OECD Environment Working Papers No. 9

# Literature Review of Recent Trends and Future Prospects for Innovation in Climate Change Mitigation

**Richard G. Newell**

https://dx.doi.org/10.1787/218688342302

**Unclassified** **ENV/WKP(2009)4**

Organisation de Coopération et de Développement Économiques
Organisation for Economic Co-operation and Development **17-Dec-2009**

**English - Or. English**

**ENVIRONMENT DIRECTORATE**

## ENVIRONMENT WORKING PAPERS No. 9

# LITERATURE REVIEW OF RECENT TRENDS AND FUTURE PROSPECTS FOR INNOVATION IN CLIMATE CHANGE MITIGATION

**Richard G. Newell**
**Administrator, Energy Information Agency**

*JEL classification: O33, O34, O38, Q55, Q58*

*Keywords: Climate change, environment & development, government policy, green technologies, sustainable development.*

**JT03276340**

## OECD ENVIRONMENT WORKING PAPERS

This series is designed to make available to a wider readership selected studies on environmental issues prepared for use within the OECD. Authorship is usually collective, but principal authors are named.

The papers are generally available only in their original language English or French with a summary in the other if available.

Comment on the series is welcome, and should be sent to either env.contact@oecd.org or the Environment Directorate, 2, rue André Pascal, 75775 PARIS CEDEX 16, France.

-------------------------------------------------------------------------
OECD Environment Working Papers are published on
www.oecd.org/env/workingpapers
-------------------------------------------------------------------------

# ABSTRACT

The international discussion about global climate change now revolves around what the necessary set of policies and technologies will be needed to realize reduction goals. Stabilizing atmospheric carbon dioxide ($CO_2$) concentrations at 450 to 550 parts per million will require policy changes along with innovation and large-scale adoption of GHG-reducing technologies throughout the global energy system. Innovations will need to be supported by international cooperation and behavioral changes to further realize the benefits of technological advances. Much discussion has therefore focused on policies that target technology directly, including research and development (R&D) activities and technology-specific incentives, as well as policies and agreements that increase diffusion and adoption.

This paper reviews the recent literature on trends and prospects for innovation in climate change mitigation, to identify the most important international and domestic actions necessary to technologically alter energy systems in a direction that can achieve GHG stabilization targets while also meeting other societal goals. It provides an overview of key technical issues associated with the development, diffusion, and adoption of technologies that mitigate climate change. It examines the role of environment and innovation policy measures to encourage innovation, and it outlines the conditions that trigger these advances.

The review highlights that establishing a GHG emission price is essential *from a technology perspective.* Such a price should be coupled with public R&D support. The review discusses policy features that impact on environmentally oriented R&D, the diffusion of environmental innovations, their deployment in developing countries. In particular, the paper outlines the positive role of international technology-oriented agreements as part of the architecture of an international climate change policy.

JEL classification: O33, O34, O38, Q55, Q58
Keywords: Climate change, environment & development, government policy, green technologies, sustainable development.

## RESUME

Le débat international au sujet du changement climatique porte maintenant sur les politiques et les technologies qui devront être mises en œuvre pour atteindre les objectifs de réduction des émissions. Pour stabiliser les émissions de dioxyde de carbone dans l'atmosphère entre 450 et 550 particules par million, il faut de nouvelles politiques mais aussi des innovations et l'utilisation à grande échelle, dans l'ensemble du système énergétique global, de technologies qui réduisent les gaz à effet de serre. L'innovation devra être encouragée par la coopération internationale et des changements de comportements, pour que les bénéfices des avancées technologiques se matérialisent. Aussi, une part importante du débat a porté sur les politiques qui soutiennent directement le développement technologique, notamment les activités de recherche et développement (R&D) et les incitations spécifiques, mais aussi sur les politiques et les arrangements qui encouragent la diffusion et l'utilisation des technologies.

Ce papier analyse la littérature récente sur les tendances récentes et à venir relatives à l'innovation pour lutter contre le changement climatique. L'objectif est d'identifier les actions prioritaires, au niveau national et international, pour changer les systèmes énergétiques d'un point de vue technologique, selon une trajectoire qui permettra d'atteindre les objectifs de stabilisation des gaz à effet de serre tout en atteignant aussi d'autres objectifs sociétaux. Le papier présente une synthèse des principales questions techniques liées au développement, à la diffusion et à l'utilisation des technologies qui contribuent à la lutte contre le changement climatique. Il analyse le rôle des politiques d'environnement et d'innovation pour soutenir l'innovation et il met en évidence les conditions qui stimulent le progrès technologique.

L'analyse souligne que, d'un point de vue technologique, il est essentiel de fixer un prix pour les émissions de gaz à effet de serre. Ce prix doit être accompagné d'une politique de soutien à la R&D. Le papier présente les attributs des politiques qui ont un impact sur la R&D liée à l'environnement, sur la diffusion des innovations environnementales et leur utilisation dans les pays en développement. En particulier, le papier souligne le rôle positif des accords internationaux qui portent sur les technologies dans le cadre de l'ensemble des politiques internationales de lutte contre le changement climatique.

Codes JEL : O33, O34, O38, Q55, Q58
Mots clés : changement climatique, développement durable, éco-innovation, environnement & développement, politiques publiques, technologies propres.

# FOREWORD

This paper was prepared by Richard G. Newell[1] for the Organisation for Economic Cooperation and Development, March 31, 2009.

It was commissioned in the context of the work developed by the Environment Directorate on eco-innovation. It complements other reviews and empirical investigations on similar issues which support the discussions at the Global Forum on Environment focused on eco-innovation, held on November 4-5, 2009, at the OECD Conference Center in Paris, France.

For more information visit www.oecd.org/environment/innovation/globalforum .

---

[1] At the time of writing the paper, Richard G. Newell was the Gendell Associate Professor of Energy and Environmental Economics at the Nicholas School of Environment, Duke University, a Research Associate at the National Bureau of Economic Research, and a University Fellow at Resources for the Future. This paper draws heavily from recent overviews and reviews of technology innovation, especially Popp et al. (2009), Gillingham et al. (2008), and Newell (2008a, 2008b). Special thanks to the coauthors in those collaborators: Kenneth Gillingham, Adam Jaffe, William Pizer, David Popp, and Robert Stavins.

## TABLE OF CONTENTS

ABSTRACT .......... 3

RÉSUMÉ .......... 4

FOREWORD .......... 5

INTRODUCTION .......... 7

KEY ISSUES ASSOCIATED WITH DEVELOPMENT AND ADOPTION OF TECHNOLOGIES THAT MITIGATE CLIMATE CHANGE .......... 9

- Negative Externalities of Climate Change .......... 9
- Knowledge Spillovers .......... 10
- The Scale of Adoption .......... 10
- Path Dependence .......... 10
- Principal-Agent Problems .......... 10
- Behavioral Change .......... 11

LITERATURE ON INNOVATION .......... 12

- Induced Innovation .......... 12
- The Impacts of Technological Change .......... 18

LITERATURE ON DIFFUSION .......... 23

- Diffusion of Environmental Technologies within Countries .......... 23
- Diffusion Across Countries .......... 25

LITERATURE ON TECHNOLOGY IN AGGREGATE ENERGY-ENVIRONMENT MODELS .......... 28

- Direct Price-Induced Technological Change .......... 28
- R&D-Induced Technological Change .......... 29
- Learning-Induced Technological Change .......... 32

LITERATURE ON ENVIRONMENTAL AND TECHNOLOGY POLICY .......... 34

CONCLUSIONS .......... 37

REFERENCES .......... 42

**Tables**

Table 1. International R&D Expenditures in 2006 (units as indicated) .......... 39
Table 2. R&D Expenditures for Top R&D-Spending Companies Worldwide .......... 40

**Figures**

Figure 1. Public Energy R&D Spending in IEA Countries .......... 41

# INTRODUCTION

The international discussion about global climate change has moved beyond an understanding that substantial reductions in worldwide greenhouse gas (GHG) emissions are necessary to significantly reduce climate risks. Policy debate now revolves around what the necessary set of policies and technologies will be needed to realize reduction goals. Stabilizing atmospheric carbon dioxide ($CO_2$) concentrations at 450 to 550 parts per million will require policy changes along with innovation and large-scale adoption of GHG-reducing technologies throughout the global energy system (IPCC 2007). The set of necessary technologies includes those for increased energy efficiency, renewable energy, fuel switching from coal to oil to gas, nuclear power, and $CO_2$ capture and storage. These innovations will need to be supported by international cooperation and behavioral changes to further realize the benefits of technological advances.

Alongside strategies aimed at reducing GHG emissions—such as emission targets in an international context or domestic GHG cap-and-trade systems or taxes—much discussion has therefore focused on policies that also target technology directly, including research and development (R&D) activities and technology-specific mandates and incentives, as well as policies and agreements that increase diffusion and adoption.

The scale of the system to be reoriented is immense. The International Energy Agency (IEA), in its most recent assessment of energy investment, projects that about $22 trillion of investment in energy-supply infrastructure will be needed over the 2006–2030 period, or almost $900 billion annually, on average (IEA 2007b). Note that this does not include expenditures on energy demand-side technologies (e.g., transportation, appliances, and equipment), which will measure in the trillions of dollars each year. Relative to this baseline investment, the Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC) estimates that an additional $200 billion in global investment and financial flows will be required annually by 2030 just to return GHG emissions to current levels (UNFCCC 2007). Modeling scenarios of cost-effective global climate mitigation policy suggest that, for targets in the range of 450–550 ppm $CO_2$, the cost of GHG mitigation through 2050 is trillions or tens of trillions of U.S. dollars of discounted GDP, or an annualized cost in the tens to hundreds of billions of dollars per year (Newell 2008). Longer-term total costs through 2100 are approximately double this amount. While these estimates are based on numerous economic and policy assumptions, they give a sense of the magnitude of the payoff from technology innovations that could significantly lower the cost of achieving various GHG emission goals.

Nations currently spend about $1 trillion globally each year on R&D, with more than 95 percent occurring in the OECD countries, Russia, and China—and 80 percent in countries represented in the G8 (Table 1). Although innovation activities are not limited to R&D, R&D remains one of the few well-tracked indicators of innovative activity and is highly correlated with other indicators. Industry is by far the largest player in R&D effort, funding more than 60 percent and performing almost 70 percent of R&D globally in 2006 (the most recent year for which complete data are available). Industrial R&D focuses on applied research and especially development, stimulated by market demand for technologically advanced products and processes. Government is the second largest funder of R&D globally (30 percent; Figure 1). Research shows that this level of funding is far lower than what is needed, and that R&D alone will not solve the problem. In the United States, a strategy summarized by Newell (2008a) would double federal 2007 climate mitigation R&D spending to US$ 8 billion by 2016. This amount, ramped up gradually over the next four to eight years, is consistent with reasonable assumptions about expected GHG mitigation costs, the prospects for R&D to lower those costs, and thus the rate of return to such R&D. Similarly, recent IEA (2008) and UNFCCC (2007) assessments suggest at least a doubling of public clean energy R&D spending among developed nations within the next several decades.

Stabilizing GHG concentrations requires large-scale and widespread substitution toward energy technologies with low- to zero-net GHG emissions throughout the global energy system. What are the most important international and domestic actions necessary to technologically alter energy systems in a direction that can achieve GHG stabilization targets while also meeting other societal goals? To find answers, this paper reviews the recent literature on trends and prospects for innovation in climate change mitigation. It provides an overview of key technical issues associated with the development, diffusion, and adoption of technologies that mitigate climate change. It examines the role of environment and innovation policy measures to encourage innovation, and it outlines the conditions that trigger these advances.

# KEY ISSUES ASSOCIATED WITH DEVELOPMENT AND ADOPTION OF TECHNOLOGIES THAT MITIGATE CLIMATE CHANGE

Within market-based economies, success is maximized if policies directly address specific market problems. By directly addressing those problems, the policies can be designed to harness the power of private sector incentives for societal gain, and the direct governmental research role can be designed to complement rather than substitute for activities commonly undertaken by industry. In the context of GHG-relevant technology innovation, there are two principal market problems (Goulder 2004; Jaffe et al. 2005; Newell 2007a).

First and foremost, there are the negative externalities of climate change. If firms and households do not have to pay for the climate damage imposed by GHG emissions, then GHG emissions will be too high. This has implications for technology innovation and adoption because, if there is no demand for GHG reductions, then the demand for GHG-reducing technologies will also be too low. In turn, there will be insufficient incentive for companies to invest in mitigation technology research and development (R&D), because there will be little market demand for any innovations that might come of it.

Second, there are problems specific to the market for innovations. Knowledge, just like a stable climate, is a public good; individual companies cannot capture the full value of investing in innovation. That value tends to spill over to other technology producers and users, thereby diminishing individual private incentives for R&D. This problem tends to worsen the more basic and long term is the research.

These two principal market problems are addressed in greater detail in the following section. In addition, a discussion of other key market issues and feedback processes is summarized.

## Negative Externalities of Climate Change

Broadly, the potentially harmful consequences of economic activities on the environment constitute an “externality,” an economically significant effect of an activity, the consequences of which are borne (at least in part) by a party or parties other than the party that controls the externality-producing activity. In the case of climate change, activities by firms (or individuals or other entities) that emit GHGs into the environment impose a cost to society. The firm that owns the factory has an economic incentive to use only as much labor or steel as it can productively employ, because those inputs are costly to the firm. The cost to society of having some of its labor and steel used up in a given factory is internalized by the firm, because it has to pay for those inputs. But the firm does not have an economic incentive to minimize the external costs of climate change.

Climate change policies may attempt to equalize this imbalance by raising the incentive for a firm to minimize the climate change externality. Policy choices accomplish this in one of two general ways—either by financially internalizing the climate change costs so the firm makes its own decisions regarding its production of GHGs, or by imposing a limit on the level of GHGs the firm may emit.

The cost of climate change policies could be in the form of decreased output of desired products, increased use of other variable inputs, purchase of specialized control equipment, or substitution of inferior or more expensive products or production methods to avoid GHG-emitting products or methods. In the short run, setting an efficient climate change policy requires a comparison of the marginal cost of reducing GHGs with the marginal benefit of a cleaner environment.

When technology enters the equation, the terms of the tradeoff between the marginal cost of GHG reduction and its marginal social benefit is altered. In particular, technology innovations typically reduce the marginal cost of achieving a given unit of GHG reduction. In most cases, technological change enables a specified level of environmental cleanup or GHG avoidance to be achieved at lower total cost to society. New innovations also make it possible for a lower total level of GHG emissions to be attained more efficiently than would be expected if the cost were higher.

### Knowledge Spillovers

The generation of knowledge through the innovative process poses the opposite problem as the negative externalities of climate change. A firm that invests in or implements a new technology typically creates benefits for others while incurring all the costs. The firm therefore lacks the incentive to increase those benefits by investing in technology. As such, even if policies to correct the environmental externalities are in place, the level of climate change R&D will still be suboptimal. Because they ignore the positive spillovers created by R&D, firms will underinvest in climate change research.

### The Scale of Adoption

For a number of reasons, the cost or value of a new technology to one user may depend on how many other users have adopted the technology. In general, users will be better off the more other people use the same technology. This benefit associated with the overall scale of technology adoption has sometimes been referred to as “dynamic increasing returns,” which may be generated by learning-by-using, learning-by-doing, or network externalities. Thus, just like the creation of the technology itself, information about the performance of a technology has an important public goods component.

### Path Dependence

The timing of innovation may precipitate an advantage of one climate change technology over the other. For example, a technology having greater short-term advantages over another technology may become established and “lock out” other technologies. Even if the long-term benefits of the “locked in” technology would result in lower overall social benefits, it succeeds at the exclusion of other technologies. However, technologies dropped at an early stage may reassert themselves at a later date and become successful. OECD (2003) describes this path dependence effect in greater detail, highlighting the example of the electric car, a technology which may be in resurgence after initial lock out decades ago.

### Principal-Agent Problems

Adoption of new technologies may be hindered by principal-agent problems, as when a builder or landlord chooses the level of investment in energy efficiency in a building, but the energy bills are paid by a later purchaser or a tenant. If the purchaser has incomplete information about the magnitude of the resulting energy savings, the builder or landlord may not be able to recover the cost of such investments, and hence might not undertake them. These market failures with respect to adoption of new technology are part of the explanation for the apparent “paradox” of underinvestment in energy-saving technologies that appear cost-effective but are not widely utilized (Jaffe and Stavins 1994; Newell et al. 2004; Gillingham et al. 2009).

### Behavioral Change

Social behavior in reducing GHG emissions could be a powerful force in mitigating climate change. OECD (2003) presents one vision (represented by Jancovici [2002]) in which individuals' efforts to reduce their own carbon footprint will achieve a major reduction on GHG emissions. However, the positive effects of behavioral change may be further complicated by a "rebound effect." That is, individuals may choose a higher-efficiency technology but "use up" the efficiency gains by increasing the activity. For example, a person may purchase a hybrid car that allows him to drive farther at lower cost but commensurately increase overall driving, thereby negating the GHG savings.

# LITERATURE ON INNOVATION

Studies of technological change in environment at the microeconomic level can be divided into two broad categories: those focusing on invention and innovation, and those focusing on diffusion. Because the externality problem complicates the process of environmentally friendly technological change, market forces provide insufficient incentive for either the creation or adoption of such technologies absent environmental policies. Thus, much research has focused on how environmental policy affects the incentives for both the creation and adoption of environmental technology. This section reviews the literature linking environmental policy and innovation, particularly with regard to climate change.

## Induced Innovation

The concept of induced innovation recognizes that research and development (R&D) is a profit-motivated investment activity and that the direction of innovation likely responds positively in the direction of increased relative prices. Since environmental policy implicitly or explicitly makes environmental inputs more expensive, the "induced innovation" hypothesis suggests an important pathway for the interaction of environmental policy and technology, and for the introduction of impacts on technological change as a criterion for evaluation of different policy instruments.

Innovation generated by policies that establish a GHG emission price is sure to come from a wide array of businesses currently engaged in the development and use of energy producing and consuming technologies, especially in the provision of electricity and transportation services. It will also come from the agro-biotech sector (assuming there are incentives for biological sequestration), from companies that produce and consume other non-CO2 GHGs (e.g., chemical companies), and from less obvious sectors such as the information technology industry (e.g., in the context of energy management and conservation). Estimates suggest that private-sector investments in energy R&D, however, have fallen significantly in real terms since peaking around 1980, in tandem with declines in energy prices and public energy R&D spending. Nonetheless, while the trend appears to have been downward over this period, current private-sector R&D investments relevant to energy technology are extremely difficult to assess, and these estimates provide a poor indication of the overall level of private-sector R&D investment that could and likely will be brought to bear on the climate technology challenge (Newell 2008a).

This is illustrated in Table 2, which shows 2006 R&D expenditures (including as a percent of sales) for the 1,250 companies that globally have the highest levels of R&D investment (U.K. Department for Innovation, Universities and Skills 2007). The list includes producers of transportation technologies—such as Ford, DaimlerChrysler, Toyota, Boeing, and Rolls-Royce—which have individual company R&D budgets measured in billions of dollars per year and which together contribute to a global R&D budget for the automotive sector of $80 billion annually. Electronic and electrical equipment companies spent over $35 billion in R&D in 2006, including companies like Siemens and Samsung, and general industrial companies, like Mitsubishi Heavy Industries and General Electric, which have annual R&D budgets of over $11 billion globally.

In the environmental literature, the relationship between innovation and policy has been explored under two broad themes. Early work focused on theoretical models to compare the effects of various environmental policy mechanisms (e.g., uniform standards, emissions taxes, or tradable permits) on environmentally friendly innovation. These papers tend to predict that market-based policies, such as a tax or tradable permit, will induce more environmentally friendly innovation than a command-and-control policy, although recent papers have shown that a precise ranking is theoretically ambiguous and dependent on a number of factors (see, e.g., Fischer et al. 2003). Empirical studies of the links between environmental policy and innovation were initially limited by a lack of data. Recently, as measures of innovative activity such as patents have become more readily available, empirical economists have begun to estimate the effects that prices and environmental policies have on environmentally friendly innovation.

### *Empirical Evidence on Induced Innovation*

A number of empirical studies examine pollution abatement control expenditures (PACE) to proxy for environmental regulatory stringency. Lanjouw and Mody (1996) use the International Patent Classification (IPC) to identify several key environmental patent classes. Using patent data from the US, Japan, Germany, and 14 low-and middle-income countries, they find that environmentally friendly innovation increases as pollution abatement cost expenditures in the country increase. Hascic et al. (2008) study the effect of environmental policy stringency on patenting activity for five different types of environmental technology – air pollution, water pollution, waste disposal, noise protection, and environmental monitoring. Using both PACE expenditures and a World Economic Forum survey of top management business executives as alternative measures of environmental stringency, they find that private expenditures on pollution control lead to greater environmental innovation, but not government expenditures on pollution control. However, higher levels of government environmental R&D do lead to more environmental patents. Popp (2006b) finds significant increases in patents pertaining to sulfur dioxide ($SO_2$) and nitrogen oxides ($NO_X$) emissions reduction in response to the passage of environmental regulations in the United States, Japan, and Germany.

Evidence of inducement has also been sought by examining the response to changing energy prices. Similar to Lanjouw and Mody, Popp (2002) uses patent classifications to identify 11 different alternative energy and energy efficiency technologies. Using a distributed lag model, Popp estimates the elasticity of energy patenting activity with respect to energy prices for these technologies. The distributed lag model is consistent with an adaptive expectations model of prices, in which expected future prices depend on a weighted average of past prices. The regression controls for the quality of knowledge available to an inventor as well as other factors influencing R&D, such as government support for energy research and technology-specific demand shifters. Using this framework, Popp finds that more than one-half of the full effect of an energy price increase on patenting will have been experienced after just five years. Thus, prices (or other regulations that increase the cost of using fossil fuels) can be expected to stimulate new research quickly.

Popp attributes the gradual decrease in induced innovation over time to diminishing returns. Furthermore, Popp (2002) shows that controlling for diminishing returns to research within a specific field does affect induced innovation estimates. To verify the importance of the existing knowledge stock on innovative activity, Popp uses citation data to create stocks of existing patented knowledge, where patents in the stock are weighted by their propensity to be cited. He finds that the stocks have a significant positive effect on energy patenting. Moreover, both Popp (2002) and Popp (2006c) find evidence that the likelihood of citations to new energy patents falls over time, suggesting that the quality of knowledge available for inventors to build upon also falls. The intuition here is that, as more and more discoveries are made, it gets harder to develop a new innovation that improves upon the existing technology. Since the quality of the knowledge stock is an important determinant of the level of innovative activity, decreasing quality of the knowledge stock over time means that diminishing returns to R&D investment will result in lower levels of induced R&D over time. Moreover, because prior research affects the potential success of future inventors, the returns to research should vary along with the quality of the existing pool of research, rather than monotonically over time.

To verify the value of using patent citation data to measure the returns to research, Popp (2002) also includes regressions in which the stock of knowledge is replaced by a time trend. If diminishing returns proceed monotonically over time, a negative time trend should work as well as the weighted knowledge stocks. That, however, is not the case. These regressions prove unreliable. In fact, the elasticity of energy R&D to energy prices appears negative when a time trend is used in place of the knowledge stocks. Since diminishing returns are a bigger problem when the level of energy R&D is highest, not controlling for this counteracts the positive effect of prices on energy R&D.

Newell et al. (1999) examine the extent to which the energy efficiency of the menu of home appliances available for sale changed in response to energy prices between 1958 and 1993, using an econometric model of induced innovation as changing characteristics of capital goods. Hicks formulated the induced innovation hypothesis in terms of factor prices. Newell et al. (1999) generalize this concept to include inducement by regulatory standards, such as labeling requirements that might increase the value of certain product characteristics by making consumers more aware of them. They find that significant amounts of innovation are due to changes in energy prices and changes in energy-efficiency standards. Most of the response to energy price changes came within less than five years of those changes. Illustrating the importance of information, they find that the effect of energy-price increases on model substitution was strongest after product labeling requirements took effect.

### *Induced Innovation and the Choice of Policy Instrument - Theoretical*

Most papers on the effect of different environmental policy instruments on innovation are theoretical in nature. In addition, these papers pay greater attention to the supply side, focusing on incentives for firm-level decisions to incur R&D costs in the face of uncertain outcomes.

The earliest work that is directly relevant is by Magat (1978), who compares effluent taxes and CAC standards using an innovation possibilities frontier model of induced innovation, where research can be used to augment capital or labor in a standard production function. He compares the output rate, effluent rate, output-effluent ratio, and bias (in terms of labor or capital augmenting technical change), but produced ambiguous results. Subsequently, Magat (1979) compares taxes, subsidies, permits, effluent standards, and technology standards, and shows that all but technology standards would induce innovation biased toward emissions reduction. In Magat’s model, if taxes and permits are set so that they lead to the same reduction in emissions as an effluent standard at all points in time, then the three instruments provide the same incentives to innovate.

It was only recently that theoretical work followed up on Magat’s attempt in the late 1970’s to rank policy instruments according to their innovation-stimulating effects. Fischer et al. (2003) find that an unambiguous ranking of policy instruments was not possible. Rather, the ranking of policy instruments depended on the innovator’s ability to appropriate spillover benefits of new technologies to other firms, the costs of innovation, environmental benefit functions, and the number of firms producing emissions. The basic model consists of three stages. First, an innovating firm decides how much to invest in R&D by setting its marginal cost of innovation equal to the expected marginal benefits. Second, polluting firms decide whether or not to adopt the new technology, use an (inferior) imitation of it, or do nothing. Finally, firms minimize pollution control expenditures by setting their marginal costs equal to the price of pollution. Policy instruments affect the innovation incentives primarily through three effects: (1) an abatement cost affect, reflecting the extent to which innovation reduces the costs of pollution control; (2) an imitation effect, which weakens innovation incentives due to imperfect appropriability; and (3) an emissions payment effect, which can weaken incentives if innovation reduces firms' payments for residual emissions. The relative strength of these effects will vary across policy instruments and particular applications, with no instrument clearly dominating in all applications.

In an analysis that is quite similar in its results to the study by Fischer et al. (2003), Ulph (1998) compares the effects of pollution taxes and command-and-control standards, and finds that increases in the stringency of the standard or tax had ambiguous effects on the level of R&D, because environmental regulations have two competing effects: a direct effect of increasing costs, which increases the incentives to invest in R&D in order to develop cost-saving pollution-abatement methods; and an indirect effect of reducing product output, which reduces the incentive to engage in R&D. Carraro and Soubeyran (1996) compare an emission tax and an R&D subsidy, and found that an R&D subsidy is desirable if the output contractions induced by the tax are small or if the government finds output contractions undesirable for other reasons. Addressing the same trade-off, Katsoulacos and Xepapadeas (1996) find that a simultaneous tax on pollution emissions and subsidy to environmental R&D may be better suited to overcoming the joint market failure (negative externality from pollution and positive externality or spillover effects of R&D).

Addressing a policymaker's choice of the level of environmental regulation, Innes and Bial (2002) start with the observation that firms often overcomply with environmental regulation. They explain this behavior using a model in which a successful innovator may prefer stricter environmental standards so as to raise costs for rival firms. An environmental tax that is efficient ex post (e.g., after a new innovation is revealed) also provides incentives for overinvestment in R&D, as firms hope to gain profits by being the first to invent an environmental technology that will affect regulatory levels and impose costs on other firms. Innes and Bial show that discriminatory standards for technology "winners" and "losers" can offset incentives for overinvestment. For example, regulators can offer non-innovating firms a lower emissions reduction target or additional time to comply with regulatory changes. If the policy levels are optimally set, technology winners still have incentive to overcomply with environmental regulation, as their profits exactly equal the social gains from their innovation.

Noting that the stringency of an optimal policy may change after new abatement technologies become available, Requate (2005) asks when policy adjustments should be made. The model considers a monopolistic provider of environmental technology that performs R&D in response to environmental regulation, and a set of competitive firms that purchase environmental equipment when required by law. The paper considers four policy options: ex post regulation after adoption of new technology, interim regulation after observing R&D success but before adoption, ex ante regulation with different tax rates contingent on R&D success, and ex ante regulation with a single tax rate whether or not R&D is successful. In this model, ex ante commitment with different tax rates dominates all other policies, and tax policies are always superior to permit policies.

A recent paper by Bauman et al. (forthcoming) raises the possibility that command-and-control policies may induce more innovation under certain scenarios. They note that the results of previous models follow when innovation lowers the marginal abatement cost curve. However, these papers assume end-of-pipe solutions to pollution reduction, such as installing a scrubber on a smokestack. For end-of-pipe solutions, the marginal cost of no abatement is zero, so that a marginal abatement cost curve starts at the origin. In such cases, innovation always results in lower marginal abatement costs. However, pollution can also be reduced by changing processes, such as using cleaner fuel or using a more efficient boiler. In such cases, innovation may make the marginal abatement cost steeper. For instance, if a plant plans to reduce emissions by shutting down temporarily, it will forego more output (and profit) when it is using a more efficient boiler. In these cases, the marginal abatement cost curve after innovation will not be unambiguously below the original marginal abatement cost curve. Should that occur, command-and-control standards may provide greater incentive for innovation than market-based policies. Note, however, that their analysis is positive rather than normative in nature and does not directly address the traditional view that market-based policies are overall more efficient than command and control.

Finally, Baker and Adu-Bonnah (2008) show that the way in which technological change affects the shape of the marginal abatement cost curve also affects R&D decisions made under uncertainty. Their model considers both uncertainty about future climate damages (and thus the optimal level of abatement needed) and uncertainty about the likelihood of success for various energy research projects. R&D investment affects the probability that a project will be successful. They consider two types of energy R&D projects: alternative energy that emits no carbon and efficiency improvements for conventional fossil fuel energy sources. For alternative energy R&D, technological improvements unambiguously lower the cost of reducing carbon emissions (e.g., shift marginal abatement costs down). In this case, the socially optimal investment in technologies is higher for riskier projects. However, the opposite is true for research on conventional energy technologies, for which technological change rotates the marginal abatement cost curve. For low levels of abatement, improvements to conventional technologies, such as increased fuel efficiency, lower abatement costs. However, if high levels of abatement are required, simply improving energy efficiency will not be sufficient—alternative clean energy sources will need to replace traditional fossil fuel sources of energy. In this case, improvements in the efficiency of conventional technologies raise the marginal abatement cost, as they raise the opportunity cost of eliminating fossil fuels. In such a case, optimal R&D investment is higher for less-risky R&D projects. These projects have a higher probability of success, but will only have moderate efficiency gains. However, moderate efficiency gains will have a large impact on the economy, because fossil fuels are widely used. In contrast, the payoff from risky R&D projects with larger efficiency gains is not as high. Efficiency gains are most valuable under low climate damage scenarios. If climate damages are high, energy efficiency gains will have little value, because fossil fuels won't be used. Thus, the need for energy efficiency breakthroughs is not as high as the need for breakthroughs for alternative energy.

### *Induced Innovation and the Choice of Policy Instrument - Empirical*

Empirically, there is little work that compares innovation under different policy types. One exception is Popp (2003), which compares innovation before and after $SO_2$ permit trading began in the United States. This paper combines patent data with plant-level data on flue gas desulfurization (FGD) units, or "scrubbers" to compare innovation before and after passage of the 1990 Clean Air Act. Popp finds that the level of innovation, measured by the number of successful patent applications by year, for FGD units was actually higher before tradable $SO_2$ permits were introduced by the 1990 Clean Air Act (CAA). However, the nature of innovation changed after passage of the Act. Before the 1990 CAA, most new coal-fired electric utilities were required to install FGD units with a removal efficiency of 90%. Because installation was mandatory, innovation focused on reducing the operating costs of these units. However, because there were no incentives for firms to exceed the 90% limit, innovation had no effect on the removal efficiency of FGD units. In contrast, because the 1990 CAA required greater $SO_2$ emissions reductions and gave firms flexibility as to how to meet those goals, post-1990 innovations did have the effect of improving the removal efficiency of scrubbers. Similarly, Taylor et al. (2003) note that the scrubber requirement led to a reduction in patents on pre-combustion techniques for reducing $SO_2$ emissions, such as cleaner coal. However, Taylor (2008) notes that, because most pollution control innovators are third-party equipment vendors, rather than the regulated firms, uncertainty over how regulated firms will react to permits (and thus uncertainty over the ultimate permit price) reduces innovation incentives from permit trading vis-à-vis other policy instruments.

In contrast, Bellas (1998) finds no evidence of progress in scrubber technology. However, his study only includes plants from 1970 to 1991. Thus, the analysis only considers plants under the command-and-control policy regime. In more recent work, Lange and Bellas (2005) update this research by estimating the effect of scrubber characteristics on both capital and operating costs of scrubbers installed before and after the 1990 CAA. The permit trading system of the 1990 CAA provided, for the first time, incentives for older plants to install scrubbers. This expanded the market for scrubbers, which, they argue, should increase incentives for technological change. Indeed, Lange and Bellas find that both capital and operating expenses drop for scrubbers installed after the 1990 CAA took effect. However, they find this drop to be a discrete event—costs are lower after the 1990 CAA, but the rate of change in costs does not change. While they find no evidence of cost differences between scrubbers installed under the 1970 CAA and the 1977 CAA (which mandated installation of scrubbers at plants built beginning in 1978), they do not explicitly address whether costs change over time during this period.

Addressing the value of flexible standards, Lanoie et al. (2007) use a survey of firms in seven OECD countries to examine the effect of various environmental policy instruments on environmental R&D. Respondents were asked to describe both the type of environmental policies faced, as well as the stringency of such policies. They find that greater stringency does induce a firm to perform more environmental R&D. More flexible performance standards, which dictate an acceptable level of environmental performance, but do not dictate how that level be achieved, induce more environmental R&D than technology standards, which require the use of a specific technology to meet regulatory targets. Surprisingly, being exposed to market-based environmental policies does not induce greater environmental R&D. One explanation given for this result is that when market-based policies are used, they may be less stringent than other environmental standards. In related work, Johnstone and Hascic (2008) show that flexible environmental regulations lead to higher quality innovation. Using a World Economic Forum survey of business executives, they show that environmental patents have larger family sizes when executives in the inventor’s home country perceive that there is greater freedom to choose different options in order to achieve compliance with environmental regulations.

There is a more extensive literature on the effects of alternative policy instruments on the innovation of energy-efficiency and alternative energy technologies. The innovation process can be thought of as affecting improvements in the characteristics of products on the market, and the process can be framed as the shifting inward over time of a frontier representing the tradeoffs between different product characteristics for the range of models available on the market. If one axis is the cost of the product and another axis is the energy flow associated with a product, that is, its energy intensity, then innovation is represented by inward shifts of the curve — greater energy efficiency at the same cost, or lower cost for given energy efficiency. With this approach, Newell et al. (1999) assess the effects of changes in energy prices and in energy-efficiency standards in stimulating innovation. Energy price changes induced both commercialization of new models and elimination of old models. Regulations, however, worked largely through energy-inefficient models being dropped—the intended effect of the energy-efficiency standards.

Finally, Johnstone et al. (2008) use a panel of patent data on renewable energy technologies across 25 OECD countries to examine the effect of different policy instruments on innovation. They compare price-based policies such as tax credits and feed-in tariffs to quantity-based policies such as renewable energy mandates. They find important differences across technologies. Quantity-based policies favor development of wind energy. Of the various alternative energy technologies, wind has the lowest cost and is closest to being competitive with traditional energy sources. As such, when faced with a mandate to provide alternative energy, firms focus their innovative efforts on the technology that is closest to market. In contrast, direct investment incentives are effective in supporting innovation in solar and waste-to-energy technologies, which are further from being competitive with traditional energy technologies. These results suggest particular challenges to policymakers who wish to encourage long-run innovation for technologies that have yet to near market competitiveness.

## The Impacts of Technological Change

The research described in the previous section focuses on the relationship between incentives (either market prices or policy) and the direction and level of technological change. In addition to these questions, another important research question is the effect of these new technologies on the environment. In the broader literature on technological change, economists consistently find that knowledge spillovers result in a wedge between private and social rates of return to R&D. Typical results include marginal social rates of return between 30 and 50 percent.

One would expect to find similar results in the environmental literature. However, two issues may complicate estimates of social returns on environmental R&D. One is the market failure problems discussed previously. The high social rates of return found in most studies of technological change occur as a result of imperfections in knowledge markets, such as spillovers. While these market failures are still an issue here, they are magnified by the externalities problem common in environmental economics. This complicates measuring the impact of environmental innovation, as the value of any resulting gains in environmental quality is difficult to quantify. For example, one could study how innovations benefit firms, either by lowering the cost of compliance with regulation, or in the case of energy efficiency, by lowering the energy costs of firms or consumers. The results will give an incomplete measure of the social returns to environmental innovation, because they do not measure the value of environmental quality improvements. While there is a broad literature on measuring the benefits of environmental quality (see, for example, Mäler and Vincent [2005]), these measures are often indirect, and have yet to be incorporated into studies on the return to environmental innovations.

### *Empirical Research*

There has been exceptionally little empirical analysis of the effects that innovation has on the costs of pollution abatement, principally because of the paucity of available data. Carlson et al. (2000) look at changes in the marginal abatement costs at power plants, and find that about 20%, or $50, of the change in marginal abatement costs that have occurred from 1985 to 1995 can be attributed to technological change. Popp (2003) uses patent data to link innovative activity to lower operating costs of scrubbers for coal-fired electric power plants. Popp aggregates patents pertaining to scrubber innovations into a knowledge stock, and then regresses the operating costs of individual scrubbers on scrubber and plant characteristics, including the knowledge stock at the time the scrubber was installed. A single patent provides a present value of $6 million in cost savings across the industry. Assuming approximately $1.5 million of R&D spent per patent granted, this yields a return similar to those found in the more general works in the technological change literature. However, these savings account only for the benefits to the power industry of lower environmental regulation compliance costs, as the social benefits of reduced $SO_2$ emissions are not included in this estimate.

In contrast, the effects of innovation on energy efficiency have been studied more widely. In addition to the studies discussed previously, Pakes et al. (1993) investigate the effects of gasoline prices on the fuel economy of motor vehicles offered for sale. They find that the observed increase in miles per gallon (mpg) from 1977 onward was largely due to the consequent change in the mix of vehicles on the market. Fewer low-mpg cars were marketed, and more high-mpg cars were marketed. Subsequently, Berry et al. (1996) combine plant-level cost data for the automobile industry and information on the characteristics of models that were produced at each plant to estimate a hedonic cost function—the supply-side component of the hedonic price function—finding that quality-adjusted costs generally increased over the period 1972–1982, thus coinciding with rising gasoline prices and emission standards.

One of the challenges of studying the effects of technology indirectly can be found by comparing empirical studies from different eras. Many studies use a time trend to represent technological change, so that the results are interpreted as the net effect of all technological change in a given period. For example, in a study of U.S. industrial energy consumption from 1958 to 1974, Jorgenson and Fraumeni (1981) find that technological change was energy-using—energy use per unit output increased over time. Of course, the time period of their data would not include any of the energy-saving innovations developed after the energy crises of the 1970s. In contrast, more recent work using a time trend to capture technological change finds that technology is energy saving. Examples include Berndt et al. (1993), Mountain et al. (1989) and Sterner (1990).

As an alternative to using a time trend to represent technology, Popp (2001) uses energy patents to estimate the effect of new technology on energy consumption. Popp begins by matching energy patents with the industries that use the inventions by using the Yale Technology Concordance (Evenson et al. 1991, Kortum and Putnam 1989, 1997). Using these patents, Popp creates stocks of energy knowledge, which are used as an explanatory variable in a system of cost functions for 13 energy-intensive industries. The knowledge stocks are defined as a cumulative function of the number of past energy patents used by each industry, adjusted for gradual decay and diffusion. Using these knowledge stocks in a cost function of energy usage, Popp finds that the median patent leads to $14.5 million dollars in long-run energy savings. In comparison, these industries spend an average of $2.25 million of R&D per patent. In addition, using estimates of the elasticity of patenting with respect to energy prices for these technologies, Popp calculates the effect of induced innovation as the combined effect of all new patents induced by a one-percent energy price increase. Interestingly, the estimated elasticities of energy use with respect to price found in that paper are lower than typically found, as they include only the effect of factor substitution, because technological change is controlled for separately. By comparison, re-running the regressions using only a time trend to represent technological change provides energy price elasticities that are consistent with those found in other studies, as such studies include the effect of price-induced innovation in their estimates.

Similarly, Sue Wing (2008) uses patent stocks in a series of industry-level regressions to identify the effects of changing industry composition, disembodied technological change, factor substitution, and induced innovation in response to energy prices on declining U.S. energy intensity. While Popp focuses on energy-intensive industries, Sue Wing's data includes 35 industries from 1958-2000. He finds changing composition and disembodied technological change to be the dominant factors. Induced innovation does have an energy-saving effect, but it is the smallest of the four factors studied.

Finally, Linn (forthcoming) looks at the effect of energy prices on the adoption of energy-saving technology in the U.S. manufacturing sector. Using Census of Manufacturers data to compare energy use in new and incumbent facilities, he finds that a 10 percent increase in the price of energy leads to technology adoption that reduces energy demand of entrants by 1 percent. Given this, Linn concludes that technology adoption explains just a small portion of changes in energy demand during the 1970s and 1980s.

### *Estimates of Technological Impact Using Learning-by-Doing*

While only a few studies make a direct link between R&D and environmental or energy impact, a more extensive literature has made use of experience curves to estimate the rates of cost decreases in energy technology. A long-recognized concept, technological learning first was quantified by Wright

(1936) for the aircraft industry. In economics, the concept is often described as learning-by-doing (LBD), and generally is defined as the decrease in costs to manufacturers as a function of cumulative output, or "learning-by-using," and the decrease in costs (and/or increase in benefits) to consumers as a function of the use of a technology (Arrow 1962, Rosenberg 1982). LBD commonly is measured in the form of "learning" or "experience" curves in terms of how much unit costs decline as a function of experience or production. Among energy analysts, these estimates are often used to calibrate energy-economic models for simulating the effects of climate policy, with a particular focus on alternative energy sources. A typical learning curve estimation regresses costs of installation (or production) at different points in time as a function of cumulative installed capacity (or sometimes cumulative output) in log-log fashion. The resulting elasticity coefficient on cumulative capacity in these models (□) is often translated into a so-called "learning rate" ($1-2^{-□}$) giving the percentage change in costs resulting from a doubling in cumulative capacity. Typically, studies on new energy technologies find faster learning for younger technologies, with estimates clustering around 15–20% for alternative energy sources such as wind and solar energy (McDonald and Schrattenholzer 2000).

One significant caveat with estimated learning rates is that they typically focus on correlations between energy technology usage and costs, rather than causation. Recent papers by Klaasen et al. (2005), Söderholm and Sundqvist (2007), and Söderholm and Klaasen (2007) attempt to disentangle the separate contributions of R&D and experience by estimating "two-factor" learning curves for environmental technologies. These two-factor curves model cost reductions as a function of both cumulative capacity (learning-by-doing) and R&D (learning-by-searching, or LBS). To be comparable with the notion of cumulative capacity, in these models R&D is typically aggregated into a stock of R&D capital. Thus, endogeneity is a concern, as we would expect both investments in capacity to be a function of past R&D expenditures and R&D expenditures to be influenced by capacity, which helps determine demand for R&D. Söderholm and Sundqvist address this endogeneity in their paper and find LBD rates around 5 percent, and LBS rates around 15 percent, suggesting that R&D, rather than learning-by-doing, contributes more to cost reductions. However, these results are very sensitive to the model specification, illustrating the difficulty of sorting through the various channels through which costs may fall over time.

To further address the problems associated with estimating and interpreting learning curves, Nemet (2006) uses simulation techniques to decompose cost reductions for PV cells into seven categories. Plant size (e.g. returns to scale), efficiency improvements, and lower silicon costs explain the majority of cost reductions. Notably, most of the major improvements in efficiency come from universities, where traditional learning by doing through production experience would not be a factor. Learning from experience (e.g., through increased yield of PV cells) plays a much smaller role, accounting for just 10 percent of the cost decreases in Nemet's sample.

While research on the various sources of cost reductions is limited, these results provide some guidelines for incorporating estimates of learning into environmental policy models. Most importantly, these results suggest that the relative importance of both learning by doing and R&D must be considered when calibrating models that include both. The main lesson here is to avoid double counting. A LBD rate of just five percent, such as found by Söderholm and Sundqvist, is lower than typically reported in the LBD literature, where learning rates of 15–20 percent are common. A simple one-factor LBD curve shows an association between capacity and costs, but does not address causation. A two-factor curve begins to address this problem by including a major omitted variable. As such, while the combined effect of LBD and LBS in a two-factor model may be comparable to learning rates from a one-factor model, the individual components should be smaller. Fischer and Newell (2008) show how one can jointly incorporate both R&D-based and learning-based technological change into an analytical and numerical model, while taking care to parameterize the model based on available empirical evidence.

### *Government R&D*

The abovementioned studies have focused primarily on the incentives faced, and activities conducted, by private firms. However, governments also play an important role in energy R&D. IEA member countries, which together account for about 85 percent of overall global R&D expenditures, spent an estimated $11 billion on publicly funded energy R&D in 2006 (IEA 2007a)—or about 4 percent of overall public R&D spending by these countries in the same year. In the United States, about half of government funding is transferred to universities, other non-profit research institutions, and industry, which perform the associated R&D within a system of contracts, grants, and other arrangements. Government funding tends to focus more on basic and applied research. In addition to creating new knowledge upon which further technological development can draw, university-based R&D supports the production of young researchers. Most of these researchers eventually move into the private sector—thus they represent an important link within the overall innovation system. Ensuring a stream of scientists, engineers, and other research professionals trained in areas relevant to clean-energy technologies can increase the necessary innovative effort and moderate its cost. The capacity of a country's workforce to absorb and apply new know-how and technology is also essential for development, and it is one of the main impediments to more rapid technology transfer to developing countries (World Bank 2008). By supporting researchers and graduate students, public funding for research affects an economy's capacity to generate and assimilate scientific advances, technology innovations, and productivity improvements. This linkage has made research funding a priority among many who are concerned about the long-term competitiveness of national economies and has led to increased support for expanded R&D spending generally, including in the United States and the European Union. At an international level, programs that facilitate the international exchange of graduate students, post-docs, and more senior scholars in areas relevant to climate-mitigation research can help to expand human-capital-related spillovers.

Government investment plays another important role: it can help to compensate for underinvestment by private firms. Unlike firms, the government is in position to consider social returns when making investment decisions. In addition, government R&D tends to have different objectives than private R&D. Government support of basic R&D is particularly important, as long-term payoffs, greater uncertainty, and the lack of a finished product at the end all make it difficult for private firms to appropriate the returns of basic R&D. Thus, the nature of government R&D is important. For example, Popp (2002) finds that government energy R&D served as a substitute for private energy R&D during the 1970s, but as a complement to private energy R&D afterwards. One explanation given for the change in impact is the changing nature of energy R&D. During the 1970s, much government R&D funding went to applied projects such as the effort to produce synfuels. Beginning with the Reagan administration, government R&D shifted towards a focus on more basic applications.

The analyses that have been conducted of U.S. federal research relating to energy and the environment have come to mixed conclusions. Cohen and Noll (1991) documented the waste associated with the breeder reactor and synthetic fuel programs in the 1970s, but in the same volume Pegram (1991) concluded that the photovoltaics research program undertaken in the same time frame had significant benefits. More recently, the U.S. National Research Council attempted a fairly comprehensive overview of energy efficiency and fossil energy research at U.S. Department of Energy (DOE) over the last two decades (National Research Council 2001). Using both estimates of overall return and case studies, they concluded, as one might expect, that there were only a handful of programs that proved highly valuable. Their estimates of returns suggest, however, that the benefits of these successes justified the overall portfolio investment.

In addition to correcting for underinvestment by private firms, many government R&D projects aim to improve commercialization of new technologies (referred to as "transfer" from basic to applied research). Such projects typically combine basic and applied research and are often done through government/industry partnerships (National Science Board 2006). For example, the United States passed several policies in the 1980s specifically designed to improve transfer from the more basic research done at government and university laboratories to the applied research done by industry to create marketable products. As such, this technology transfer can be seen as a step between the processes of invention and innovation.

A small number of papers have addressed the role that government R&D plays facilitating transfer of energy technology. Jaffe and Lerner (2001) study the effectiveness of federally funded research and development centers (FFRDCs) owned by the DOE. Jaffe and Lerner supplement a detailed patent citation analysis of patents assigned either directly to the laboratories or to private contractors who collaborated on research at the DOE labs with case studies of two DOE laboratories where technology transfer efforts increased in the 1980s and 1990s. They find that both patenting and the number of citations received per patent increased at DOE laboratories since the policy shifts of the 1980s. That citations received also increase after the 1980 policy changes contrasts with the findings of researchers studying academic patenting, where patenting increases, but the quality of patents appears to decline. They also find that the type of research performed at a laboratory affects technology transfer. Transfer is slower when more basic research is performed, or when the research has national security implications. Interestingly, FFRDCs with greater contractor turnover appear to be more successful at commercializing new technologies.

Popp (2006c) examines citations made to patents in 11 energy technology categories, such as wind and solar energy. He finds that energy patents spawned by government R&D are cited more frequently than other energy patents. This is consistent with the notion that these patents are more basic. More importantly, after passage of the technology transfer acts in the early 1980s, the children of these patents (that is, privately held patents that cite government patents) are the most frequently cited patents, suggesting that transferring research results from the government to private industry produces valuable research results.

## LITERATURE ON DIFFUSION

Technological advances are of limited effect unless society ultimately makes use of the innovation through technology diffusion, that is, the process by which a new technology penetrates the relevant market. The profits through diffusion of technological advances often drives innovation. These processes are therefore at times difficult to separate. Because innovation and adoption often tie together, it is important to lay out the key features and considerations of technological diffusion and adoption. However, the literature on diffusion encompasses research beyond the scope of this report. This section concentrates on literature on diffusion that directly affects innovation choices. For more extensive coverage of the literature on diffusion, see Popp et al. [forthcoming]).

### Diffusion of Environmental Technologies within Countries

Several theoretical studies have found that the incentive for the adoption of new technologies is greater under market-based instruments than under direct regulation (Zerbe 1970; Downing and White 1986; Milliman and Prince 1989; Jung et al. 1996). However, theoretical comparisons among market-based instruments have produced only limited agreement. In a frequently cited article, Milliman and Prince (1989) examine firm-level incentives for technology diffusion provided by five instruments: command-and-control; emission taxes; abatement subsidies; freely allocated emission permits, and auctioned emission permits. They found that auctioned permits would provide the largest adoption incentive of any instrument, with emissions taxes and subsidies second, and freely allocated permits and direct controls last. The study was echoed by Milliman and Prince (1992) and Jung et al. (1996): auctioned permits provided the greatest incentive, followed by taxes and subsidies, free permits, and performance standards. Subsequent theoretical analyses (Parry 1998; Denicolò 1999; Fischer et al. 2003) show that auctioned and freely allocated permits have lesser diffusion incentives than an emission tax (but superior to command-and-control instruments). Under tradable permits, technology diffusion lowers the equilibrium permit price, thereby reducing the incentive for participating firms to adopt. Thus, a permit system provides a lower adoption incentive than a tax, assuming the two instruments are equivalent before diffusion occurs.

A common finding in the empirical literature of environmental technology adoption is that environmental regulation is necessary to encourage adoption of pollution control techniques. For example, Kerr and Newell (2003) find that, in the case of regulation on technology adoption decisions by petroleum refineries during the leaded gasoline phasedown., increased regulatory stringency encouraged greater adoption of lead-reducing technology. They also find that the tradable permit system provided incentives for more efficient technology adoption decisions. Likewise, Keohane (2007) finds that increased flexibility of a market-based instrument can provide greater incentives for technology adoption. In the study, a firm's choice to adopt a "scrubber" to remove $SO_2$—rather than purchasing (more costly) low-sulfur coal—was more sensitive to cost differences (between scrubbing and fuel-switching) under the tradable permit system than under the earlier emissions rate standard. In a study of $NO_X$ pollution control technologies, Popp (2006d) demonstrates that that the mere presence of environmental technologies is not enough to encourage its usage. Technological advances are adopted only when needed to comply with the strictest emission limits.

In general, firms can choose one of two strategies to comply with environmental regulations. End-of-the-pipe abatement reduces emissions by using add-on technologies to clean the waste stream coming from a plant. In contrast, cleaner production methods reduce emissions by generating less pollution in the production process. Frondel et al. (2007) look at the factors influencing the choice of one strategy over the other. They find that many plants in OECD nations make use of cleaner production methods. However, environmental regulations are more likely to lead to the adoption of end-of-the-pipe techniques. In contrast, market forces such as cost savings or environmental audits lead to the adoption of cleaner production processes.

Another body of research has examined the effects on technology diffusion of command-and-control environmental standards when they are combined with "differential environmental regulations." In many situations where command-and-control standards have been used, the required level of pollution abatement has been set at a far more stringent level for new sources than for existing ones. There is empirical evidence that such differential environmental regulations have lengthened the time before plants were retired (Maloney and Brady 1988; Nelson et al. 1993). Further, this dual system can actually worsen pollution by encouraging firms to keep older, dirtier plants in operation (Stewart 1981; Gollop and Roberts 1983; McCubbins et al. 1989).

In addition to economic incentives, direct regulation, and information provision, some research has emphasized the role that "informal regulation" or community pressure can play in encouraging the adoption of environmentally clean technologies. Community pressure can increase adoption of more environmentally friendly practices, as found by Blackman and Bannister (1998) and Popp et al. (2008). Not surprisingly, prices also serve as an incentive for adoption. This is particularly important for technologies that improve energy efficiency, as individual users can appropriate some of the benefits of these technologies through lower energy bills, even if no other regulatory incentives exist. In studying fuel-saving technology, Rose and Joskow (1990), Boyd and Karlson (1993), and Pizer et al. (2001) find that both energy prices are positively related to the adoption of energy-saving technologies. Conversely voluntary environmental programs, such as the U.S. Green Lights and Energy Star programs seem to have little effect on technology diffusion (Howarth et al., 2000).

Information plays an important role in the technology diffusion process. Information, however, is a public good that may be expected in general to be underprovided by markets—resulting in a market failure. Likewise, a market failure can occur because technology adoption creates a positive externality and is therefore likely to proceed at a socially suboptimal rate. Anderson and Newell (2004), in examining how firms respond to energy audits offered through the US Department of Energy's Industrial Assessment Centers (IAC), find that that firms' adoption rates are higher for projects with shorter paybacks, lower costs, greater annual savings, higher energy prices, and greater energy conservation. Plants are 40 percent more responsive to initial costs than annual energy savings. Using multiple decisions for a given firms, Anderson and Newell estimate a "payback threshold" for a typical firm, below which all projects are adopted and above which all projects are rejected. They find that over 98 percent of firms have payback thresholds of less than five years, with a median payback threshold of just 1.2 years.

Uncertainty is another factor that may limit the adoption of new technology (Geroski 2000). Uncertainty can be inherent in the technology itself, in the sense that its newness means that users are not sure how it will be perform (Mansfield 1968). For resource-saving technology, there is the additional uncertainty that the economic value of such savings depends on future resource prices, which are themselves uncertain. This uncertainty about future returns means that there is an "option value" associated with postponing the adoption of new technology (Pindyck 1991; Hassett and Metcalf 1995, 1996). Closely related to the issue of uncertainty is the issue of the discount rate or investment hurdle rate used by purchasers in evaluating the desirability of new technology, particularly resource-conserving technology. A large body of research demonstrates that purchasers appear to use relatively high discount rates in evaluating energy-efficiency investments (Hausman 1979; Ruderman et al. 1987; Ross 1990).

Finally, the presence of increasing returns in the form of learning effects, network externalities, or other positive adoption externalities presents the possibility that market outcomes for technologies exhibiting these features, including those with environmental consequences, may be inefficient. For example, the idea that we are "locked into" a fossil-fuel-based energy system is a recurring theme in policy discussions regarding climate change and other energy-related environmental problems. At a more aggregate level, there has been much discussion of the question of whether it is possible for developing countries to take less environmentally damaging paths of development than have currently industrialized countries, for example by relying less on fossil fuels.

### Diffusion Across Countries

While international technology transfer has received much attention in the broader economic literature, few applications focus specifically on environmental technologies. Nearly all of the papers cited so far focus on highly developed economies. This is not surprising, as these countries were the first to enact environmental protections and most R&D expenditures occur in these countries. In 2006, global R&D expenditures were about $960 billion, with 85 percent of this R&D occurring in the OECD, and half in the United States and Japan alone (Newell 2008a, OECD 2008b).

Nonetheless, diffusion of environmental technologies, particularly to developing countries, is currently one of the most pressing environmental concerns. Much of this concern stems from the need to address climate change, while allowing for economic development. Rapid economic growth in countries such as China and India not only increases current carbon emissions from these countries, but results in high emission growth rates from these countries as well. In 1990, China and India accounted for 13 percent of world $CO_2$ emissions. By 2004, that figure had risen to 22 percent, and it is projected to rise to 31 percent by 2030 (EIA 2007). Given these concerns, designing policy that encourages the transfer of clean technologies to developing countries has been a major discussion point in climate negotiations. Currently, the Kyoto agreement includes the Clean Development Mechanism (CDM), which allows polluters in industrialized countries with emission constraints to receive credit for financing projects that reduce emissions in developing countries, which do not face emission constraints under the Kyoto Protocol. Because carbon emissions are a global public good, CDM can help developed countries reach emission targets at a lower total cost, by allowing developed country firms to substitute cheaper emissions reductions in developing countries for more expensive reductions in the home country. For developing countries, technology transfer and diffusion of clean technologies may be an additional benefit from CDM.

How often do CDM projects transfer knowledge and skills that not only allow a developed country investor to meet emission reduction credits, but also enable the recipient developing country to make continual improvements to their own emission levels? Dechezleprêtre et al. (2008) look at 644 CDM projects registered by the Executive Board of the UNFCCC. They find that 279 projects, or 43%, involve technology transfer (however, these projects are among the most significant CDM projects, as they account for 84% of the expected emissions reductions from registered CDM projects). Of these, 57 transfer equipment, 101 transfer knowledge, and 121 transfer both equipment and knowledge. A project is more likely to include technology transfer if it is larger, if the project developer is a subsidiary of a company in a developed country, and if the project includes one or more carbon credit buyers. Before credits for a project can be sold, the emission reductions must be certified. Because they have an interest in obtaining emission credits, credit buyers help to facilitate this process.

Most economic applications of environmental technology transfer have been more general. In the broadest sense, environmental technological change is addressed in literature on trade and the environment. There, economists decompose the effect of international trade on environmental quality in developing countries into three components. First, scale effects account for increased pollution levels due to the greater wealth and increased economic activity that follows international trade. Second, composition effects refer to reductions in pollution resulting from a preference for cleaner goods that develops as countries become richer. Third, technique effects refer to emission reductions that occur because trade expands access to cleaner technologies (Esty 2001, Copeland and Taylor 2003). Attempts to identify this technique effect can be seen as examples of technology transfer.

Fisher-Vanden and Ho (2006) consider the interaction of scale and technique effects in a simulation of increased science and technology (S&T) capabilities and energy use in China. They note that improving S&T capabilities has two offsetting effects. While technological development can lead to the use of cleaner technologies (the technique effect), increases in S&T also lead to larger energy intensive industries (the scale effect). They find that the S&T takeoff should have an energy-saving bias, resulting in lower energy prices. However, this leads to more economic growth and greater energy consumption by households, so that the net effect of the S&T takeoff is greater energy use and more carbon emissions.

Khanna and Zilberman (2001) illustrate the importance of trade to diffusion in a study of the adoption of energy-efficient technologies at electric power plants in India. Emissions could be reduced by the adoption of high quality coal. However, such coal would need to be imported. In an effort to protect the domestic coal industry, such imports were virtually banned by the Indian government. Khanna and Zilberman find that while an emissions tax is necessary to achieve optimal levels of abatement, simply removing domestic and trade policy distortions would increase adoption of energy efficient technology and potentially decrease carbon emissions.

Popp (2006b) addresses the links between regulations and innovations across countries, using patent data to study innovation on air pollution control technologies for coal-fired power plants in the United States, Japan, and Germany. He finds that inventors respond primarily to domestic regulatory incentives. In each country, the largest increase in domestic patent applications occurs after the country passes regulations affecting power plants. Moreover, Popp finds evidence of innovation even in countries that adopt regulations late, suggesting that these countries do not simply take advantage of technologies “off the shelf” that have been developed elsewhere. Instead, adaptive R&D seems to be necessary to suit the technology to the local market, as these later patents are more likely to cite earlier foreign than domestic inventions. Thus, the foreign knowledge serves as blueprints for further improvements, rather than as a direct source of technology. Furthermore, Hilton (2001) finds that late adopters of regulation can learn from early adopters: late adopters are able to move more quickly because they benefit from lessons learnt by early adopters.

Because most pollution control technologies are first developed in industrialized countries, and because environmental regulations are needed to provide incentives to adopt these technologies, Lovely and Popp (2008) focus on the adoption of environmental regulation as the first step in the international diffusion of environmental technologies. They study the adoption of regulations limiting emissions of $SO_2$ and $NO_x$ at coal-fired power plants in 39 countries. Their sample includes both developed and developing countries. They focus on access to technology as an important factor influencing regulatory adoption. As pollution control technologies improve, the costs of abatement, and thus the costs of adopting environmental regulation, fall. As such, they find that, over time, countries adopt environmental regulation at lower levels of per capita income. Moreover, they find that openness to international trade is important for providing access to these technologies, providing support for the technique effect discussed earlier.

In contrast to pollution control technologies, energy efficiency technologies will diffuse even without environmental policy in place, as they offer users the opportunity of cost savings. Fisher-Vanden et al. (2006) studied improvements in energy efficiency in Chinese enterprises and attribute reductions in energy use primarily (54%) to price change, secondarily (17%) to technological change. Fisher-Vanden (2003) finds that while centrally managed Chinese firms are the first to acquire new technology, locally managed firms complete integration of the technology throughout the firm more rapidly.

Golombek and Hoel (2004) raise the possibility that induced technological change could help alleviate the problem of incomplete participation in climate treaties. The standard presumption is that when only some countries commit to reducing carbon emissions, high-carbon industries will migrate to non-participating countries, resulting in *carbon leakage*. Golombek and Hoel note that, in the countries committed to carbon reductions, induced technological change will lower abatement costs. In some cases, these cost reductions will be sufficient to encourage non-participating countries to reduce carbon emissions as well. Di Maria and van der Werf (2008) perform a similar analysis and show that induced technological change always reduces the rate of carbon leakage. Others have also investigated how the nature of global environmental problems, technological diffusion, and international trade can provide arguments for issues linkage where more countries may participate and comply with international agreements on environmental policy and technology policy if they are linked than if they are treated separately (see, for example, Folmer and van Mouche 1993, Carraro and Egenhofer 2002, and Kemfert 2004).

Newell (2008b) considers opportunities for improved and expanded international development and transfer of climate technologies. He clarifies the importance of options for inducing technology market demand through domestic GHG pricing, international trade, and international development assistance, and then turns to upstream innovation strategies, including international coordination and funding of climate technology R&D, and knowledge transfer through intellectual property. Newell concludes that a successful international effort to accelerate and then sustain the rate of development and transfer of GHG mitigation technologies must harness a diverse set of markets and institutions beyond those explicitly related to climate, to include those for energy, trade, development, and intellectual property.

Barriers to diffusion of solar thermal technologies are explored in a case study by Philibert (2006). The main barriers include technical problems such as a lack of competent installers, problems with retrofitting existing appliances and household systems, and a reputation that the solar technologies are unreliable, based on problems encountered with earlier models. In addition, economic barriers also strongly inhibit diffusion, particularly because the predominant availability of solar energy (during the warm months) comes when demand is lowest, and the reverse is also true—availability is lowest when demand is highest (cold months). The technology needed to store the energy from one season to the next is not yet available. Costs for installing the technology are highly variable from country to country and across climate conditions; costs are especially a barrier for solar air conditioning technology and for retrofitting existing facilities (as compared with new construction). In addition, economic barriers exist because of high upfront costs and long payback time horizons. Other social and legal barriers compound the challenge of diffusion. Philibert suggests a number of policies to overcome barriers to solar technology diffusion, such as supporting R&D and demonstration projects to alleviate technological barriers and reduce the industrial costs of production; supporting market deployment by a certification program service contracts, and outreach and training, and other measures; and regulations such as streamlined permitting, protecting citizens' "solar rights," and building performance standards.

## LITERATURE ON TECHNOLOGY IN AGGREGATE ENERGY-ENVIRONMENT MODELS

The potential environmental impacts of technological change play an important role in the long-term sustainability of economic growth. This is particularly true in the realm of climate policy, for which most impacts will not be felt for years to come, and for which current technologies are not sufficient to meet many of the emissions targets advocated at politically acceptable cost. To assess the role of technological change on long-term environmental and economic well-being, economists have developed aggregate economic models that integrate economic growth, technological change, and environmental impacts. These models demonstrate both the potential for new technologies to limit the environmental impact of economic growth, and the challenges of accurately forecasting long-term technological trends.

Although one of the most difficult questions remaining in aggregate energy-economic modeling is the appropriate treatment of technological change in these models—particularly for analyzing long-term environmental and resource problems—the discussion in this paper is limited to the implications of these long-term models on technology innovation and their relevance for decisionmaking. In these models, technological change is often treated as exogenous, but is sometimes considered a complex endogenous process that depends on time and current prices, but also on historic indicators of prices and activity. One approach is to summarize the influence of historic prices and activity in terms of an unobserved "knowledge stock" that governs overall level and direction (i.e., input-bias) of technological change. The difficulty lies in determining exactly how this stock accumulates and affects future energy use and emissions. As the empirical evidence suggests, prices, R&D, and learning through past experience all play some role in the accumulation of this stock, yet there is no single structural theory that addresses exactly how this occurs, and hence, how each influences future production possibilities.

### Direct Price-Induced Technological Change

Direct price-induced technological change is a relatively straightforward method of endogenizing technological change. In the context of climate policy modeling, if the price of energy rises, price-induced technological change will lead to greater energy efficiency, often through a productivity parameter that is tied to historic prices (or whose change is tied to current prices) or through earlier diffusion of energy-efficient technologies. The exact pathway through which this occurs depends greatly on the model structure. There are only a few examples of direct price-induced technological change used in climate policy models due to the somewhat ad hoc, reduced-form nature of specifying the relationship between price and technological change.

Perhaps the most faithful representation of price-induced technological change is Jakeman et al. (2004), who assume a fixed amount of technological change in each region and time period, which is allocated across inputs to all industries according to the relative prices of the inputs. In this case, including price-induced technological change reduces the cost of meeting carbon mitigation targets. Other examples in energy-economic modeling include (Dowlatabadi 1998) and the U.S. Energy Information Administration's NEMS model (EIA 2003). The empirical evidence presented in section 3 suggests that the price-inducement form of technological change has merit as a partial explanation;

higher energy prices clearly are associated with faster improvements in energy efficiency. However, the reduced-form approach largely has been passed over for the R&D- or learning-induced technological change methodologies.

### R&D-Induced Technological Change

R&D-induced technological change is one of the most common approaches used to endogenize technological change, and a variety of models have been developed along these lines. Several themes resonate throughout the R&D model literature. Two key points are whether R&D-induced technological change is associated with an innovation market imperfection due to spillovers, and whether carbon-saving R&D crowds out R&D in other sectors. There clearly exists a tension between spillovers and crowding out, with the former tending to point to greater cost savings when endogenous technological change is included and the latter dampening or even overturning that effect. In many models, the degree to which spillovers and crowding out arise is a complex interaction among underlying assumptions about model structure and distortions in the R&D market. Yet, these assumptions have important ramifications for the total cost of a climate policy as well as the conclusions drawn about the degree to which estimates based on exogenous technology assumptions are biased.

A third issue is the important difference among models in the elasticity of the supply, or opportunity cost, of additional R&D. If there is a relatively inelastic supply of R&D (e.g., capable engineers and scientists), more effort on climate mitigation R&D reduces the ability of other firms or sectors to perform R&D, effectively crowding out R&D activity. This implies that the cost of a carbon constraint could be more or less costly with the inclusion of endogenous technological change (versus presumptively leading to lower costs).

Including a knowledge stock in the production function does not on its own imply a pathway for inducing carbon-saving technological change. In the simple formulation of a knowledge stock that is most true to the endogenous growth literature, the knowledge stock increases the productivity of all inputs equally. For example, Buonanno et al. (2003) extend the Nordhaus and Yang (1996) RICE model to implement such a knowledge stock in the endogenous technological change-RICE numerical model. This simple methodology for endogenizing technological change may be useful to capture important aggregate dynamics, but it does not provide a pathway for relative prices to influence energy-saving or carbon-saving innovation.

Smulders and de Nooij (2003) and van Zon and Yetkiner (2003) both build on the endogenous growth literature that includes a continuum of intermediate goods (e.g., Romer [1990]) and apply a variation of this modeling approach to an economy that includes energy as an input to production. In Smulders and de Nooij, endogenous technological change is achieved by improvements in the quality of the continuum of intermediate goods through investment in R&D, while van Zon and Yetkiner achieve endogenous technological change through increases in the variety of the continuum of intermediate goods through R&D investment. Both papers demonstrate the important theoretical point that profit maximization by innovating intermediate goods producers can give rise to a change in the direction of technological change toward energy-saving technological change based on increasing energy prices or constrained energy quantities.

Smulders and de Nooij's modeling framework allows for policy analysis examining the short- and long-run growth implications of energy conservation policies but does not address questions of economic welfare. They find that energy-conservation policy will lead to reduced net per capita income levels due to the direct costs of the policy outweighing the offsetting effect of induced innovation. Nonetheless, the endogenous technological change framework does reduce the cost of a policy, although non-energy R&D activities may be crowded out, with no increase in total R&D. In fact, a theoretical result based on this model structure is that the gains from induced innovation will never offset the initial policy-induced decline in per capita income levels, obviating the possibility of "win-win" situations. As a general proposition, endogenous technological change should induce higher long-run output only if spillovers are relatively high in carbon-saving innovation compared to other areas that would otherwise receive R&D effort. This appears not to be the case in Smulders and de Nooij's model. The same messages arise in Goulder and Schneider (1999) and Gerlagh (2008).

In contrast, van Zon and Yetkiner use a blueprint framework to find that an energy tax that is recycled in the form of an R&D subsidy may increase long-run growth, through R&D-induced technological change. This result stems from two different market imperfections in the R&D market: (1) firms do not consider the effect that current R&D has on increasing the productivity of future R&D investment because it is not captured appropriately in the price of the blueprints and (2) a market imperfection in the supply of intermediates that leads to too low of a demand for those intermediates relative to the social optimum. Effectively, these market imperfections imply an intertemporal spillover for each firm, rather than a spillover from the research of one firm to other firms. Crowding out also plays a less prominent role in the van Zon and Yetkiner model than in Smulders and de Nooij.

Sue Wing (2006) further develops this theory in the context of climate change policy by adding externalities and environmental taxation to Acemoglu's (2002) model. Sue Wing shows that an environmental tax always biases production away from the dirty good towards the clean good. However, this does not necessarily mean that the environmental tax also biases innovation towards research on the clean good. Rather, this depends on the substitutability between clean and dirty inputs. If the clean input is not readily substitutable for the more expensive dirty input, the absolute quantity of dirty R&D exhibits a hump-shaped profile, so that it increases under small environmental taxes, but declines under higher environmental taxes. That is, a low environmental tax encourages research to make the dirty input more productive, so as to get more output from each unit of the dirty input.

Unfortunately, theoretical models with continuous intermediate goods and abstract representations of blueprints are not well suited to match technological change up to measurable real-world variables or technologies that most numerical models attempt to represent. However, the more general notion of including a Hicks-neutral knowledge stock, as shown above in Buonanno et al. (2003) or factor-augmenting knowledge stock, as in Smulders and de Nooij (2003), is a common choice for numerical models that include an economy-wide production function.

In the DICE model (Nordhaus 1994), one of the best known models of climate policy, carbon intensity (i.e., carbon per unit of GDP) is affected by the substitution of capital and labor for carbon energy. This is modified in the R&DICE model in Nordhaus (2002), so that carbon intensity is determined by an innovation possibility frontier, which is a function of R&D inputs into the carbon-energy sector. The cost of investing in knowledge through R&D is subtracted from consumption in the DICE model's output balance equation, analogous to conventional investment. In the case of R&D investment, however, the cost of research is multiplied by four to reflect a generic innovation market imperfection; that is, that the social opportunity cost of R&D exceeds its private cost due to crowding out. Nordhaus' primary conclusion is that induced innovation is likely to be less powerful of a factor in reducing emissions than substitution. This result is related directly to the calibration that assumes the returns to R&D equal the opportunity costs, allowing crowding out to have an important effect. Buonanno et al. (2003) provide a different variation on Nordhaus' approach by making emission intensity a function of a knowledge stock that accumulates one-to-one with R&D investment and depreciates at an exogenous rate; however, there is no potential for climate-friendly R&D to compete with or crowd out other R&D. As such, they find a much larger role for induced innovation. Using the ENTICE model, Popp (2004) investigates the importance of R&D crowding out more carefully and concludes that induced innovation increases welfare by 9%. Assuming no crowding out increases the welfare gains from induced innovation to as much as 45%. Similarly, assuming full crowding of R&D reduces welfare gains to as little as 2%. Finally, Gerlagh (2008) extends this work by separately modeling the choice of carbon-energy producing R&D, carbon-energy saving R&D, and neutral R&D. In such a case, it is carbon-producing R&D, rather than neutral R&D, that is crowded out by induced carbon-energy saving R&D. As a result, the impact of induced technological change is larger, with optimal carbon taxes falling by a factor of 2.

Goulder and Schneider (1999) develop a partial equilibrium analytical framework and then implement some of the resulting insights in a numerical general equilibrium model that endogenizes technological change, with a particular emphasis on spillover effects. The authors find that the presence of endogenous technological change in their model leads to lower costs of achieving a given abatement target, but higher gross costs of a given carbon tax (i.e., costs before netting out climate benefits). In fact, both costs and benefits of a given carbon tax are higher relative to their model with only exogenous technological change, due to more extensive carbon abatement, for the economy responds more elastically to price shocks from the policy. With environmental benefits included, Goulder and Schneider find greater net benefits of this higher abatement level for a given carbon tax when endogenous technological change is present. This outcome can be reinforced or muted if there are prior distortions in R&D markets, depending on the type of distortions.

One important feature underlying these results is a crowding-out effect where expansion of knowledge generation in one sector comes at a cost to other sectors due to the limited pool of knowledge-generating resources (i.e., there is a positive and increasing opportunity cost to R&D in one sector). A carbon-tax policy serves to spur R&D in the alternative energy sector, but discourages R&D in non-energy and conventional energy sectors due both to slower growth of output in those industries and the limited pool of knowledge-generating resources. On the other hand, the knowledge spillover effects, whereby policy-induced R&D has social returns above private returns, provide additional benefits from a climate policy above the environmental benefits. However, the presence of endogenous technological change with spillovers does not imply the possibility of zero-cost carbon abatement, unless the spillovers overwhelm the crowding out effect, a largely empirical question.

Sue Wing (2003) incorporates endogenous technological change into a detailed general equilibrium model, building on several of the concepts in Goulder and Schneider (1999) and others. At the core of Sue Wing's model is a recursive, dynamic general equilibrium model in which a representative agent maximizes welfare. A major difference between Sue Wing's model and previous models is that Sue Wing further distinguishes several of the factors influencing innovation to gain insight into the general equilibrium effects of inducing innovation in one sector and its consequences for the cost of carbon policies. Conceptually, Sue Wing describes his approach in terms of two commodities: a "clean" commodity and a "dirty" commodity. He finds that a carbon tax reduces aggregate R&D, slowing the rate of technological change and the growth in output. Given the fixed-saving rule and absence of knowledge spillovers in the model, this follows from having a smaller economy due to the carbon tax. However, the relative price effects of a carbon tax lead to considerable reallocation of knowledge services, enabling the economy to adjust to the carbon tax in a more elastic manner, reducing the total costs of the carbon tax.

Simulations under the World Induced Technological Change Hybrid (WITCH) model (described in detail by Bosetti et al. (2006, 2007)]) confirm the potential power of carbon pricing to catalyze R&D, according to OECD (2008a). The WITCH model is a global energy/economy/climate change model that fully integrates a detailed representation of the energy sector into a macro model of the world economy. The WITCH model estimates that investments in renewable energy R&D would need to quadruple to meet a reduction goal of 445 ppm concentration by 2050 (compared with baseline).

The model simulations indicate that R&D policy alone is not enough to stabilize GHG emissions, even with a dramatic 30-fold increase in spending (constituting 1% of world GDP). For greater effect, R&D investments needs to be coupled with carbon pricing, and even this "may not be enough to ensure adequate deployment of existing low-carbon technologies."

In Bosetti et al. (2009), the WITCH model is enhanced and used to explore the effect on technological change of various public policies, including carbon pricing, R&D policies, and subsidies for dissemination of existing technologies. The model then assesses the policy mixes to determine future GHG emissions scenarios and associated costs of stabilization. Bosetti and coauthors find that the carbon price conclusively affects R&D and diffusion of the technology innovation. Carbon effects increase over time, with marginal abatement costs and R&D investment both rising disproportionately with emission reduction requirements. The authors also find that R&D investment today depends on the stringency of the goal set for the future, with greater R&D investment at 450 ppm $CO_2$ concentration stabilization than at 550 $CO_2$, because of the expectation that future carbon prices with rise under the more stringent scenario. A strong price signal is needed to spur R&D investments, whether these investments result in breakthrough technologies or less dramatic innovation advances. The authors find that mitigation costs will not significantly rise with higher R&D investments and diffusion in the absence of technological breakthroughs, and that with technological breakthroughs due to R&D investment, future mitigation costs could fall significantly. These lower-cost future benefits would conversely be associated with an increase in mid-term costs, which would be even greater than the R&D spending seen at its historical high point in the mid-1980s. Similar to simulations with the earlier WITCH model, the authors find that R&D alone is not sufficient to stabilize GHG levels in this century. Without an accompanying carbon price, R&D alone would be hampered by lags in the diffusion of the technologies to market and because of the outperformance by current technologies in energy production.

## Learning-Induced Technological Change

Learning-induced technological change approaches tend to be quite different than R&D-induced approaches. These models use the concept of learning-by-doing (LBD), in which costs to manufacturers decrease as a function of cumulative output, or "learning-by-using," in which the decrease in costs (and/or increase in benefits) to consumers comes as a function of the use of a technology (Arrow 1962, Rosenberg 1982). The primary disadvantage to the incorporation of learning-induced technological change into aggregate economic modeling is that the ease with which learning curves can be estimated may give a false sense of comfort and precision that may belie the R&D or other resources that went into the technology development (Clarke and Weyant 2002).

A common result of including endogenous technological change through LBD is that the carbon tax needed to attain a specific $CO_2$ concentration target tends to be lower than in models without LBD. This result is intuitive—with LBD modeled as described above, no R&D expenditure is needed and any additional capacity of carbon-free energy technologies will lower the costs of that technology in the future, leading to more emissions reductions per dollar of further investment. Another commonly observed result of incorporating LBD in climate policy models is that the optimal abatement path to reach a given concentration target involves increased near-term abatement and less abatement later (Grübler and Messner 1998). This result occurs because increased near-term abatement encourages earlier LBD in low-carbon technologies, which lowers the long-term costs of abatement. Van der Zwaan et al. (2002) also find a strong effect of LBD on the timing of abatement, showing that earlier abatement is desirable when LBD is included in climate models, and that the carbon taxes needed to achieve these reductions are lower, due to the cost savings resulting from LBD.

Other studies suggest that there are actually two competing effects. On one hand, there is the added value to near-term technology investment due to LBD, as just mentioned. On the other hand, LBD also leads to lower costs of future abatement, which implies that abatement should be delayed. The net result of the two opposing effects may be theoretically ambiguous, but numerical simulations by Manne and Richels (2004) suggest that the slope of the abatement curve over time actually may be steeper with LBD included, contrary to previous findings, such as those of Grübler and Messner (1998) described above.

Goulder and Mathai (2000) look at optimal carbon abatement policy in a dynamic setting, considering not only the optimal overall amount of abatement but also its timing. They consider separately cases in which innovation comes through R&D and in which innovation comes via learning-by-doing. In the R&D model, there are two effects of induced innovation on optimal abatement: it reduces marginal abatement costs, which increases the optimal amount of abatement. But it also increases the cost of abatement today relative to the future, because of lower abatement costs in the future. The combination of these effects implies that with R&D-induced innovation, optimal abatement is lower in early years and higher in later years than it would otherwise be. In contrast, in the learning-by-doing model, there is a third effect: abatement today lowers the cost of abatement in the future. This reinforces the tendency for cumulative optimal abatement to be higher in the presence of induced innovation, but makes the effect on optimal near-term abatement ambiguous. Bramoullé and Olson (2005) formalize the relationship between learning and policy, noting that if technology improves by learning by doing, abatement across time should be allocated so that marginal abatement costs are equal across time, with an adjustment for the cumulative marginal savings that current abatement provides for future costs.

## LITERATURE ON ENVIRONMENTAL AND TECHNOLOGY POLICY

The combination of environmental externalities and knowledge market failures provide two hurdles for policy makers to address when providing incentives for environmental innovation, and suggests two possible avenues through which policy can encourage the development of environmentally friendly technologies: correcting the environmental externality and/or correcting knowledge market failures. At a minimum, effective long-run environmental policies require both. Because knowledge market failures apply generally across technologies, policies addressing knowledge market failures may be general, addressing the problem in the economy as a whole, such as patent protection, R&D tax credits, and funding for generic basic research. Such policies focus on the overall rate of innovation—how much innovative activity takes place. In contrast, policies aimed specifically at the environment focus on the direction of innovation. While this includes policies regulating externalities, such as a carbon tax or cap-and-trade system, it also includes environmental and energy policies using more general R&D policy mechanisms with a specific focus on the environment. Technology policies specific to energy include targeted government subsidies for adoption of alternative energy, and funding for targeted basic and applied research.

Studies evaluating the effectiveness of these various policy options find that environmental and technology policies work best in tandem. While technology policy can help facilitate the creation of new environmentally friendly technologies, it provides little incentive to adopt these technologies. Fischer (2008) develops a theoretical model showing that government support for emissions control R&D is only effective if there is at least moderate environmental policy in place to encourage adoption of the resulting technologies. Bosetti et al. (2009) similarly show that R&D alone is insufficient to stabilize $CO_2$ levels without an accompanying carbon tax. Using a computable general equilibrium model to study the potential effects of energy R&D for climate change mitigation, Schneider and Goulder (1997) show that policies to address knowledge spillovers are more effective if they address all knowledge spillovers, rather than focusing exclusively on R&D pertaining to alternative energy. Not surprisingly, technology subsidies alone have a smaller environmental impact than policies that directly address the environmental externality.

Popp (2006a) considers the long-run welfare gains from both an optimally designed carbon tax (one equating the marginal benefits of carbon reductions with the marginal costs of such reductions) and optimally designed R&D subsidies. Popp finds that combining both policies yields the largest welfare gain. However, a policy using only the carbon tax achieves 95% of the welfare gains of the combined policy, while a policy using only the optimal R&D subsidy attains just 11% of the welfare gains of the combined policy in his model. In contrast to Schneider and Goulder, R&D policy has less effect in this study, as the subsidies only apply to the energy sector.

Given the importance of emissions policies to encourage R&D, two recent papers ask whether initial emissions policies should be made stronger, in order to achieve lower costs through an initial burst of induced innovation. Using a growth model, Hart (2008) shows that, in general, it is not optimal to raise an emissions tax above the level necessary to account for the environmental externality. One exception is if the shadow price of the emissions stock is rising and the initial level of emissions-saving knowledge is low. In this case, the spillovers from emissions-savings knowledge will be more valuable than spillovers from other innovations, justifying a temporary increase in the optimal emissions tax to account for differences in the social benefits of spillovers across technologies. Presumably a targeted R&D subsidy could also accomplish this, and perhaps with greater efficiency. Greaker and Pade (2008) find additional justification for higher emissions taxes if patent policy is weak— that is, as a second-best policy if the knowledge market spillover has not been adequately addressed.

The above studies focus on the macro level, and assume that technologies, once created, are optimally deployed. Fischer and Newell (2008) use a micro approach to study a broader set of policies, including those encouraging technology adoption, to assess policies for reducing $CO_2$ emissions and promoting innovation and diffusion of renewable energy. They evaluate the relative performance of policies according to incentives provided for emissions reduction and economic efficiency, and also assess how the nature of technological progress (i.e., learning versus R&D) and the degree of knowledge spillovers, affects the desirability of different policies. Although the relative cost of individual policies in achieving emissions reductions depends on parameter values and the emissions target, in a numerical application to the U.S. electricity sector, they find the ranking is roughly as follows: (1) emissions price, (2) emissions performance standard, (3) fossil power tax, (4) renewables share requirement, (5) renewables subsidy, and (6) R&D subsidy. Nonetheless, an optimal portfolio of policies—including emissions pricing and R&D—achieves emission reductions at significantly lower cost than any single policy.

In a similar exercise, Gerlagh and van der Zwaan (2006) find an emissions performance standard to be cheapest policy for achieving various carbon stabilization goals. They note that, like a carbon tax, the emissions performance standard directly addresses the environmental externality. In addition, like a renewable subsidy, the emissions performance standard stimulates innovation in a sector with high spillovers. In comparing the results of these two papers, Gerlagh and van der Zwaan note that the ordering of policies depends on the assumed returns to scale of renewable energy technologies. Fischer and Newell assume greater decreasing returns to renewable energy, due to the scarcity of appropriate sites for new renewable sources. Thus, an important question raised by Gerlagh and van der Zwaan is whether the cost savings from innovation will be sufficient to overcome decreasing returns to scale for renewable energy resulting from limited space for new solar and wind installations.

An additional problem resulting from the long time frame of environmental concerns such as climate change is uncertainty over future policies. Consider, for example, a firm planning research on fuel cells for cars. Given that such technologies are not currently competitive with traditional fuel sources, and that sufficient policies are not in place to overcome these cost differences, what matters to the firm is not the effective price of carbon emissions today. Rather, it is the expected price of carbon emissions a decade or more in the future, when the vehicle might actually be on the market. Such long-term issues arise often when studying problems such as climate change, and they raise the question of whether additional policy measures are needed that (1) enable the government to manipulate expectations of future prices, or (2) perform the initial research necessary to get ground-breaking technologies close to market, thus lowering the cost (and raising political support for) future environmental policy. That is, one can look at this question as whether environmental policy should come first, and be designed in a way to encourage long-run innovation, or whether technology policy needs to accompany or precede environmental policy, so as to lower the costs of implementing environmental cleanup. A related concern is the credibility of governments to use the promise of high future emissions prices to boost current innovation, since such high prices may no longer be needed once the resulting cost reductions arrive (Kennedy and Laplante 1999; Montgomery and Smith 2007).

General purpose technologies (GPT) may also magnify the interaction between the two market failures. GPTs are technologies that find use in many distinct application sectors within the economy, such as the electric motor, the steam engine, the internal combustion engine, semiconductors, and the

Internet (Bresnahan and Trajtenberg 1995). The development of such technologies increases the returns to R&D designed to incorporate them into the different applications sectors; development of such applications in turn increases the return to improving the GPT. Because of these dynamic feedback effects, GPTs may be an important factor in economic growth (Helpman 1998). The dynamic feedback between a GPT and its applications sectors also creates an important example of "path dependence." With respect to the environment, whether the GPTs that drive a particular era are pollution-intensive or pollution-saving may have profound implications for the long-term environmental prognosis. These phenomena can be critical to understanding the existing technological system, forecasting how that system might evolve, and predicting the potential effect of some policy or event.

# CONCLUSIONS

Technological change plays an important role in climate change policy. While new technologies can make cleaner production and more efficient resource use possible, markets are unlikely to provide proper incentives for the development of no- or low-carbon technologies, absent public policy. As in other areas of technological change, knowledge spillovers lead to underinvestment in R&D by private firms. However, even if all knowledge market failures were addressed, firms would still underinvest in environmental R&D, as many of the benefits to providing a cleaner environment are external. By addressing the externality problem, environmental policy increases incentives for environmental R&D.

There are many excellent treatments of the advantages of economy-wide, long-term, multi-gas, flexible emission policies that attach a cost to GHG emissions. The Kyoto Protocol, the EU Emission Trading System, and the legislative proposals with the most traction in the United States have embraced this approach. Establishing a GHG emission price (through policies such as cap-and-trade or emission taxes) is considered essential *from a technology perspective* for two primary reasons. First, because the GHG price attaches a financial cost to GHGs and—just as people will consume less of something expensive than something given away for free—will induce households and firms to buy technologies with lower GHG emissions. Ideally, the GHG price would be designed to encourage the adoption of the most cost-effective technologies for reducing emissions by sending a consistent financial signal to households and businesses across the economy.

The second reason the GHG price is considered essential from a technology perspective is because it creates a demand-driven, profit-based incentive for the private sector to invest effort in developing new, lower-cost climate-friendly innovations. Market-demand pull will encourage manufacturers to invest in R&D and other innovative efforts to bring new lower-GHG technologies to market, just as they do for other products and processes (for surveys see Jaffe et al. 2003 and Popp et al. 2008). Members of the U.S. Climate Action Partnership (USCAP 2007)— a coalition of major U.S. companies and environmental organizations—agreed when they concluded that “the most efficient and powerful way to stimulate private investment in research, development, and deployment is to adopt policies establishing a market value for GHG emissions over the long term.”

While any environmental policy should provide some additional incentive for environmentally oriented R&D, much research has focused on how the proper design of policy will lead to greater innovation. In particular, flexible policy instruments that provide rewards for continual environmental improvement and cost reduction tend to have better dynamic efficiency properties than policies that specify a specific behavior. One such instrument that has received attention lately to encourage R&D is the idea of innovation inducement prizes for climate mitigation The idea is to offer financial or other rewards for achieving specific innovation objectives that have been specified in advance (Newell and Wilson 2005, Kalil 2007, NRC 2007, Brunt et al. 2008).

As with environmental innovation, studies on the diffusion of environmental technologies also find that regulation is necessary for diffusion to occur. One notable difference is between environmental technologies (e.g., pollution control) and energy-efficiency technologies. Without environmental regulation, there is little private benefit to pollution control. Thus, as expected, regulation is necessary for diffusion to occur. On the other hand, individual consumers or firms can benefit from choosing energy-efficient technologies, as adopters benefit from lower energy bills. However, research on the adoption of energy-efficiency technologies suggests that decision making by both firms and consumers is potentially subject to market and behavioral failures (Gillingham et al. 2009).

In recent years, researchers have begun to investigate the role of international technology diffusion for environmental technologies. International diffusion is particularly important for problems such as climate change, as carbon emissions are growing faster in developing nations than in the developed world. Recent research suggests that these developing countries can take advantage of clean technologies developed in high income countries, but that both environmental and trade policies will affect the pace and quality of international technology diffusion.

The positive role of international technology-oriented agreements as part of the architecture of an international climate change policy has become more clear (de Coninck, et al. 2008, Justus and Philibert 2005). Specific activities under such agreements could include knowledge sharing and coordination, joint R&D, technology transfer, and technology deployment mandates, standards, or incentives. These activities can lower the costs of mitigation technologies, resulting in the greater likelihood that countries will implement significant GHG reductions. As outlined by Justus and Philibert, the benefits include "synergies in research, cost saving and risk mitigation, acceleration of developments, harmonization of standards, and reduced costs of national deployment support policies." The authors highlight a number of case studies in which collaboration helped advance technology innovation. For example, the IEA Wind Agreement between four participating countries reduced the total cost of aerodynamic testing to US$ 2-4 million, rather than a projected total cost of $12 million that would have been spent by the countries working individually.

A well-targeted set of climate policies, including those targeted directly at science and innovation, could help lower the overall costs of mitigation. It is important to stress, however, that poorly designed technology policy will *raise* rather than *lower* the societal costs of climate mitigation. To avoid this, policy can create substantial incentives in the form of a market-based price on GHG emissions, and directed government technology support can emphasize areas least likely to be undertaken by a private sector. This would tend to emphasize strategic basic research that advances science in areas critical to climate mitigation. In addition to generating new knowledge and useful tools, such funding also serves the critical function of training the next generation of scientists and engineers for future work in the private sector, at universities, and in other research institutions.

Effective climate technology policy complements rather than substitutes for emissions pricing. On the research side, R&D without market demand for the results is like pushing on a rope, and would ultimately have little impact. On the deployment side, technology-specific mandates and subsidies tend to generate emissions reductions in a relatively expensive, inefficient way relative to an emissions price, and under an economy wide cap-and-trade system will not actually generate any additional reductions. The scale of the climate technology problem and our other energy challenges requires a solution that maximizes the impact of the scarce resources available for addressing these and other critical societal goals. Research suggests that an emissions price coupled with R&D provides the basic framework for such a solution.

**Table 1. International R&D Expenditures in 2006 (units as indicated)**

| | All sources | | Percent financed by | | Percent performed by | | | Researchers |
|---|---|---|---|---|---|---|---|---|
| Country | (US$ billions) | Percent world R&D | Industry | Government | Industry | Universities | Government | (1000 FTEs) |
| United States | 344 | 35.8 | 65 | 29 | 70 | 14 | 11 | 1,388 |
| Japan | 139 | 14.4 | 77 | 16 | 77 | 13 | 8 | 710 |
| Germany | 67 | 6.9 | 68 | 28 | 70 | 16 | 14 | 282 |
| France | 41 | 4.3 | 52 | 38 | 63 | 18 | 17 | 204 |
| United Kingdom | 36 | 3.7 | 45 | 32 | 62 | 26 | 10 | 184 |
| Canada | 24 | 2.5 | 48 | 33 | 54 | 36 | 9 | 125 |
| Russia | 20 | 2.1 | 29 | 29 | 67 | 6 | 27 | 464 |
| Italy | 18 | 1.8 | 40 | 51 | 50 | 30 | 17 | 82 |
| Other EU-27 | 82 | 8.5 | 51 | 37 | 60 | 25 | 14 | 199 |
| **G-8 total** | **770** | **80.0** | **62** | **29** | **68** | **17** | **12** | **3,637** |
| Korea | 36 | 3.7 | 75 | 23 | 77 | 10 | 12 | 200 |
| Australia | 12 | 1.2 | 53 | 41 | 54 | 27 | 16 | 81 |
| Mexico | 6 | 0.6 | 47 | 45 | 50 | 27 | 22 | 48 |
| Turkey | 5 | 0.5 | 46 | 49 | 37 | 51 | 12 | 43 |
| Switzerland | 7 | 0.7 | 70 | 23 | 74 | 23 | 1 | 25 |
| Norway | 4 | 0.4 | 46 | 44 | 54 | 30 | 16 | 22 |
| New Zealand | 1 | 0.1 | 41 | 43 | 42 | 33 | 26 | 17 |
| **OECD total** | **818** | **85.0** | **64** | **30** | **69** | **17** | **11** | **3,979** |
| **OECD + Russia** | **838** | **87.1** | **62** | **30** | **69** | **17** | **11** | **4,443** |
| China | 87 | 9.0 | 69 | 25 | 71 | 9 | 20 | 1,223 |
| Chinese Taipei | 17 | 1.8 | 67 | 31 | 68 | 12 | 20 | 95 |
| Israel | 8 | 0.8 | 69 | 23 | 78 | 13 | 5 | — |
| Singapore | 5 | 0.5 | 59 | 36 | 66 | 24 | 10 | 25 |
| South Africa | 4 | 0.4 | 44 | 38 | 58 | 19 | 21 | 17 |
| Argentina | 2 | 0.2 | 29 | 67 | 30 | 27 | 41 | 35 |
| Romania | 1 | 0.1 | 30 | 64 | 49 | 18 | 32 | 21 |
| **World total*** | **962** | **100** | **63** | **30** | **69** | **16** | **13** | **5,859** |

Source : OECD (2008). Non-U.S. totals are based on purchasing power parity (PPP) exchange rates

* Note: Not all non-OECD countries are included; however, almost all R&D occurs in the included countries

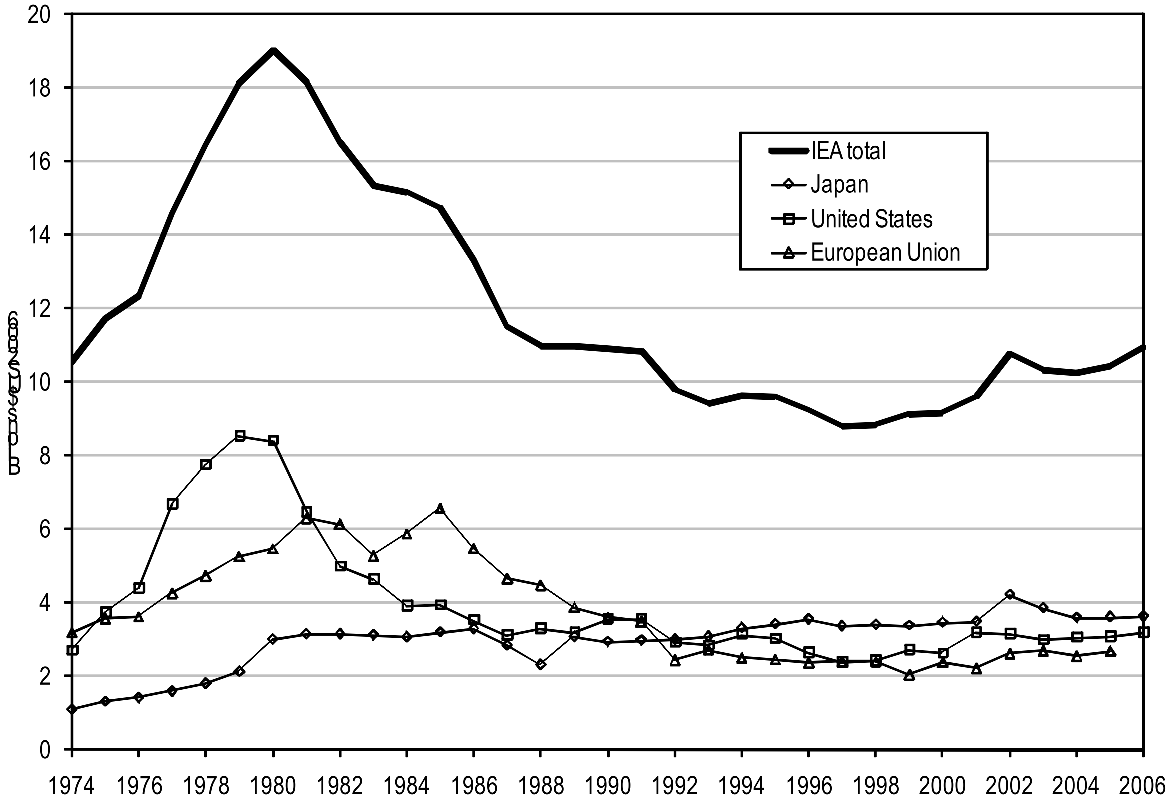
**Table 2. R&D Expenditures for Top R&D-Spending Companies Worldwide**

for 2006, units as indicated

| Sector (number of companies) | R&D | |
|---|---|---|
| | US$ (millions) | Percent of sales |
| All sectors (1,250) | 478,129 | 3.5 |
| Aerospace & defence (39) | 21,160 | 4.9 |
| Automobiles & parts (78) | 80,284 | 4.1 |
| Chemicals (91) | 22,341 | 3.1 |
| Construction & materials (23) | 2,374 | 0.9 |
| Electricity (16) | 2,918 | 0.9 |
| Electronic & electrical equipment (102) | 35,150 | 4.5 |
| Forestry & paper (8) | 573 | 0.5 |
| Gas, water & multiutilities (7) | 738 | 0.3 |
| General industrials (36) | 11,583 | 2.1 |
| Household goods (24) | 5,011 | 2.3 |
| Industrial engineering (70) | 11,737 | 2.7 |
| Industrial metals (23) | 3,201 | 0.8 |
| Industrial transportation (6) | 440 | 0.3 |
| Mining (3) | 604 | 0.7 |
| Oil & gas producers (18) | 6,465 | 0.3 |
| Oil equipment, services & distribution (10) | 1,748 | 1.9 |
| Pharmaceuticals & biotechnology (157) | 92,881 | 15.9 |
| Software & computer services (113) | 34,359 | 10.1 |
| Technology hardware & equipment (207) | 84,517 | 8.6 |

Note: Table includes sectors that may be relevant to GHG innovation, as well as certain very large R&D-performing sectors, from the *R&D Scorecard*'s 1,250 companies globally with the highest R&D expenditures (U.K. Department for Innovation, Universities and Skills 2007). These 1,250 companies account for about 80 percent of global industry R&D.

**Figure 1. Public Energy R&D Spending in IEA Countries (1974-2006)**



*Source* : IEA (2007a). Other IEA governments spend less than $500 million annually on energy R&D

## REFERENCES

Acemoglu, D. (1998), “Why do new technologies complement skills? Directed technical change and wage inequality”, Quarterly Journal of Economics 113:1055-1089.

Arrow, K.J. (1962), “The Economic implications of learning by doing”, Review of Economic Studies 29:155-173.

Baker, E. and K. Adu-Bonnah (2008), “Investment in risky R&D programs in the face of climate uncertainty”, Energy Economics 30(2):465-486.

Bauman, Y., M. Lee, and K. Seeley (forthcoming), “Does technological innovation really reduce marginal abatement costs? Some theory, algebraic evidence, and policy implications”, Environmental and Resource Economics.

Bellas, A.S. (1998), “Empirical evidence of advances in scrubber technology”, Resource and Energy Economics 20:327-343.

Berndt, E.R., C.D. Kolstad, and J. Lee (1993), “Measuring the energy efficiency and productivity impacts of embodied technical change”, The Energy Journal 14:33–55.

Berry, S., S. Kortum, and A. Pakes (1996), "Environmental change and hedonic cost functions for automobiles", Proceedings of the National Academy of Sciences (U.S.A. 93:12731-12738).

Blackman, A. and G.J. Bannister (1998), "Community pressure and clean technology in the informal sector: An econometric analysis of the adoption of propane by traditional Mexican brickmakers", Journal of Environmental Economics and Management 35(1):1-21.

Bosetti, V., C. Carraro, M. Galeotti and E. Massetti (2006), “A World Induced Technical Change Hybrid Model”, The Energy Journal, Hybrid Modeling of Energy Environment Policies: Reconciling Bottom-up and Top-down, Special Issue.

Bosetti, V., E. Massetti and M. Tavoni (2007), “The WITCH Model. Structure, Baseline, Solutions”, FEEM Working Paper, 10-2007.

Bosetti, Valentina, Carlo Carraro, Romain Duval, Alessandra Sgobbi, and Massimo Tavoni. 2009. The role of R&D and technology difussion in climate change cmtigation: New perspectives using the WITCH model. OECD Economics Department Working Papers, No. 664. Paris: Organisation for Economic Co-operation and Development.

Boyd, G.A. and S.H. Karlson (1993), "The impact of energy prices on technology choice in the United States steel industry", The Energy Journal 14(2):47-56.

Bramoullé, Y. and L.J. Olson (2005), “Allocation of pollution abatement under learning by doing”, Journal of Public Economics 89:1935-1960.

Brunt, Liam, Josh Lerner, and Tom Nicholas (2008), “Inducement Prizes and Innovation”, CEPR Discussion Paper No. DP6917. London: Social Science Research Network.

Buonanno, P., C. Carraro, and M. Galeotti (2003), “Endogenous induced technical change and the costs of Kyoto”, Resource and Energy Economics 25(1):11-34.

Carlson, C., D. Burtraw, M. Cropper, and K. Palmer (2000), “Sulfur dioxide control by electric utilities: What are the gains from trade?” Journal of Political Economy 108:1292–1326.

Carraro, C. and C. Egenhofer (2002), Firms, governments, and climate policy: Incentive-based policies for long-term climate change. (Cheltenham: Edward Elgar).

Carraro, C. and A. Soubeyran (1996), “Environmental policy and the choice of production technology”, in: C. Carraro et al., eds., Environmental Policy and Market Structure (Kluwer Academic Publishers, Dordrecht) 151-180.

Clarke, L. and J. Weyant (2002), “Modeling induced technological change: An overview”, in: A. Grübler, N. Nakicenovic and W. Nordhaus (Ed.), Technological Change and the Environment. (Resources for the Future Press, Washington, DC).

Cohen, L.R. and R.G. Noll (1991), The Technology Pork Barrel (Brookings, Washington, DC).

Copeland, B.R. and M.S. Taylor (2003), Trade and the Environment: Theory and Evidence (Princeton University Press, Princeton, NJ).

de Coninck, Helen, C. Fisher, Richard G. Newell, and Takahiro Ueno (2008), “International technology-oriented agreements to address climate change”, Energy Policy 36:335-356.

Dechezleprêtre, A., M. Glachant, and Y. Ménière (2008), “The clean development mechanism and the international diffusion of technologies: An empirical study”, Energy Policy 36:1273-1283.

Denicolò, V. (1999), "Pollution-reducing innovations under taxes or permits", Oxford Economic Papers 51:184-199.

Di Maria, C. and E. van der Werf (2008), “Carbon leakage revisited: unilateral climate policy with directed technological change”, Environmental and Resource Economics 39(1):55-74.

Dowlatabadi, H. (1998), “Sensitivity of climate change mitigation estimates to assumptions about technical change”, Energy Economics 20(5-6):473-493.

Downing, P.B. and L.J. White (1986), "Innovation in pollution control", Journal of Environmental Economics and Management 13:18-29.

Edmonds, J., J. Roop, M. Scott (2000), Technology and the Economics of Climate Change Policy. (Pew Center on Global Climate Change, Arlington, VA).

EIA. 2003. National Energy Modeling System: An Overview 2003. DOE/EIA-0581. Energy Information Administration, Department of Energy, Washington, DC.

EIA (Energy Information Administration) (2007), International Energy Outlook: 2007 (U.S. Department of Energy, Washington, DC).

Esty, Daniel C. (2001), “Bridging the trade-environment divide”, Journal of Economic Perspectives 15(3):113-130.

Evenson, R.E., J. Putnam, S. Kortum (1991), “Estimating patent counts by industry using the Yale-Canada concordance,” Final Report to the National Science Foundation.

Fischer, C. and R. Newell (2008), “Environmental and technology policies for climate mitigation”, Journal of Environmental Economics and Management 55(2):142-162.

Fischer, C., I.W.H. Parry, and W.A. Pizer (2003), “Instrument choice for environmental protection when technological innovation is endogenous”, Journal of Environmental Economics and Management 45(3):523–545.

Fisher-Vanden, K. (2003), “Management structure and technology diffusion in Chinese state-owned enterprises”, Energy Policy 31(3):247-257.

Fisher-Vanden, Karen and M.S. Ho (2006), “Technology, development, and the environment,” Working paper, Dartmouth College.

Fisher-Vanden, K., G. Jefferson, J. Ma, and J. Xu (2006), “Technology development and energy productivity in China”, Energy Economics 28(5/6):690-705.

Folmer, H. and P. van Mouche (1993), “Interconnected games and international environmental problems”, Environmental and Resource Economics 3:313-335.

Frondel, M., J. Horbach, and K. Rennings (2007), “End-of-pipe or cleaner production? An empirical comparison of environmental innovation decisions across OECD countries”, Business Strategy and the Environment 16:571-584.

Gerlagh R. (2008), “A climate-change policy induced shift from innovations in carbon-energy production to carbon-energy savings”, Energy Economics 30:425-448.

Geroski, P.A. (2000), “Models of technology diffusion”, Research Policy 29:603-626.

Gillingham, K., R.G. Newell, and K. Palmer (2006), “Energy efficiency policies: A retrospective examination”, Annual Review of Environment and Resources 31:162-192.

Gillingham, Kenneth T., Richard G. Newell, and William A. Pizer. 2008. “Modeling Endogenous Technological Change for Climate Policy Analysis.” Energy Economics 30(6): 2734–2753.

Gillingham, K., R.G. Newell, and K. Palmer. 2009. Energy Efficiency Economics and Policy. Manuscript prepared for the Annual Review of Resource Economics.

Gollop, F.M. and M.J. Roberts (1983), “Environmental regulations and productivity growth: The case of fossil-fueled electric power generation”, Journal of Political Economy 91:654-674.

Golombek, R. and M. Hoel (2004), "Unilateral emission reductions and cross-country technology spillovers", Advances in Economic Analysis & Policy 4(2):Article 3. Available at: http://www.bepress.com/bejeap/advances/vol4/iss2/art3.

Goulder, Lawrence. H. 2004. Induced Technological Change and Climate Policy. Pew Center on Global Climate Change, Washington, DC.

Goulder, L.H. and S. Schneider (1999), "Induced technological change and the attractiveness of CO2 abatement policies." Resource and Energy Economics 21:211-253.

Goulder, L.H. and K. Mathai (2000), "Optimal CO2 abatement in the presence of induced technological change", Journal of Environmental Economics and Management 39:1-38.

Grübler, A., and S. Messner (1998), "Technological change and the timing of mitigation measures", Energy Economics 20:495-512.

Haščič, I., N. Johnstone, and C. Michel (2008), "Environmental policy stringency and technological innovation: Evidence from patent counts", paper presented at the European Association of Environmental and Resource Economists 16th Annual Conference, Gothenburg, Sweden, June 26, 2008.

Hassett, K.A. and G.E. Metcalf (1995), "Energy tax credits and residential conservation investment: Evidence form panel data", Journal of Public Economics 57:201-217.

Hassett, K.A. and G.E. Metcalf (1996), "Can irreversibility explain the slow diffusion of energy saving technologies?", Energy Policy 24:7-8.

Hausman, J.A. (1979), "Individual discount rates and the purchase and utilization of energy-using durables", Bell Journal of Economics 10:33.

Hilton, F.H. (2001), "Later abatement, faster abatement: Evidence and explanations from the global phaseout of leaded gasoline", Journal of Environment and Development 10(3):246-265.

Howarth, R.B., B.M. Haddad, and B. Paton (2000), "The economics of energy efficiency: Insights from voluntary participation programs", Energy Policy 28:477-486.

IEA. 2007a. Energy Technology RD&D Budgets 2007. Paris: OECD/IEA.

IEA (International Energy Agency). 2007b. World Energy Outlook 2007. Paris: OECD/IEA.

IEA (International Energy Agency). 2008. Energy Technology Perspectives 2008. Paris: OECD/IEA.

Innes, R. and J.J. Bial (2002), "Inducing innovation in the environmental technology of oligopolistic firms", Journal of Industrial Economics 50(3):265-287.

IPCC (Intergovernmental Panel on Climate Change). 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A.(eds.)]. IPCC: Geneva, Switzerland.

Jaffe, A.B. and Josh Lerner (2001), "Reinventing public R&D: Patent policy and the commercialization of national laboratory technologies", RAND Journal of Economics 32(1):167-198.

Jaffe, A.B. and R.N. Stavins (1994), “The energy paradox and the diffusion of conservation technology”, Resource and Energy Economics 16:91-122.

Jaffe, A.B., R.G. Newell, and R.N. Stavins (2003), “Technological change and the environment”, in K.-G. Mäler and J. Vincent, eds., Handbook of Environmental Economics, Vol. 1. Edited by Handbooks in Economics series, K.J. Arrow and M.D. Intriligator, series eds. (Amsterdam: North-Holland/Elsevier) 461-516.

Jakeman, G., K. Hanslow, M. Hinchy, B. Fisher, and K. Woffenden (2004), “Induced innovations and climate change policy”, Energy Economics 26(6):937-960.

Jancovici, J.M., 2002, L’avenir climatique – Quel temps ferons-nous?, Science Ouverte, Seuil, Paris.

Johnstone, N. and I. Hascic (2008), “Environmental policy design and the fragmentation of markets for innovation,” paper presented at the Venice Summer Institute 2008 Workshop on “Reforming Rules and Regulations - Laws, Institutions and Implementation,” (http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1396583# ).

Johnstone, N., I. Hascic, and D. Popp (2008), “Renewable energy policies and technological innovation: Evidence based on patent counts”, in *Environmental and Resource Economics*, forthcoming.

Jorgenson, D.W., and B.M. Fraumeni (1981), Relative prices on technical change”, in: B.C. Field, and E.R. Berndt, eds., Modeling and Measuring Natural Resource Substitution. (MIT Press, Cambridge, MA) 17–47.

Jung, C.H., K. Krutilla and R. Boyd (1996), "Incentives for advanced pollution abatement technology at the industry level: An evaluation of policy alternatives", Journal of Environmental Economics and Management 30:95-111.

Justus, Debra, and Cédric Philibert. 2005. International Energy Technology Collaboration and Climate Change Mitigation: Synthesis Report. COM/ENV/EPOC/IEA/SLT(2005)11 Paris: Organization for Economic Co-operation and Development.

Kalil, Thomas. 2006. “Prizes for Technological Innovation.” Hamilton Project Discussion Paper 2006-08, Brookings Institution, Washington, DC.

Katsoulacos, Y. and A. Xepapadeas (1996), “Environmental innovation, spillovers and optimal policy rules”, in: C. Carraro et al., eds., Environmental Policy and Market Structure (Kluwer Academic Publishers, Dordrecht) 143-150.

Kemfert, C. (2004), “International climate coalitions and trade: Assessment of cooperation incentives by issue linkage.” Energy Policy 32:455-465.

Keohane, N.O. (2007), “Cost savings from allowance trading in the 1990 Clean Air Act: Estimates from a choice-based model”, in: Charles E. Kolstad and Jody Freeman, eds., Moving to Markets in Environmental Regulation: Lessons from Twenty Years of Experience (Oxford University Press, New York).

Kerr, S. and R.G. Newell (2003), “Policy-induced technology adoption: Evidence from the U.S. lead phasedown”, Journal of Industrial Economics 51(3):317-343.

Khanna, M. and D. Zilberman (2001), “Adoption of energy efficient technologies and carbon abatement: the electricity generating sector in India”, Energy Economics 23:637-658.

Klaassen, G., S. Miketa, K. Larsen, and T. Sundqvist (2005), “The impact of R&D on innovation for wind energy in Denmark, Germany and the United Kingdom”, Ecological Econ 54:227-240.

Kortum, S. and J. Putnam (1989), “Estimating patents by industry: Part I and II,” (unpublished manuscript, Yale University).

Kortum, S. and J. Putnam (1997), “Assigning patents by industry: tests of the Yale Technology Concordance”, Economic Systems Research 9:161–175.

Lange, Ian and Allen Bellas (2005), “Technological change for sulfur dioxide scrubbers under market-based regulation”, Land Economics 81(4):546-556.

Lanjouw, J.O. and A. Mody (1996), "Innovation and the international diffusion of environmentally responsive technology", Research Policy 25:549-571.

Linn, J. (forthcoming), “Energy prices and the adoption of energy-saving technology,” Economic Journal.

Lovely, M. and D. Popp (2008), “Trade, technology and the environment: Why do poorer countries regulate sooner?” NBER Working Paper #14286.

Magat, W.A. (1978), "Pollution control and technological advance: A dynamic model of the firm", Journal of Environmental Economics and Management 5:1-25.

Mäler, K. and J. Vincent, eds. (2005), Handbook of Environmental Economics: Valuing Environmental Changes, K.J. Arrow and M.D. Intriligator, series eds. (Amsterdam: North-Holland/Elsevier).

Maloney, M.T. and G.L. Brady (1988), “Capital turnover and marketable Pollution rights”, Journal of Law and Economics 31:203-226.

Manne, A., and R. Richels (2004), “The impact of learning-by-doing on the timing and costs of CO2 abatement”, Energy Economics 26:603-619.

Mansfield, E. (1968), Industrial Research and Technological Innovation (Norton, New York).

McCubbins, M.D., R.G. Noll, and B.R. Weingast (1989), “Structure and process, politics and policy: Administrative arrangements and the political control of agencies”, Virginia Law Review 75:431-482.

McDonald A. and L. Schrattenholzer (2000), “Learning rates for energy technologies”, Energy Policy 29:255-261.

Milliman, S.R. and R. Prince (1989), "Firm incentives to promote technological change in pollution control", Journal of Environmental Economics and Management 17:247-265.

Milliman, S.R. and R. Prince (1992), "Firm incentives to promote technological change in pollution control: Reply", Journal of Environmental Economics and Management 22:292-296.

Mountain, D.C., B.P. Stipdonk, and C.J. Warren (1989), "Technological innovation and a changing energy mix—A parametric and flexible approach to modeling Ontario manufacturing", The Energy Journal 10:139-158.

National Science Board (2006), Science and Engineering Indicators 2006. (National Science Foundation. Chapter 4: Research and Development: Funds and Technology Linkages, Arlington, VA).

Nelson, R., T. Tietenberg, and M. Donihue (1993), “Differential environmental regulation: Effects on electric utility capital turnover and emissions”, Review of Economics and Statistics 75:368-373.

Nemet, G.F. (2006), “Beyond the learning curve: Factors influencing cost reductions in photovoltaics”, Energy Policy 34(17):3218-3232.

Newell, R.G. 2008a. A U.S. Innovation Strategy for Climate Change Mitigation. Hamilton Project Discussion Paper 2008-15, Brookings Institution, Washington, DC.

Newell, R.G. 2008b. International Climate Technology Strategies. Discussion Paper 08-12, Harvard Project on International Climate Agreements, Cambridge, MA.

Newell, R. and N. Wilson (2005), “Technology Prizes for Climate change Mitigation”, Resources for the Future Discussion Paper No. 05-33.

Newell, R., A. Jaffe, and R. Stavins (1999), “The induced innovation hypothesis and energy-saving technological change”, The Quarterly Journal of Economics 114(3):941-975.

Newell, R.G., A.B. Jaffe, and R.N. Stavins (2004), “The economics of energy efficiency”, in: C. Cleveland, ed., Encyclopedia of Energy, Vol. 2 (Amsterdam: Elsevier) 79–90.

Nordhaus, W.D. (1994), Managing the Global Commons: The Economics of Climate Change (MIT Press, Cambridge, MA).

Nordhaus, W.D. (2002), “Modeling induced innovation in climate change policy”, in: A. Grubler, N. Nakicenovic and W. Nordhaus, eds., Technological Change and the Environment. (Resources for the Future Press, Washington, DC).

Nordhaus, W.D. and Z. Yang (1996), “A regional dynamic general-equilibrium model of alternative climate-change strategies”, American Economic Review 86(4):741-765.

NRC (National Research Council). 2007. Innovation Inducement Prizes at the National Science Foundation. Washington, D.C.: National Academies Press.

OECD (Organisation of Economic Co-operation and Development). 2003. “Technology Innovation, Development and Diffusion.” OECD/IEA Information Paper COM/ENV/EPOC/IEA/SLT(2003)4. Prepared by Cédric Philibert. Paris: Organisation of Economic Co-operation and Development.

OECD (Organisation of Economic Co-operation and Development). 2008a. “The Economics of Climate Change Mitigation: Policies and Post-2012 Options.” Paris: OECD.

OECD (Organisation of Economic Co-operation and Development). 2008b. Main Science and Technology Indicators, Volume 2008/1. Paris: OECD.

Pakes, A., S. Berry, and J.A. Levinsohn (1993), "Applications and limitations of some recent advances in empirical industrial organization: Prices indexes and the analysis of environmental change", American Economic Review 83:240-246.

Parry, I.W.H. (1998), "Pollution regulation and the efficiency gains from technological innovation", Journal of Regulatory Economics 14:229-254.

Pegram, W.M. (1991), “The photovoltaics commercialization program,” in: Cohen, L. and Noll, R. eds., The Technology Pork Barrel (Brookings Institution, Washington, DC).

Philibert, Cédric. 2006. Barriers to Technology Diffusion: The Case of Solar Thermal Technologies. COM/ENV/EPOC/IEA/SLT(2006)9. Paris: OECD/IEA.

Pindyck, R. (1991), “Irreversibility, uncertainty, and investment”, Journal of Economic Literature 29:1110-1152.

Pizer, W.A., W. Harrington, R.J. Kopp, R.D. Morgenstern, and J. Shih (2001), “Technology Adoption and Aggregate Energy Efficiency”, Resources for the Future Discussion Paper 01-21 (Resources for the Future, Washington, DC).

Popp, D. (2001), The effect of new technology on energy consumption”, Resource and Energy Economics 23(3):215-239.

Popp, D. (2002), “Induced innovation and energy prices”, American Economic Review 92(1):160-180.

Popp, D. (2003), “Pollution control innovations and the Clean Air Act of 1990”, Journal of Policy Analysis and Management 22:641-660.

Popp, D. (2004), “ENTICE: Endogenous technological change in the DICE model of global warming”, Journal of Environmental Economics and Management 48:742-768.

Popp, D. (2006a), “R&D subsidies and climate policy: Is there a ‘free lunch’?”, Climatic Change 77(3-4):311-341.

Popp, D. (2006b), “International innovation and diffusion of air pollution control technologies: The effects of NOX and SO2 regulation in the U.S., Japan, and Germany”, Journal of Environmental Economics and Management 51(1):46-71.

Popp, D. (2006c), “They don't invent them like they used to: An examination of energy patent citations over time”, Economics of Innovation and New Technology 15(8):753-776.

Popp, D. (2006d), “Exploring the links between innovation and diffusion: Adoption of NOX control technologies at U.S. coal-fired power plants”, NBER Working Paper #12119.

Popp, D., Tamara Hafner, and Nick Johnstone (2008), “Policy vs. consumer pressure: Innovation and diffusion of alternative bleaching technologies in the pulp industry,” NBER Working Paper #13439.

Popp, David, Richard G. Newell, and Adam B. Jaffe. Forthcoming. "Energy, the Environment, and Technological Change." In Handbook of Economics of Technical Change, Bronwin Hall and Nathan Rosenberg, eds. Oxford: Elsevier

Requate, T. (2005), "Timing and commitment of environmental policy, adoption of new technology, and repercussions on R&D," Environmental and Resource Economics 31:175-199.

Romer, P. (1990), "Endogenous technological change", Journal of Political Economy 98(5)S71-S102.

Rose, N. and P. Joskow (1990), "The diffusion of new technologies: Evidence from the electric utility industry", Rand Journal of Economics 21:354-373.

Rosenberg, N. (1982), Inside the Black Box: Technology and Economics (Cambridge University Press, Cambridge, UK).

Ross, M. (1990), "Capital budgeting practices of twelve large manufacturers", in: P. Cooley, ed., Advances in Business Financial Management (Dryden Press, Chicago) 157-170.

Ruderman, H., M.D. Levine, and J.E. McMahon (1987), "The behavior of the market for energy efficiency in residential appliances including heating and cooling equipment", The Energy Journal 8:101-123

Scherer, F., D. Harhoff, and J. Kukies (2000), "Uncertainty and the size distribution of rewards from technological innovation", Journal of Evolutionary Economics 10:175-200.

Smulders, S. and M. de Nooij (2003), The impact of energy conservation on technology and economic growth," Resource and Energy Economics 25(1):59-79.

Söderholm P. and G. Klaassen (2007), "Wind power in Europe: A simultaneous innovation-diffusion model", Environmental and Resource Economics 36:163-190.

Söderholm, P. and T. Sundqvist. 2007. "Empirical Challenges in the Use of Learning Curves for Assessing the Economic Prospects of Renewable Energy Technologies," Renewable Energy 2007:32(15).

Sterner, T. (1990), "Energy efficiency and capital embodied technical change: the case of Mexican cement manufacturing", The Energy Journal 11:155–167.

Stewart, R.B. (1981), "Regulation, innovation, and administrative law: A conceptual framework", California Law Review 69:1256-1270.

Sue Wing, I. (2003), "Induced technical change and the cost of climate policy." Joint Program on the Science and Policy of Global Change Report no. 112. (Massachusetts Institute of Technology, Cambridge, MA).

Sue Wing, I. (2006), "Representing induced technological change in models for climate policy", Energy Economics 28:539-562.

Sue Wing, I. (2008), "Explaining the declining energy intensity of the U.S. economy", Resource and Energy Economics 30(1):21–49.

Taylor M.R. (2008), “Cap-and-trade programs and innovation for climate safety,” (Working Paper, University of California-Berkeley).

Taylor, M.R., E.S. Rubin, and D.H. Hounshell (2003), “Effect of government actions on technological innovation for SO2 Control”, Environmental Science & Technology 37:4527-4534.

Ulph, D. (1998), "Environmental policy and technological innovation," in: C. Carraro and D. Siniscalaco, eds., Frontiers of Environmental Economics (Edward Elgar, Cheltenhsam, UK).

UNFCCC (United Nations Framework Convention on Climate Change). 2007. Investment and Financial Flows to Address Climate Change. Bonn: UNFCCC.

UNFCCC (United Nations Framework Convention on Climate Change). 2008. Report of the Conference of the Parties on its thirteenth session, held in Bali from 3 to 15 December 2007. Addendum. Part Two: Action taken by the Conference of the Parties at its thirteenth sessionBonn: UNFCCC.

USCAP (U.S. Climate Action Partnership). 2007. A Call for Action. Washington, DC: USCAP.

van der Zwann, B., R. Gerlagh, G. Klaassen, and L. Schrattenholzer. 2002. Endogenous technological change in climate change modeling. Energy Economics 24, 1–19.

van Zon, A., and I.H. Yetkiner (2003), “An endogenous growth model with embodied energy-saving technical change”, Resource and Energy Economics 25(1):81-103.

World Bank. 2008c. Global Economic Prospects: Technology Diffusion in the Developing World. Washington, DC: The World Bank.

Wright, T.P. (1936), “Factors affecting the costs of airplanes”, Journal of Aeronautical Sciences 3:122-128.

Zerbe, R.O. (1970), "Theoretical efficiency in pollution control", Western Economic Journal 8:364-376.