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INNOVATION AND CLIMATE POLICY

David Popp

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ABSTRACT

Reducing emissions of the greenhouse gases that cause climate change will require dramatic changes in the way that energy is produced and consumed. The cost of technological changes such as alternative energy sources and improved energy efficiency will play a large role in determining the overall cost of combating climate change. The development of these technologies will be heavily influenced by government policy. Both environmental and R&D policies provide incentives encouraging the development of clean technologies. Understanding the incentives provided by these policies, and their influence on the development of new technologies, is important for understanding the ultimate effects of climate policy. This chapter reviews the literature on environmental innovation and diffusion, with a focus on studies relevant to the development of clean energy technologies necessary to address climate change. I discuss the implications of this literature for the development of climate policy.

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As concerns about the potential future damages from climate change grow, there is increased support for policies to slow or even reverse the growth in greenhouse gas emissions that has occurred during the Industrial Revolution. The "American Clean Energy and Security Act" passed by the U.S. House of Representatives on June 26, 2009 calls for reducing U.S. greenhouse gas emissions by 17 percent below 2005 levels by 2020, and 83 percent by 2050. European Union proposals to stabilize global temperatures an average of two degrees Celsius over pre-Industrial Revolution levels imply stabilizing atmospheric carbon dioxide (CO_2) concentrations at 450 parts per million (ppm). Current levels already exceed 380 ppm. To meet such targets, annual CO_2 emissions would need to peak at about 9 billion tons of carbon per year by about 2012, and fall to as little as 3.5 billion tons per year by 2100 (Holdren 2006).

Meeting emission reduction targets such as these will not be possible without major changes in the way that energy is produced and consumed. Given the current status of alternative technologies, making such changes will be costly. Generation of electricity and heat is the largest source of carbon emissions, accounting for 41% of carbon emissions worldwide in 2006, followed by transportation at 23% (IEA 2008). In both cases, alternative carbon-free energy sources such as wind, solar, or hydrogen fuels all are priced higher than traditional fossil fuels (IEA 2006). Other possible solutions, such as carbon capture and storage, are even more costly, and include uncertainties about the geological feasibility of storage sites (Barrett 2009). Nonetheless, the International Energy Agency projects that, to stabilize concentrations at 450 ppm, 60 percent of passenger vehicles sold worldwide in 2030 would need to be hybrid, plug-in hybrid, or electric vehicles. Also by 2030, more electricity would need to be generated from wind and other non-hydro renewable sources than by coal, even with the possibility that some coal generation would include carbon capture and storage (IEA 2009a).

However, technology improvements are likely to occur, leading to lower costs. Much uncertainty surrounds the potential for technological change. In its latest report on climate change, the Intergovernmental Panel on Climate Change (IPCC) reports estimates of the costs of stabilizing global carbon concentrations from a variety of climate models. To stabilize concentrations at a level of 550 parts per million (ppm), the estimated costs, in terms of lost GDP in the year 2050, range from a four percent loss to a slight increase in GDP, relative to baseline growth (IPCC 2007). Projections of future technological change are an important driver of these differences, and affect not only the cost of reducing emissions, but also predictions of what emissions levels will occur in the absence of climate policy initiatives.

Understanding the potential for technological change requires an understanding of the process through which these changes occur. All private sector innovation suffers from market failures. These are even more acute in the case of climate change, as environmental market failures compound the problem. Thus, policy plays a key role shaping both the direction and magnitude of climate-friendly technological change. In turn, these policy-induced innovations will lower the cost of reducing carbon emissions. For instance, in a review of cost-benefit studies of proposed U.S. environmental regulations, Harrington *et al*. (2000) find pre-policy predictions of the net benefits of environmental regulation to be lower than evaluations after the fact, as newly developed technologies lower the costs of complying with regulation.

In this paper, I review the literature on environmental technological change, focusing on the implications of this research for climate policy. The literature on environmental technological change is large, and I do not attempt a complete review here. Rather, the focus is on selected studies that can be used to inform the design of climate policy. For a more thorough review, see Popp, Newell, and Jaffe (2009). Moreover, the focus is at the microeconomic level.

For recent reviews of the growing literature on the macroeconmic effects of endogenous technological change for climate policy, see Köhler *et al* (2006) and Gillingham *et al*. (2008).

I. Market Failures and the Policy Response

To consider the incentives (or lack thereof) that firms have to develop and deploy environmental technologies, I first consider the incentives faced for the development and deployment of new technologies. Technological change proceeds in three stages. At each stage, incentives, in the form of prices or regulations, affect the development and adoption of new technologies:

Invention: an idea must be born.

Innovation: new ideas are then developed into commercially viable products. Often, these two stages of technological change are lumped together under the rubric of research and development (R&D).

Diffusion: to have an effect on the economy, individuals must choose to make use of the innovation.

A. Market Failures for Environmental R&D

At all three stages, market forces provide insufficient incentives for investment in either the development or diffusion of environmentally-friendly technologies. Economists point to two market failures as the explanations for underinvestment in environmental R&D. These market failures provide the motivation for government policy designed to increase such research.

One market failure is the traditional problem of environmental externalities. Because pollution is not priced by the market, firms and consumers have no incentive to reduce emissions without policy intervention. Thus, without appropriate policy interventions, the market for technologies that reduce emissions will be limited, reducing incentives to develop such technologies. For climate change, examples of such technologies include alternative energy sources, capturing methane gas from landfills, and carbon capture and sequestration. Note that, even without climate policy in place, there are incentives to develop and deploy energy efficient technologies, as improving energy efficiency not only reduces emissions, but also lowers costs. Indeed, since 1980, energy intensity, defined as energy consumption per dollar of GDP, has fallen at a rate of 1.5% per year since 1995.[1] The market failure problem simply means that individuals do not consider the social benefits of using technologies that reduce emissions, so that firms underinvest in energy efficient technologies.

The second market failure pertaining to R&D is the public goods nature of knowledge (see, for example, Geroski 1995). In most cases, new technologies must be made available to the public for the inventor to reap the rewards of invention. However, by making new inventions public, some (if not all) of the knowledge embodied in the invention becomes public knowledge. This public knowledge may lead to additional innovations, or even to copies of the current innovations.[2] These knowledge *spillovers* provide benefit to the public as a whole, but not to the innovator. As a result, private firms do not have incentives to provide the socially optimal level of research activity.

Much economic research has been done quantifying the effect of such spillovers. Economists studying the returns to research consistently find that knowledge spillovers result in a wedge between private and social rates return to R&D. Examples of such studies include

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[1] Calculated from data available at http://www.eia.doe.gov/emeu/international/energyconsumption.html, accessed June 4, 2008.

[2] Intellectual property rights, such as patents, are designed to protect inventors from such copies. However, their effectiveness varies depending on the ease in which inventors may "invent around" the patent by making minor modifications to an invention. See, for example, Levin *et al.* (1987).

Mansfield (1977, 1996), Pakes (1985), Jaffe (1986), Hall (1996), and Jones and Williams (1998). Typical results include marginal social rates of return between 30 and 50 percent. In comparison, estimates of private marginal rates of return on investments range from 7 to 15 percent (Bazelon and Smetters 1999, Jones and Williams 1998, Hall 1996). Since firms make investment decisions based on their private returns, the wedge between private and social rates of return suggests socially beneficial research opportunities are being ignored by firms because they are unable to fully capture the rewards of such innovations.

B. Policy Responses

The combination of environmental externalities and knowledge market failures 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. 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. Examples include 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, such as targeted government subsidies for adoption of alternative energy, and targeted funding for 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. 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.

Acemoglu *et al*. (2009) develop a two-sector model of directed technical change, in which a single output is produced using inputs from a clean and dirty sector, to evaluate the role of taxes and R&D subsidies. In their model, two effects influence the direction of innovative activity: a market size effect that directs innovation towards the larger sector, and a price effect that directs innovation towards the sector with a higher price. Because the dirty sector (e.g. fossil fuel production) is currently the larger sector, in the absence of policy the market size effect causes the productivity gap between the dirty and clean sectors to grow over time. Thus, any delays in climate policy are costly, as fossil fuel productivity develops faster than the productivity of clean alternatives in the absence of policy. As such, more stringent (and thus costlier) policies will be needed at later dates to close the gap between clean and dirty fuels. Regarding the choice of policies, Acemoglu *et al*. also find that the optimal policy mix includes both a carbon tax and R&D subsidies. Using the R&D subsidy to direct research towards the clean energy sector results in a lower (and thus less distortionary) carbon tax than would be necessary if the carbon tax were used alone to both reduce emissions and redirect research inputs.

The intuition behind each of these studies is that, while R&D subsidies aid the development of new technologies, environmental policy is necessary to ensure the diffusion of these technologies. However, each of the aforementioned studies focus on the macro level, and assume that technologies, once created, are optimally deployed in response to whatever policy incentives may or may not be in place. 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 carbon dioxide emissions and promoting innovation and diffusion of renewable energy. 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.

II. Innovation and Climate Policy

While the studies in previous section demonstrate the importance of both climate and R&D policy, they provide less guidance on the policy mechanisms to be used. There are a wide range of policies in place that could be classified as "climate policy." These include broad-based policies such as carbon taxes and cap-and-trade systems to limit carbon emissions, to targeted policies such as renewable portfolio standards, restrictions on incandescent light bulbs, fuel economy standards, and investment tax credits for solar energy.

Focusing on energy usage as a means of reducing greenhouse gas emissions depends on one of two strategies (Holdren 2006).[3] One is to reduce the carbon intensity of energy use (that is, the amount of carbon emitted per unit of energy consumed). This ratio has been falling over time, as the deployment of cleaner energy sources such as natural gas and wind increases. A second option is to reduce energy intensity (energy usage per dollar of GDP) by improving energy efficiency. More efficient technologies enable a country to achieve greater economic output from a given amount of energy.

This distinction suggests two places to look for evidence of the effect of climate policy on innovation. One is energy prices. Policies designed to reduce carbon emissions will increase the price of fossil fuels, raising the incentives for innovation on both energy efficiency and on clean energy technologies. This is true not only for policies such as a carbon tax, but also, for example, of mandates that change the nature of electricity production. Experiences from past increases in energy prices provide evidence on how innovation may respond to future price increases resulting from climate policy.

However, climate policies do more than raise prices. They also change the relative costs and benefits of competing technologies. Carbon taxes make coal relatively more expensive than natural gas. Renewable energy portfolio standards and renewable energy investment tax credits increase the rewards for innovation on alternative energy sources. Thus, understanding the influence of policies, whether technology-specific or broad based market policies, is also important. Because countries have only recently begun to adopt policies specifically designed to address climate change, only a few empirical papers specifically address the effects of climate policy on innovation. However, there is a much broader literature on the effects of

[3] While other strategies, such as reforestation, are also important, I focus on energy usage as most efforts to improve technology in response to climate change have focused on the energy sector.

environmental policy on innovation that provides guidelines as to how climate policy may affect innovation.

A. Induced Innovation and Environmental Policy

Studies on the effect of policy or prices on innovation draw their motivation from the notion of induced innovation (Hicks 1932, Binswanger and Ruttan 1978, Acemoglu 2002), which recognizes that R&D is a profit-motivated investment activity and that the direction of innovation likely responds positively in the direction of increased relative prices. Empirical studies on the effect of policy and prices on environmental innovation both support the conjectures of the induced innovation hypothesis and provide evidence of the magnitude of these effects. Early studies of induced innovation from environmental policy made use of pollution abatement control expenditures (PACE) to proxy for environmental regulatory stringency. Jaffe and Palmer (1997) examine the correlation between PACE by industry and indicators of innovation more broadly. They find a significant correlation within industries over time between the rate of expenditure on pollution abatement and the level of R&D spending. They do not, however, find evidence of an effect of pollution control expenditure on overall patenting. Hamamoto (2006) finds similar effects on R&D spending in Japan. Brunnermeier and Cohen (2003) estimate the relationship between PACE and environmental patents across various U.S. industries, finding that patents increase by just 0.04 percent when PACE increases by $1 million.

One limitation of these papers is that they do not take advantage of the disaggregated nature of patent data. Each looks at innovation within specific industries. Jaffe and Palmer include *all* patents associated with an industry, whether or not they are environmental technologies, and Hamamoto includes all R&D activities, not just those focused on the environment. Brunnermeier and Cohen focus specifically on environmental technologies, but group several such technologies together for each industry. Thus, effects of innovation on specific technologies may be masked by stagnant trends in other technologies. Research focusing on specific technologies finds stronger effects. For instance, 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. Popp (2006b) finds significant increases in patents pertaining to sulfur dioxide and nitrogen oxides 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. 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 over time, they decompose changes in energy efficiency into changes due to price-based substitution and changes due to innovation. Their estimates show how the product characteristic transformation surface changes over time. Using these estimates, they simulate changes in energy efficiency for each product both with and without the historical changes in energy price and efficiency standards. Newell *et al*. find that technological change in air conditioners was biased against energy efficiency in the 1960s (when real energy prices were falling), but that this bias was reversed after the two energy shocks of the 1970s. Suggesting the role that policy-induced technological change may play as climate policy moves forward, they find that energy efficiency in 1993 would have been about one-quarter to one-half lower in air conditioners and gas water heaters if energy prices had stayed at their 1973 levels, rather than following their historical path.

While these earlier works demonstrate links between energy prices, policy, and innovation, they do not provide elasticities between prices and R&D. One paper that does is Popp (2002). Similar to Lanjouw and Mody, Popp 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.[4] Popp finds a long-run elasticity of energy patenting with respect to energy prices of 0.354.

Both studies also find that the innovative response happens quickly. Newell *et al*. find that most of the response to energy price changes came in less than five years of those changes. Popp (2002) finds that the mean lag response time between energy prices and patenting activity occurs in 3.71 years, and the median lag in 4.86 years. Thus, similar to Newell *et al*., over one-half of the full effect of an energy price increase on patenting will have been experienced after just five years. When looking at the innovative response to environmental regulation, rather than energy prices, the response time is even faster. Popp (2006b) finds an almost immediate innovative response to the passage of clean air regulations in the US, Japan, and Germany. Similarly, Johnstone *et al*. (2009) find that patenting activity for renewable energy technologies,

[4] For example, for patents on using waste products as energy, the price utilities pay to purchase waste products for fuel is included in the regression. This figure captures the increased supply of waste that became available as fuel owing to concerns about declining landfill space during the 1980's.

measured by applications for renewable energy patents submitted to the European Patent Office (EPO), has increased dramatically in recent years, as both national policies and international efforts to combat climate change begin to provide incentives for innovation. Figure 1 illustrates these trends for five technologies: wind, solar, geothermal, ocean power, and electricity from biomass and waste. With the exception of biomass and waste, each technology experiences an increase in innovation after signing of the Kyoto Protocol in December 1997.

[INSERT FIGURE 1 ABOUT HERE]

Finally, it is important to consider where the resources for policy-induced R&D come from. This question of crowding out is raised in two recent simulations of climate policy. Using the ENTICE model, Popp (2004) begins with a base case that assumes one-half of new energy R&D crowds out other R&D. In this case, induced innovation increases welfare by 9%. Assuming no crowding out increases the welfare gains from induced innovation to as much as 45%, while 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.

Given the range of possible outcomes depending on assumptions about crowding out, I turn to empirical evidence on the effects of energy R&D on non-energy R&D. Popp and Newell (2009) use patent and R&D data to examine both the private and social opportunity costs of climate R&D. Looking first at R&D spending across industries, they find that funds for energy R&D do not come from other sectors, but may come from a redistribution of research funds in sectors that are likely to perform energy R&D. Given this, they link firm-level patent and financial data to take a detailed look at climate R&D in two sectors – alternative energy and automotive manufacturing – asking whether an increase in alternative energy patents leads to a decrease in other types of patenting activity. They find evidence of crowding out for alternative energy firms, but no evidence of crowding out for automotive firms. Interestingly, the patents most likely to be crowded out by alternative energy research are innovations enhancing the productivity of fossil fuels, such as energy refining and exploration. This is consistent with the notion that any apparent crowding out reacts to market incentives – as opportunities for alternative energy research become more profitable, research opportunities for traditional fossil fuels appear less appealing to firms. This provides support for Gerlagh's result that crowding out is less damaging to the economy if it is carbon-energy enhancing technologies that are crowded out.

B. Innovation and the Choice of Policy Instrument

These empirical studies on induced innovation provide some insight as to the pace of environmental innovation. Also important, however, is the nature of policies used to stimulate innovation. Policymakers have a range of policy instruments available to regulate environmental quality. Command-and-control regulations direct a specific level of performance. For instance, performance standard sets a uniform control target for firms (such as pounds of sulfur dioxide emissions per million BTUs of fuel burned), but do not dictate how this target is met. Technology-based standards specify the method, and sometimes the actual equipment, that firms must use to comply with a particular regulation, such as requiring that a percentage of electricity be generated using renewable sources. Market-based policies establish a price for emissions, either directly through the use of fees, such as a carbon tax, or indirectly through the use of permits that can be bought and sold among firms, such as in the U.S. SO_2 market or the European Union's Emission Trading Scheme for carbon.

In general, market-based policies are thought to provide greater incentives for innovation, as they provide rewards for continuous improvement in environmental quality (e.g. Magat 1978, 1979; Milliman and Prince 1989). In contrast, command-and-control policies penalize polluters who do not meet the standard, but do not reward those who do better than mandated. More recent works suggest that the effects are more nuanced. Ulph (1998) considers not only the effect of policy and innovation on the polluting activity of firms, but also on the product market. Comparing the effects of pollution taxes and command-and-control standards, he finds that increases in the stringency of the standard or tax had ambiguous effects on the level of R&D. 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.

Similarly, Fischer *et al*. (2003) find that an unambiguous ranking of policy instruments was not possible. 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. As a result, the ranking of policy instruments depends 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.

Finally, a recent paper by Bauman, Lee, and Seeley (2008) raises the possibility that command and control policies may induce *more* innovation under certain scenarios. 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.

Given the ambiguous predictions of these models, empirical evidence on the effects of various market instruments on innovation is important. Popp (2003) studies U.S. innovations for SO_2 control before and after the 1990 Clean Air Act (CAA) instituted permit trading. Before this Act, new plants were required to install a flue gas desulfurization (FGD) unit capable of removing 90 percent of SO_2. As a result, the innovations that occurred before the 1990 CAA focused on reducing the cost of FGD units, rather than on improving their environmental performance. After passage of the 1990 CAA, the nature of innovation changed, with a greater focus on improving the ability of FGD units to remove SO_2 from a plant's emissions. 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.

Moreover, even among market-based policies, differences between policies matter. Johnstone *et al*. (2009) examine the effect of different policy instruments on renewable energy innovation in 25 OECD countries. They compare price-based policies such as tax credits and feed-in tariffs[5] to quantity-based policies such as renewable energy mandates, and find important differences across technologies. Quantity-based policies, such as renewable energy certificates, 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 policy makers who wish to encourage long-run innovation for technologies that have yet to near market competitiveness. Economists generally recommend using broad-based environmental policies, such as emission fees, and letting the market "pick winners." This leads to lower compliance costs in the short-run, as firms choose the most effective short-term strategy. However, this research suggests complications for the long-run. Because firms will focus on those technologies closest to market, market-based

[5] Feed-in tariffs, used in various European countries, guarantee renewable energy producers a minimum price for the electricity they produce.

policy incentives do not provide as much incentive for research on longer-term needs. This suggests a trade-off: directed policies such as investment tax credits or technology mandates more effectively encourage the deployment of more expensive emerging technologies that are not yet cost-effective. However, this raises the costs of compliance, as firms are forced to use technologies that are not cost-effective. One possible solution here is to use broad, market-based policies to ensure short-run compliance at low costs, and use support for the research and development process to support research on emerging technologies. Thus, the focus is on continued improvement for emerging technologies, rather than on deployment of them. I turn next to a discussion of the issues surrounding public R&D financing.

C. Government R&D

Until now, we have focused primarily on the incentives faced, and activities conducted, by private firms. However, as noted earlier, even when environmental regulations that encourage eco-innovation are in place, private firms will focus research efforts on technologies that are closest to market. One of the particular problems faced with many climate-friendly innovations is the long-time frame from the initial invention to successful market deployment. Consider, for instance, the case of solar energy. Despite research efforts that began during the energy crises of the 1970s, solar is still only cost competitive in niche markets, such as remote off-grid locations.

This leaves a potential role for government-sponsored R&D to fill in the gaps, particularly in the case of climate change, where a diversified energy portfolio will be necessary to meet currently proposed emission reduction targets. Public R&D spending plays a particularly important role in the energy sector. In 2004, the last year for which private energy R&D data are available, U.S. industry spent $2.4 billion on energy R&D, while the U.S. government spent $2.9 billion (National Science Foundation 2008, IEA 2009b). In 2008, the U.S. government spent $4.3 billion on energy R&D. Of this, 23% went to nuclear energy R&D, with about 10% each going to renewable energy, fossil fuels, and energy efficiency. Total global government energy R&D were estimated to be $12.7 billion. The share of support going to nuclear power is larger globally, at 39%. Twelve percent of this $12.7 billion goes to renewable energy. Since the signing of the Kyoto Protocol in December 1997, the share of energy R&D devoted to renewables has grown. Beginning in 1998, public renewable energy R&D spending has nearly doubled, while overall public energy spending has increased by just 45% (IEA 2009b).

This government investment plays several roles. First, note that government R&D 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 is particularly important for basic R&D, 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. These results suggest that, if a goal of government policy is to avoid duplicating and potentially crowding out private research efforts, then government R&D support should focus on basic research or on applied research whose benefits are difficult to capture through market activity. For instance, improved electricity transmission systems benefit all technologies, and will typically not reap great rewards for the innovator. Applied technologies whose costs are still high, such as solar photovoltaics, will also see less private investment, as firms focus on projects with greater short-term payoffs. In cases such as these, public R&D efforts will be less likely to crowd out private research efforts.

The uncertain nature of long-term research also makes government R&D valuable. In a situation where failure is more likely than success, but the successes will have great social value, government can bear the costs of a diversified R&D portfolio more easily than any one private firm. Consider, for example, the U.S. National Research Council's review of energy efficiency and fossil energy research at DOE over the last two decades (National Research Council 2001). Using both estimates of overall return and case studies, they concluded 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. These uncertain returns to research argue for diversified government R&D portfolios, rather than trying to pick winning technologies at early stages of development.

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, 2008). 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.[6] 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 of 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 U.S. Department of Energy (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.[7] They find that both patenting and the number of citations received per patent increased at DOE laboratories since the policy shifts of the 1980s. 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.

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.

Finally, an important question for policy makers is how much government R&D money to spend on energy. Here, however, economics provides less of an answer. Cost-benefit analysis

[6] Examples include the Stevenson-Wylder Technology Innovation Act of 1980, the Bayh-Dole Act of 1980, and the Federal Technology Transfer Act of 1986.
[7] The two laboratories are Lawrence Livermore National Laboratory and Idaho National Engineering and Environmental Laboratory.

provides a useful tool for post-hoc evaluation of R&D spending, but estimating the potential benefits from new energy spending is more difficult. Engineers are better suited to determine which projects are most deserving from a technical standpoint. Given the need for a diversified energy portfolio to address climate change, it is hard to imagine that there would not be enough deserving technologies for the research funding available. Rather, economic analysis suggests that the constraints for funding are likely to come from other sources, such as what is the pool of scientist and engineering personnel currently available to work on energy projects, and how quickly can we grow this pool. That is, the limits to how much we can spend come not from the number of deserving projects, but rather limits of the existing research infrastructure.

As an example, consider the experience of the U.S. National Institutes of Health (NIH), which supports biomedical research in the U.S. The NIH budget has traditionally grown at a slow, steady pace. However, between 1998-2003, annual NIH spending nearly doubled, from $14 billion to $27 billion. Adjusted for inflation, this represents a 76% in just five years, and was nearly twice as high as the increase for the entire decade before. This rapid increase resulted in high adjustment costs. New post-doctorate researchers needed to be brought in to support research projects. Managing a larger budget entails administrative costs for NIH. Moreover, after this rapid doubling, research funds were cut, so that real NIH spending was 6.6% lower in 2007 than in 2004. This created a career crisis for the same post-doctorate researchers supported by the earlier doubling of support, as there was more competition for funds to start their own research projects. Moreover, scientists spent more time writing grant proposals. Because the probability of funding for any one proposal falls as the NIH budget falls, researchers submitted multiple proposals in the hope that one would succeed (Freeman and van Reenen, 2009). This

NIH experience suggests the value of slow and steady growth in energy R&D budgets, which allows time for the development of young researchers in the field.

III. Diffusion of Climate-Friendly Technologies

Technological advances are of little use unless society ultimately makes use of the innovation through technology diffusion, that is, the process by which a new technology penetrates the relevant market. Often times, a technology that appears to surpass competing technologies in performance and cost will not immediately be chosen over existing technologies. A key question is whether this slow diffusion is a result of rational actors responding to varying incentives or due to market inefficiencies. In this section I briefly review the literature on diffusion of environmental technologies, focusing on two key questions. First is the time lag between invention and adoption, focusing on the adoption of technologies within a single market. Second is the flow of knowledge across regions.

A. Diffusion Within Countries

The diffusion of a new technology is a gradual, dynamic process. New technologies are not adopted en masse. Rather, adoption usually begins with a few early adopters, followed by a more rapid period of adoption, with the rate of adoption leveling off once most potential users have adopted the technology. This process generates the well-known S-shaped diffusion curve: the rate of adoption rises slowly at first, speeds up, and then levels off as market saturation approaches. Early attempts to explain this process focused on the spread of information (epidemic models, such as Griliches 1957) and differences among firms (probit models, such as David 1997). More recently, researchers combine these explanations while adding potential strategic decisions of firms. These papers find that firm-specific differences explain most variation in adoption rates, suggesting that gradual diffusion is a rational process in response to varying incentives faced by individual actors.

Environmental technologies can be different, however. Incentives to adopt end-of-pipe technologies that only serve to reduce emissions must come from environmental regulation. Therefore, it is not surprising that studies addressing adoption of environmental technologies find that regulations dominate all other firm-specific factors. Examples include Kerr and Newell (2003) on the removal of lead from gasoline in the United States, Kemp (1998) on the effect of effluent charges on biological treatment of wastewater, Snyder *et al*. (2003) on the diffusion of membrane-cell technology in the chlorine manufacturing industry, and Popp (2009) on NO_X pollution control technologies at power-plants. Pertaining to climate policy, these studies suggest that clean energy technologies will not diffuse without the support of policy. While the use of renewable energy sources provides benefits such as reduced carbon emissions and, in some cases, improved energy security, in the absence of policy these benefits are largely external to the individual power producer. Without environmental policy addressing carbon emissions from fossil-fuels, firms do not have incentive to adopt more costly technologies that reduce emissions but provide no additional cost savings to the firm.

In contrast, energy efficiency and fuel-saving technologies will diffuse even without the aid of policy, as they do provide cost-saving benefits to the user. Rose and Joskow (1990), for example, find that the adoption of fuel-saving technology by U.S. electric utilities is positively correlated with fuel prices. Adoption of these technologies is generally more gradual, following typical S-shaped diffusion patterns. However, to the extent that fuel prices do not capture the external costs of energy use, such as carbon emissions, energy prices alone will not encourage a socially optimal level of adoption for energy efficiency technologies.

An important puzzle in the literature on energy technology diffusion is the notion that seemingly cost-effective energy-efficient technologies diffuse slowly, suggesting what has become to be known as an "energy efficiency paradox." To the extent that diffusion is limited by other market failures, policy measures that simply increase the economic incentive to adopt environmentally-friendly technologies will be insufficient. In addition, policies focused directly on the correction of adoption market failures can be justified.

Several researchers have examined this energy efficiency paradox, offering explanations including consumers using high discount rates, credit-constrained consumers caring more about up-front costs than lifetime cost savings, agency problems (such as in landlord/tenant relationships), and uncertainty over future costs. Jaffe and Stavins (1994) find that higher energy prices lead to greater use of insulation in new home construction, but that the costs of installation are a more important consideration. Anderson and Newell (2004) examine the role of information by asking how firms respond to energy audits offered through the US Department of Energy's Industrial Assessment Centers (IAC). This program has offered energy assessments at no cost to small and medium-sized manufacturers since 1976. Anderson and Newell note that firms adopted only 53 percent of recommended projects, even though the average payback time for these projects was just 1.29 years. When adopting new energy-saving technologies, plants are 40 percent more responsive to initial costs than annual energy savings. Anderson and Newell 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.

There are several possible explanations for the finding that installation costs have a greater effect on adoption than energy prices. One is that current prices may be an imperfect proxy for expectations of future prices, so that consumers are uncertain whether high prices at the time of adoption to persist. Another possibility is that consumers are credit constrained, thus making access to credit an important part of any diffusion policy. As no one consensus explanation has emerged in the literature, better understanding the energy paradox is a fruitful topic for future research.

B. Diffusion Across Countries

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 2002, global R&D expenditures were at least $813 billion. 77 percent of this R&D was done in the OECD, with 45 performed by the United States and Japan alone (National Science Board, 2008). Focusing specifically on climate-friendly technologies, Dechezleprêtre *et al*. (2009) examine patents pertaining renewable energy technologies, carbon capture and storage, and energy efficiency technologies for buildings, lighting, and cement manufacture. Their data cover the years 1978-2003, and include patents from 76 countries. The US, Japan, and Germany account for two-thirds of the innovations in their sample.

Dechezleprêtre *et al*. find some evidence of innovation in emerging economies. As a whole, emerging economies accounted for 16.3% of climate-friendly innovations in 2003. China, South Korea, Russia, and Brazil are all among the world's top 10 inventors, ranked by the average percentage of innovations from 1998-2003 in each technology. Interestingly, the technologies most prevalent in these countries are cement manufacture, geothermal, and biomass technologies. Of these technologies, cement manufacture and geothermal innovations take place mostly on a local scale, with less than 15% of these patents appearing in multiple countries. This is consistent with the nature of these industries, which typically serve local markets and, in the case of geothermal, may face different technological needs depending upon local conditions.

Given the concentration of R&D efforts in high-income countries, technology transfer will be particularly important for addressing climate change. 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. For instance, in 1990, China and India accounted for 13 percent of world carbon dioxide (CO_2) emissions. By 2006, that figure had risen to 25 percent, and it is projected to rise to 34 percent by 2030 (Energy Information Administration, 2009). Overall, the U.S. Energy Information Administration projects that CO_2 emissions from non-OECD countries will exceed emissions from OECD countries by 77 percent in the year 2030 (Energy Information Administration, 2009). While international technology transfer has received much attention in the broader economic literature, few applications focus specifically on environmental technologies.[8]

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

[8] For a general review of the literature on international technology transfer, see Keller (2004).

technologies (Esty 2001, Copeland and Taylor 2003). Attempts to identify this technique effect can be seen as examples of technology transfer.

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 sulfur dioxide and nitrogen oxides at coal-fired power plants in 39 countries. Their sample includes both developed and developing countries. While the adoption of pollution control technologies within a country responds quickly to environmental regulation, they find that adoption of the regulations themselves follows the typical S-shaped pattern noted in studies of technology diffusion. In their work, 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.

Similarly, Hilton (2001) finds that late adopters of regulation can learn from early adopters. Using data on 48 nations, he looks at the time it took each country to eliminate lead from fuel. This time is measured from the time that each country first began phasing out lead in fuel to the time in which the country achieved lead levels at or below 0.5 grams of lead per gallon. Countries that began the process after 1979 completed the lead phase-out five years faster, on average, than those beginning before 1979. Moreover, among those countries that did not completely phase out lead, countries that begin the phase-out process earlier achieve greater reductions. Hilton concludes with evidence that late adopters are able to move more quickly because they benefit from lessons learnt by early adopters.

Another important finding is that adaptive R&D will often be necessary to suit technologies to local markets. Popp (2006b) finds innovation responds to policy 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, late adopters often undertake adaptive R&D to fit the technology to local markets. As evidence, Popp finds that these later patents are more likely to cite earlier foreign rather than domestic inventions. Lanjouw and Mody (1996) find similar evidence that the environmentally-friendly innovations that do occur in developing countries are smaller inventive steps, typically done to modify existing technologies to local conditions. Foreign knowledge serves as blueprints for further improvements, rather than as a direct source of technology. When policymakers consider the potential for technological change to reduce environmental impacts in developing countries, they must make allowances for adaptive R&D to fit technologies to local conditions, or else be prepared for less than desired results when the transferred technology is not a perfect fit for the local market.

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. As an example, Fisher-Vanden *et al*. (2006) use a panel of 22,000 Chinese large and medium enterprises to study improvements in energy efficiency. Between 1997 and 1999, total energy use fell by 17%. 54% of this decline can be explained by price changes. Technological change, measured by firm-level R&D, accounts for 17% of this change, and changes in ownership account for another 12%.

These studies have several implications for climate policy. Most importantly, they emphasize the potential value of environmental regulations to promote transfer of climate-friendly technologies to developing countries. Such technologies have external benefits. Without policies to internalize these benefits, demand for climate-friendly technology transfer will be low. These studies also emphasize, however, that the current lack of emission reduction commitments from developing countries is no different than the approach taken by developing countries with other pollutants. Developed countries have traditionally acted first, after which the resulting technological innovations made it easier for developing countries to adopt regulations at a later date. There is no reason to expect climate policy to be any different.

Instead, current policy incentives for technology transfer are linked to emission reduction commitments among developed countries, through the Clean Development Mechanism (CDM). CDM allows polluters in industrialized countries with emission constraints to receive credit for financing projects that reduce emissions in developing countries. 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.

Related to technology transfer is a concern often raised by critics of CDM – the problem of "low-hanging fruit."[9] The low-hanging fruit critique follows from the economic principle of diminishing returns. Proponents of the "low-hanging fruit" theory worry that if developed

[9] See, for example, references in footnote 1 of Narain and van't Veld (2008).

countries receive credit now for performing the cheapest emissions reductions options in developing countries, these options will be unavailable for later use by developing countries. As such, these countries will be worse off when later attempting to reduce emissions on their own, and will be less willing to agree to binding emissions reductions at a later date.[10] In essence, such projects move a country to a higher point on their marginal abatement cost curve, as shown by the first marginal abatement cost curve (MAC_0) in Figure 2.

[INSERT FIGURE 2 ABOUT HERE]

However, technology transfer can counteract the impact of diminishing returns. While it is true that the costs of additional emissions reductions *at a given time* will increase as more projects are completed, the arrival of new technologies provide new opportunities for emissions reductions, so that the future costs of reducing emissions can be lower. As these technologies become available in developing countries, the costs of emissions reductions will fall. This shift will partially (MAC_1 in Figure 2) or completely (MAC_2 in Figure 2) offset the low-hanging fruit problem. By lowering future marginal abatement costs, such technology transfers also increase the possibility that developing countries will agree to future emission constraints.

For CDM to help contribute to these falling costs, it is important that projects (a) include a component of technology transfer, and (b) that this transfer include spillovers to the recipient country, rather than just be a transfer of equipment, so that the benefits can potentially reduce marginal abatement costs for future related projects. Dechezleprêtre *et al*. (2008) provide evidence of the potential of CDM to provide such benefits, asking how many CDM projects

[10] Note that developing countries can be compensated for future cost increases, so that CDM projects become mutually beneficial. Indeed, since such projects require the voluntary agreement of all parties, one would expect such compensation to take place (Narain and van't Veld, 2008; Rose *et al*. 1999). However, even if compensation is received, so that the recipient country isn't made worse off, the developing country recipient may still delay undertaking their own emissions reductions and participating in future treaties if the easiest options for lowering emissions have already been exhausted.

transfer "hardware", such as equipment or machinery, as opposed to "software", which they consider to be knowledge, skills, or know-how. That is, 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*. look at 644 CDM projects registered by the Executive Board of the UNFCCC. They find that 279 projects, or 43%, involve technology transfer.[11] 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. Emphasizing the importance of adaptive R&D, Dechezleprêtre *et al*. find that the technological capacity of a country enhances technology transfer, by making the recipient better able to absorb new knowledge.

IV. Conclusions

Technological advances in the way that energy is generated and delivered will play an important role in efforts to stabilize greenhouse gas emissions. As this review demonstrates, well-designed climate policy can help shape the development of these technologies. These policies must address market failures pertaining both to the environmental externalities of greenhouse gas emissions and knowledge spillovers. This will require a menu of policy options. Simply providing R&D support is not sufficient, as without environmental policy, there is little

[11] However, these projects are among the most significant CDM projects, as they account for 84% of the expected emissions reductions from registered CDM projects.

incentive to adopt clean technologies. At the same time, while broad-based environmental policies such as a carbon tax or cap-and-trade scheme provide an overall framework for emission reductions, this review suggests that other market failures remain important. Private firms will focus on technologies most likely to generate short-term profits. For instance, renewable portfolio standards are likely to promote wind energy at the expense of solar, as wind is currently the most cost-effective renewable option. Similarly, because improving electricity transmission efficiency systems benefits all technologies, private innovators are likely able to capture only a small portion of the social benefits of such innovation. Long-term benefits, spillovers, and uncertain R&D returns all suggest a potential role for public R&D support, either through direct financing or targeted policy incentives.

Finally, once technologies are available, government intervention can also increase the rate of diffusion relative to that in the private market. As the research in Section III shows, even energy innovations with relatively short payback periods diffuse slowly. This suggests that simply getting the prices right through policies such as a carbon tax will not be sufficient. Moreover, while most clean technology research occurs in high-income countries, carbon emissions are growing more rapidly in the developing world. As such, future policy efforts will also need to pay more attention to the incentives provided for technology transfer across borders.

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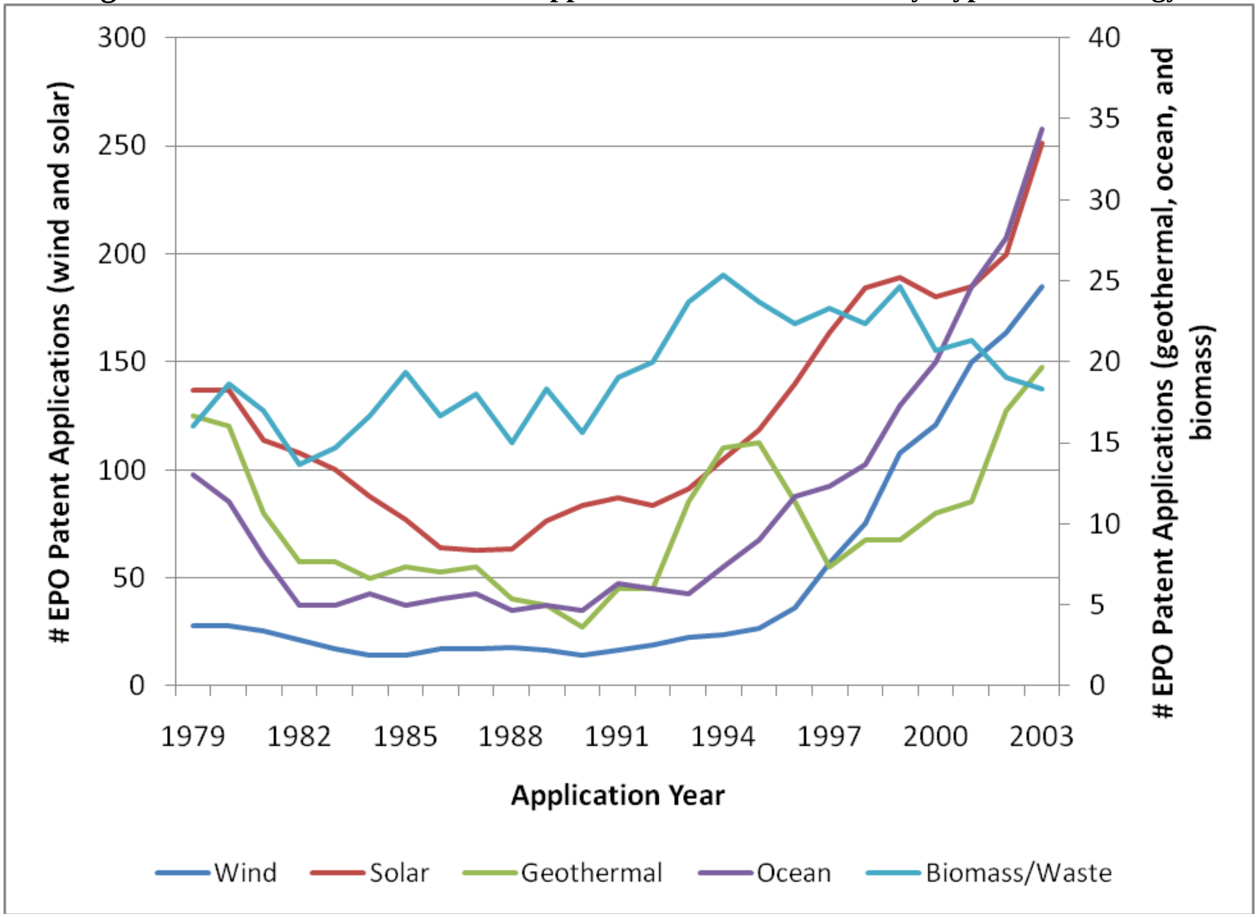
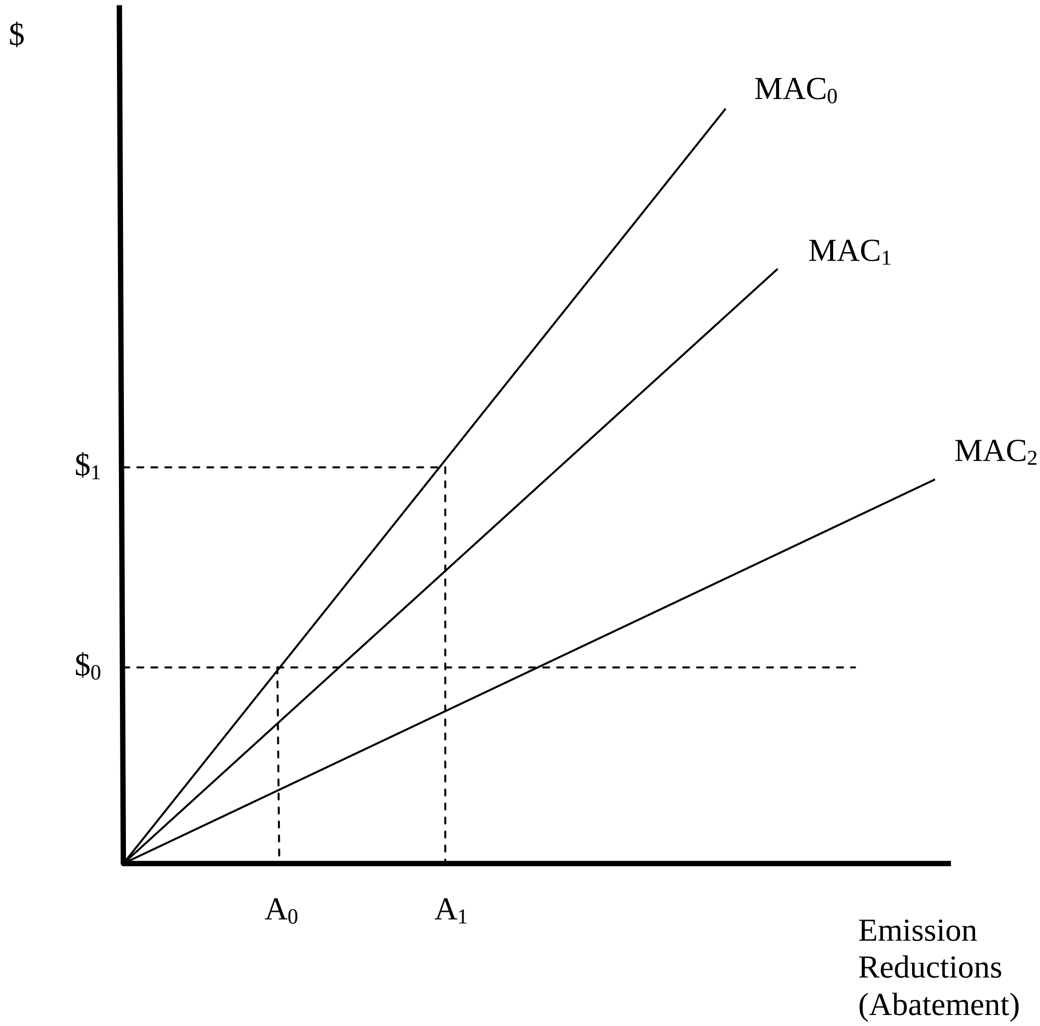
Figure 1 – Number of EPO Patent Applications for Renewables by Type of Technology



Source: Based on data from Johnstone *et al*. (2009)

The figure shows the number of European Patent Office (EPO) applications for patents pertaining to various renewable energy technologies, sorted by the year of application. Patent counts for wind and solar technologies are on the left vertical axis, with counts for the remaining technologies on the right vertical axis.

Figure 2 – Low-Hanging Fruit and Knowledge Spillovers



In Figure 2, the marginal abatement cost curve MAC_0 represents the costs associated with current technologies in developing countries. Initial abatement levels are A_0, with marginal costs $\$_0$. A sponsored project increases abatement to A_1, raising the marginal abatement cost to $\$_1$. As a result, future abatement efforts by developing countries will cost more – the "low-hanging fruit" effect. This cost increase can be offset if technology transfer results in spillovers that lower the marginal abatement cost. Here, MAC_1 represents a shift which partially offsets the "low-hanging fruit" effect, while MAC_2 represents a shift where new technologies completely offset the "low-hanging fruit" effect, so that further abatement is possible at a marginal abatement cost less than $\$_0$.