel energy) sector. The impacts are a mirror-image of the effects on the alternative energy sector. The carbon tax discourages R&D in conventional energy, causing it to fall relative to its baseline (no-policy-change) path. If the policy is introduced without prior announcement, the drop in R&D starts at the time of implementation, whereas an advance announcement causes the decline to begin at the time of the announcement. Spreading the reduction in R&D and physical capital over a longer time interval also reduces costs to firms in this sector.

These cost reductions—to both the alternative and conventional energy industries—translate into reductions in the GDP costs of the carbon tax. This is shown in Figure 8. The brown line indicates GDP costs when the policy comes as a surprise (i.e., is announced and introduced in year 10). The green line shows costs when the policy is introduced in year 10, but announced today. The beige line represents the GDP cost of the announced policy where the tax rate is normalized, or appropriately scaled, so that cumulative emissions reductions are the same as in the surprise-policy case. When the tax is a surprise, there are no GDP costs until the policy is implemented. When the tax is announced in advance, GDP costs are incurred immediately, but after 10 years—that is, once the policy is implemented—costs are lower than in the surprise policy case.

Specifically, the Goulder-Schneider experiment predicts that the present value of GDP costs for a $25 per ton carbon tax policy over the 2000-2100 timeframe is $272.8 billion under the surprise policy compared to $181.2 billion under the appropriately scaled policy with prior announcement.[42] In other words, announcing the policy in advance reduces GDP costs by 34 percent relative to the comparable surprise policy.

These results should be interpreted as suggesting orders of magnitude for cost savings; they do not attempt to pinpoint the savings from prior announcements. The Goulder-Schneider model includes a very simplified treatment of energy production. In addition, considerable uncertainties surround the curvature of adjustment cost functions.

In reality, producers are likely to have less than 100 percent confidence that a prior policy pledge (particularly one that is made many years in advance) will actually be fulfilled. To the extent that producers question the credibility of the announcement, the impacts on near-term behavior will be muted and associated cost savings will be reduced. The flipside of this point is that cost savings will increase to the extent that the policy announcement is regarded as credible and thereby leads to larger anticipatory responses. This suggests that legislative commitments can yield greater savings than non-binding pledges.

V. Why Inducing Additional Technological Change Is Warranted, Despite Uncertainties

The foregoing discussion points to a number of uncertainties associated with many aspects of ITC. Although ITC can be expected to lower the costs of climate policies, the extent of the cost-reduction is highly uncertain. In addition, it is impossible to gauge with precision the optimal timing of emissions abatement, partly because the extent of future technological change (whether BAU or induced) is highly uncertain. Moreover, the cost savings from prior announcements are very hard to quantify because of difficulties in specifying the adjustment costs to firms of altering their stocks of physical capital or knowledge capital.

Even with these uncertainties, there remains a strong case—on the basis of widely recognized market failures—for adopting climate policies of both the direct emissions and technology-push varieties. Absent such policies, incentives to undertake R&D or gain experience with alternative, low-GHG technologies will be inefficiently low, given prevailing expectations about potential payoffs from such activities. This conclusion can be reached even without being able to predict in advance the extent of potential future cost savings, specify precisely the optimal timing of abatement, or determine the exact magnitude of gains from advance announcements of policy.

The justification for policy action to induce technological change stems from the two market failures introduced in Section I.D. One reflects the inability of investors to appropriate all the knowledge generated by R&D investment. Some of the knowledge stemming from R&D spills over and benefits firms other than the investing firm. As a result, in the absence of public intervention, investments in R&D tend to fall short of the amount which would maximize social net benefits. This provides a rationale for technology-push policies, including subsidies to R&D.

A second market failure stems from the climate change externality associated with the combustion of fossil fuels. The use of fossil fuels imposes external costs to the extent that this contributes to damaging changes in climate. In the absence of public policy, the market prices of these fuels usually reflect private costs, but fail to include the external cost. Hence price tends to be below the full social cost, the sum of private and external cost. This promotes dependence on fossil fuels that is excessive in terms of economic efficiency—at the margin, the value of fossil fuels consumed is below the true cost to society. This provides a compelling rationale for direct emissions policies—such as carbon caps or taxes—that can bring the prices of fossil fuels more in line with their social cost.

Such policies would not only discourage consumption of such fuels, but would also expand incentives to develop alternative, low-carbon technologies by leveling the playing field—removing or reducing the price advantage of conventional energy that stems from its being priced below social cost. When the price of conventional energy rises to reflect social costs, alternative energy sources face less of a hurdle to gain a foothold in the market. This raises potential profits to the invention of new, low-carbon technologies, and thereby expands incentives to engage in R&D in such technologies. Moreover, to the extent that new, lower-carbon fuels and processes become more competitive, learning-by-doing will be accelerated, and the costs of emissions abatement can fall more quickly.[43]

As mentioned in the introduction, technology-push policies have had some political success at the federal level in the United States, while direct emissions policies have had much less. Unfortunately, technology-push policies alone cannot substitute effectively for direct emissions policies because each operates through different channels.[44] Thus, meeting a given abatement target through one approach is likely to be more costly than meeting the same target through a combination of the two approaches.

The cost savings achievable through a combined approach may be striking. Schneider and Goulder (1997) assess the costs of achieving a 15 percent reduction in U.S. CO_2 emissions over the interval 1995-2095 by way of an R&D subsidy to low-carbon energy alone and compare the result to achieving the same objective through a combination of R&D incentives and a carbon tax (or equivalent carbon caps). They find that the cost of meeting this target using the combined approach is an order of magnitude less than when relying only on R&D incentives.[45]

A qualification is in order. Although known market failures clearly provide a basis for some level of policy intervention, uncertainties about the magnitude—either of spillover effects or of climate-related externalities—make it difficult for policy-makers to assess how much intervention is efficient, whether in terms of setting subsidy amounts for R&D or determining appropriate tax or cap levels for GHG emissions. If R&D subsidies are set too high, or if fossil fuel prices are raised too much by way of taxes or emissions caps, policy intervention can reduce economic efficiency and social welfare. This concern is sometimes used to argue that remaining uncertainties warrant inaction until they can be conclusively resolved. However, so long as there are some spillovers from R&D and, on balance, negative externalities from fossil-fuel combustion, taking no action guarantees that there will continue to be an excessive reliance on fossil fuels and under-investment in clean technologies from the point of view of economic efficiency. A more satisfactory approach is to take action in a prudent way. Such an approach would recognize the range of uncertainties about potential spillovers and climate-related externalities and involve policies that, given these ranges, are unlikely to be excessive.

VI. Conclusions

This report has examined the economics of policy-induced technological change and considered its implications for climate policy. The main conclusions are discussed below.

1) The presence of ITC lowers the costs of achieving emissions reductions. By stimulating additional technological change, climate policy can reduce the costs of meeting a given target for reductions in GHG emissions or concentrations. Until recently, most economy-wide climate change policy studies ignored ITC. Models that disregard policy-induced technological advances will tend to overestimate policy costs.

2) The presence of ITC justifies more extensive reductions in GHGs than would otherwise be called for. Because ITC lowers the costs of achieving emissions reductions, the optimal extent of GHG reduction is greater than would be predicted by models that ignore ITC. The net benefits from climate policy are larger as well.

3) The presence of ITC alters the optimal timing of emissions abatement. In general, technological change tends to justify increasing amounts of emissions abatement over time. This result is supported by both theoretical analyses and simulation studies. At the same time, available analyses offer contrasting views as to how the presence of *induced* technological change alters the optimal time-profile of abatement, relative to a situation where policy does not alter the rate of technological change. Insofar as technological change results from R&D, the presence of ITC generally justifies less abatement in the near-term and relatively more abatement in the future (when R&D-based technological change has lowered the costs of abatement). On the other hand, to the extent that ITC stems from learning-by-doing, more ambitious short-term abatement can be called for, since early abatement efforts accelerate the learning process and thereby lower costs. The overall impact of ITC on the time-profile of optimal abatement paths depends on specific aspects of firms' production technologies.

4) In the presence of ITC, announcing climate policies in advance can reduce policy costs. Announcing policies in advance can lower the costs of meeting given targets for emissions abatement or reductions in

GHG concentrations. Illustrative results suggest that announcing a $25 per ton carbon tax 10 years in advance can reduce discounted GDP costs by about a third compared to the same climate policy imposed with no prior notice.

5) Economic analysis offers a justification for public policies to induce technological change, even when the returns are highly uncertain. Uncertainties surround many aspects of ITC. Neither the returns to a given level of investment in R&D, nor the extent of future learning-by-doing, can be precisely predicted. As a result, one cannot pinpoint the cost savings from ITC or the optimal timing of abatement. Furthermore, uncertainties about costs of adjustment make it very difficult to gauge with precision the potential cost-savings from prior announcements of climate policies. Despite these uncertainties, the rationale for public policy to induce technological change remains strong. So long as there are beneficial knowledge spillovers to other firms from increased R&D and negative externalities from the combustion of carbon-based fuels, investments in alternative energy technologies will be inefficiently low in the absence of policy intervention. Direct emissions policies and technology-push policies can help raise R&D and learning-by-doing to efficient levels—that is, to levels consistent with maximizing social benefits net of the costs of increased R&D.

6) To induce technological change and reduce GHG emissions most cost-effectively, both direct emissions policies and technology-push policies are required. This study finds that both types of policies are necessary to achieve given abatement targets (whether expressed as reductions in emissions or GHG concentrations) at least cost to society. The inability to appropriate all the knowledge from investments in R&D, and the climate-related externality from the combustion of fossil fuels, imply two market failures. Technology incentives mainly deal with the inability of private investors' to appropriate all the knowledge gains generated by R&D, while direct emissions policies mainly address the climate-related externalities of fossil fuel combustion and other GHG-generating activities. Attempting to promote technological change (or, more broadly, to address the climate change problem) with only one of these policy approaches cannot correct both market failures. As a result, sole reliance on one approach will usually involve higher costs than utilizing the two approaches in tandem. To date, direct emissions policies have had little political success at the federal level. But there is a strong need for these policies, along with R&D subsidies, to induce efficient levels of technological change and to deal with the prospect of climate change in a cost-effective manner.

Endnotes

1. Atmospheric CO_2 concentrations have increased from a pre-industrial level of about 280 parts per million (ppm) to about 370 ppm at present.

2. See, for example, McCarthy et al. (2001) and Mendelsohn (2003).

3. For further discussion of technological change and substitution, see Clarke and Weyant (2002) and Jorgenson and Goettle (2000).

4. Gasoline use for on-road transportation accounts for 60 percent of total CO_2 emissions from transportation at 307.1 million metric tons of carbon (MMTC). This represents around 20 percent of overall U.S. carbon emissions, which totaled 1558.8 MMTC in 2001 (EIA, 2002).

5. Some analysts use “induced technological change” to refer more broadly to any technological change that is due to changes in prices or other economic conditions. We will use the term “endogenous technological change” to denote this broader concept, and use “induced technological change” to refer only to technological change attributable to public policy initiatives.

6. For discussions of a range of theoretical and empirical issues associated with incorporating ITC in energy and environmental models, see Weyant and Olavson (1999), Carraro (1997), and Löschel (2002). For a somewhat more general discussion of the connection between technologies, technological change, and climate policy, see Edmonds, Roop, and Scott (2000) and Jaffe, Newell, and Stavins (2003a). For an introduction to the economics of climate change policy, including but not limited to technology issues, see Weyant (2000) and Congressional Budget Office (2003).

7. Direct emissions policies are examples of what some studies call *demand-pull* policies: these are policies that stimulate technological change by altering the demands for different goods in such a way as to increase the potential profitability of new technologies. For a discussion see, for example, Clarke and Weyant (2002).

8. An example of a performance requirement is the California mandate that for the seven largest auto manufacturers, by 2003 10 percent of the cars sold in that state must be zero-emissions or partial-zero-emissions vehicles (electric vehicles, hybrid electric vehicles, or conventional vehicles with certain emissions control add-ons). Another example is the U.S. Department of Energy’s standards on the energy efficiency of residential appliances, including central air conditioners, dishwashers, clothes washers and dryers, air conditioners, and water heaters. Such standards were introduced as part of the Energy Policy and Conservation Act of 1975.

9. However, direct emissions policies are beginning to appear as part of State-level initiatives. For example, Massachusetts requires electric power plants to achieve specified reduction levels for CO_2 and other pollutants. The New Hampshire Clean Power Act targets CO_2 and other emissions, and requires the state’s three existing fossil-fuel power plants to stabilize the CO_2 emissions at 1990 levels. Oregon prescribes formal standards for CO_2 releases from new electricity facilities. New Jersey has a comprehensive strategy controlling CO_2 emissions from the energy, transportation, and other sectors. For further details, see Rabe (2002).

10. Of course, technology subsidies impose costs on the taxpaying public, which must finance them. However, the costs of the subsidies are spread over a large number of taxpayers and thus individual taxpayers may have little incentive to undertake the efforts necessary to oppose these measures in the political process. In contrast, the benefits from these subsidies are more concentrated. Hence the beneficiaries have significant incentives to endure the costs of becoming politically involved. This asymmetry in the concentration of benefits and costs can help explain the success of technology policies. Under direct emissions policies, in contrast, the potential losers are highly concentrated, while the beneficiaries are less so. This can help explain the inability of such policies to gain much political ground. For a seminal article on this issue, see Olson (1965).

11. The appropriability problem and associated market failure justifies subsidies to R&D in many economic domains, not just in the energy sector. However, there may be a particularly strong rationale for subsidies to alternative energy technologies in light of the externalities associated with the use of conventional energy. For a review of technology market failure issues, see Carlton and Perloff (2000) and Jaffe, Newell, and Stavins (2003a,b). For an examination of the various ways that technology-oriented programs can contribute to climate policy, see Alic, Mowery, and Rubin (2003).

12. Combustion of fossil fuels also leads to emissions of other gases, including carbon monoxide (CO), sulfur dioxide (SO_2), and nitrogen oxides (NO_X). These emissions imply other external costs, including local adverse health effects. Reducing fossil fuel emissions thus can help address both climate-change and local air quality problems.

13. Some of the issues in this paper are considered in the earlier Pew Report, "Technology and the Economics of Climate Change Policy" (Edmonds, Roop, and Scott, 2000). A main difference is that the present report concentrates mainly on the economics and climate-policy implications of the induced component of technological change.

14. A key exception has been modeling work conducted by the team of Dale Jorgenson, Richard Goettle, Peter Wilcoxen, and Mun Ho. See, for example, Jorgenson and Wilcoxen (1993, 1995) and Jorgenson and Goettle (2000). In this work, the extent of technological progress depends on the relative prices of inputs to production. Thus, insofar as public policies alter input prices, they affect the pattern of technological change. Other recent exceptions are Goulder and Schneider (1999), Nordhaus (1997), Manne and Richels (2002), Wing (2003), and Popp (2004). While most economy-wide (national or international) models have tended to neglect endogenous technological change until recently, various sector-specific models have for many years considered the endogeneity of technological change. For a comparison of economy-wide and sector-specific models, see Edmonds, Roop, and Scott (2000).

15. This source of technological change was originally analyzed by Arrow (1962).

16. This is a central estimate reported in McDonald and Schrattenholzer (2001).

17. The social cost of the R&D expenditure is not necessarily the same as the firm's private cost. For example, if the R&D expenditure is subsidized, its social cost will exceed the firm's cost. Similarly, pre-existing taxes or regulations could cause R&D to be poorly allocated across industries, so that the social cost of R&D deviates from the firm's private cost. Goulder and Schneider (1999) examine these issues.

18. Climate policy may increase R&D in alternate coal technologies, notably Integrated Gasification Combined Cycle (IGCC) with carbon capture and storage.

19. This is the case in simulations performed by Goulder and Schneider (1999).

20. On this issue see, for example, Laitner, DeCanio, and Peters (2000) and DeCanio (1998).

21. For a detailed discussion, see Margolick and Russell (2001).

22. Researchers offer contrasting views about the extent to which climate policy—or, more generally, environmental regulation—can raise profits to the regulated firms by stimulating cost-saving substitutions or innovations. Porter and Linde (1995) offer an optimistic outlook; Palmer, Oates, and Portney (1995) are considerably more skeptical.

23. Carraro (1997) offers a thoughtful discussion of the difficulties involved in determining the direction and magnitude of the net spillover effect.

24. The results presented here are from models that explicitly capture the effects of R&D or learning-by-doing for technological change. The approach to endogenous technological change in these models contrasts with the approach taken by Jorgenson, Goettle, Wilcoxen, and Ho, who consider R&D and learning-by-doing only implicitly in specifying technological change as a function of time and of the prices of inputs and outputs. See, for example, Jorgenson and Goettle (2000) and Jorgenson and Wilcoxen (1993, 1995).

25. One might note from the figure that ITC also *raises* the GDP costs from a given carbon tax—the figure shows results for tax rates of $12.50, $25, and $50 per ton of carbon. This is the case because ITC adds flexibility to the economy. Greater flexibility means that a given carbon tax rate will generate higher amounts of abatement, implying greater gross costs and greater net benefits.

26. In the Goulder-Mathai model, technological change from investments in R&D or learning-by-doing reflects both internal effects and spillover impacts. Other numerical models incorporating ITC via learning-by-doing include van der Zwaan *et al.* (2002) and Gerlagh and van der Zwaan (2003).

27. Under BAU assumptions, CO_2 concentrations are expected to reach about 740 ppm, or double current concentrations, by 2100, and increase to about 890 ppm by 2200. A given target for cumulative abatement over a given time interval is not equivalent to a given target for concentration-reductions over that same interval. Because of natural removal mechanisms for atmospheric GHGs (e.g., through chemical decomposition or absorption by the oceans), a given amount of cumulative abatement can imply slightly different concentrations at the end of the time interval—depending on the timing of abatement.

28. See Goulder and Mathai (2000, page 29) for further discussion of this issue.

29. Although the concentration target of 838 ppm is lax compared to other targets considered, in the Goulder-Mathai model this target still requires emissions abatement: in that model, under BAU the concentration in the year 2200 is 890 ppm. In addition to cost-effectiveness analyses, Goulder and Mathai employ their model to determine the concentration target that maximizes the net benefits (avoided damages minus abatement costs) of climate policy. Their model finds that net benefits are maximized with a concentration target of 838 ppm.

30. One mill equals one-tenth of one cent or 0.001 dollars.

31. See Manne and Richels (2002, Figure 6).

32. A recent paper by Popp (2004) extends the R&DICE model to examine the impact of ITC as well as the importance of incorporating an alternative, carbon-free "backstop" technology.

33. One can define a marginal cost of abatement function as the relationship between the extent of abatement and the incremental cost of (further) abatement. Goulder and Mathai show that the impacts of ITC on the optimal abatement path depend on how quickly the marginal costs of abatement rise with the extent of abatement. In particular, ITC has a large impact when the marginal cost of abatement function is significantly convex—that is, when the function gets rapidly steeper with increased levels of abatement. The marginal costs of abatement are more convex in the Goulder-Schneider model than in the Goulder-Mathai and Nordhaus models. Hence the impact of ITC is greater in the former model. A second reason for the larger impact of ITC in the cost-effectiveness cases is that the imposed abatement requirement is considerably more stringent than the optimal amount of abatement that emerges from the net-benefit-maximization exercises.

34. de Groot (2001) offers a thoughtful discussion of a range of climate policy timing issues, including the significance of policy-induced technological change.

35. BAU technological change can include both exogenous and endogenous components. The exogenous component is that which is independent of changes in relative prices. The endogenous component is that which results from changes in relative prices that take place in the absence of a policy change.

36. In the low-cost learning-by-doing case considered by Manne and Richels (2002), the magnitude of emissions reductions grows until 2070 and then declines somewhat after that.

37. As discussed previously, the total impact of learning-by-doing in the Manne and Richels analysis includes both BAU and policy-induced components.

38. The issue of whether to commence abatement action now is complicated by the fact that the benefits from climate-change policy are highly uncertain. Analyses tend to support current action, despite the uncertainties. One can think of current action as providing insurance against potentially very serious social damages from climate change. For analyses of the issue of whether current action is justified in the presence of uncertainty, see Manne and Richels (1992, chapter 4) and Aldy et al (2001).

39. It may be noted that the Kyoto Protocol called for larger reductions in percentage terms: industrialized nations were required to reduce their emissions by 5 percent below their 1990 emissions levels, or by about 2 percent per year relative to projected business-as-usual emissions through 2008-2012.

40. More precisely, the value of the firm is the present value of after-tax dividends, net of new share issues. See Goulder and Schneider (1999).

41. The size of the cost reduction depends on the “curvature” of the adjustment cost functions; that is, on how fast firms’ marginal costs rise with changes in stocks of physical capital or knowledge capital. The Goulder-Schneider model employs available estimates for these functions, but there is considerable uncertainty about the true magnitudes.

42. The present value of GDP costs (over a 100-year time-horizon, using a 5 percent discount rate) is $280.9 billion under the announced policy involving the $25 per ton carbon tax. This is slightly higher than under the surprise scenario. However, as mentioned, the cumulative emissions reduction is larger as well.

43. Theoretical studies indicate that although both carbon taxes and carbon caps expand R&D incentives for low-carbon technologies, their incentive effects are not identical (see, for example, Milliman and Prince (1989), Jung et al. (1996), and Parry (1998)).

44. If there were no knowledge-spillovers, the problem of appropriating knowledge would disappear and there would be little rationale for technology-push policies. A recent discussion paper by Fischer and Newell (2003) supports this point. The authors find that in the absence of spillover effects a direct emissions policy is much more cost-effective than a technology-push policy like an R&D subsidy.

45. Concentrating on a carbon tax alone is either slightly more or slightly less costly than employing both a carbon tax and an R&D subsidy, depending on assumptions about the nature of spillovers in alternative energy and other sectors.

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This report analyzes the critical process of inducing technological change through a range of climate policies in order to cost-effectively mitigate global climate change. The Pew Center on Global Climate Change was established by the Pew Charitable Trusts to bring a new cooperative approach and critical scientific, economic, and technological expertise to the global climate change debate. We intend to inform this debate through wide-ranging analyses that will add new facts and perspectives in four areas: policy (domestic and international), economics, environment, and solutions.

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