DISCUSSION PAPER

October 2004 ■ RFF DP 04-38

A Tale of Two Market Failures

Technology and Environmental Policy

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A TALE OF TWO MARKET FAILURES:

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Key words: technology, research and development, environment, externality, policy
JEL codes: O38; Q28; H23

A TALE OF TWO MARKET FAILURES: TECHNOLOGY AND ENVIRONMENTAL POLICY

Abstract

Market failures associated with environmental pollution interact with market failures associated with the innovation and diffusion of new technologies. These combined market failures provide a strong rationale for a portfolio of public policies that foster emissions reduction as well as the development and adoption of environmentally beneficial technology. Both theory and empirical evidence suggest that the rate and direction of technological advance is influenced by market and regulatory incentives, and can be cost-effectively harnessed through the use of economic-incentive based policy. In the presence of weak or nonexistent environmental policies, investments in the development and diffusion of new environmentally beneficial technologies are very likely to be less than would be socially desirable. Positive knowledge and adoption spillovers and information problems can further weaken innovation incentives. While environmental technology policy is fraught with difficulties, a long-term view suggests a strategy of experimenting with policy approaches and systematically evaluating their success.

1. INTRODUCTION

The influence of technological development on energy and environmental systems permeates discussions of energy and environmental policy. New technology has been credited with solving environmental problems by mitigating the effects of pollutants, and has been maligned as a source of increased pollution. For modeling long-term environmental problems such as global climate changes, the effects of technological change compounded over long time horizons will likely be large. Thus, the single largest source of difference among modelers' predictions of the cost of climate policy is often differences in assumptions about the future rate and direction of technological change (Clark and Weyant 2002; Carraro, van der Zwaan, and Gerlagh 2003; Energy Modeling Forum 1996).

But technological change does not exist in a vacuum. Environmental policy interventions, such as carbon cap and trade systems and carbon taxes, generate incentives that will affect which new technologies will be developed and how rapidly and deeply they will diffuse. The induced effects of environmental policy on technology can therefore have substantial implications for the normative analysis of policy. While researchers dispute the extent to which environmental policy-induced technological change reduces the social cost of environmental compliance, there is little dispute among economists that flexible, incentive-oriented policy approaches are more likely to foster low-cost compliance paths than prescriptive regulatory approaches.[1]

The realization that the process of technological change is itself characterized by market failures complicates policy analysis, and increases the likelihood that a portfolio of policies, rather than policy directed at emissions reduction alone, will offer a more complete response to environmental problems. The seeming intractability of some energy and environmental problems, such as global climate change, combined with considerable uncertainties and the long time frame over which their ultimate consequences will play out, may make the development and deployment of new technologies attractive as a major policy response. That is, policies whose purpose is generating technological change are likely to be important parts of the policy portfolio for addressing certain environmental problems, in addition to the rules and regulations we normally think of as environmental policies. Technology policy can be a costly approach, however, if it is used as a substitute for, rather than complement, to environmental policy. Environmental policy targeted directly at emissions (for example through an emissions tax or cap-and-trade system) will still typically provide the most important single element of a cost-effective environmental policy strategy.

This paper provides background for consideration of these issues. We begin by discussing the key analytic issues that permeate policy discussions occurring at the nexus

[1] For a detailed survey of the influence of environmental policies on innovation and diffusion see Jaffe, Newell and Stavins (2003).

between technology and environmental policy. Section 3 discusses the possibilities for policies designed to operate directly on technology to improve our ability to cope with environmental problems. We offer concluding observations in Section 4.

2. KEY ANALYTICAL ISSUES

2.1. Fundamentals of Environmental Economics

Economic analysis of environmental policy is based on the idea that 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. A factory that pollutes the air, water, or land imposes a cost on 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 pollution.

Environmental policies attempt to equalize this imbalance by raising the incentive for a firm to minimize these externalities. Policy choices accomplish this in one of two general ways—either by internalizing the environmental costs so polluters make their own decisions regarding their consumption of environmental inputs, or by imposing a limit on the level of environmental pollution.

The cost of environmental policies could be in the form of decreased output of desired products (for example, a scrubber on an electric power plant reduces its electricity production from a given quantity of fuel), increased use of other variable inputs (for example, eliminating certain gases from the waste stream in a smokestack may require more fuel to be burned), purchase of specialized pollution control equipment (for example, catalytic converters on automobiles), or substitution of inferior or more expensive products or production methods to avoid pollution-causing products or methods (for example, less effective pesticides used when DDT was banned).

In the short run, setting an efficient environmental policy requires a comparison of the marginal cost of reducing pollution with the marginal benefit of a cleaner environment. All else being equal, emissions of pollutants that are very harmful should be greatly restricted, because the pollutants otherwise produce large marginal costs to society. But, all else being equal, emissions of pollutants that are very costly to eliminate should be tolerated, because the marginal cost of reducing them is high.

When technology enters the equation, the terms of the tradeoff between the marginal cost of pollution control and its marginal social benefit is altered. In particular, technology innovations—such as new pollution control equipment, cleaner production methods, or new substitutes for environmentally harmful products—typically reduce the marginal cost of achieving a given unit of pollution reduction. This means that a specified level of environmental cleanup can be achieved at lower total cost to society, and it also means that a lower total level of pollution can be attained more efficiently than would be expected if the cost of cleanup were higher. Thus, in this simple static picture, technology improvements can be good for the environment and good for the firm that must meet environmental mandates.

2.2. Fundamentals of the Economics of Technology

In this simple analytic scenario, the technology innovation results in greater overall social benefit because the cost of reducing pollution has decreased and environmental health has improved. If this were the end of this static story, than the only effect would be to convert the analysis of environmental policy from a static cost/benefit tradeoff to a dynamic one. Policies to reduce pollution have two effects, however—they reduce pollution today, and they also typically change the incentives that firms face with regard to investing resources in developing new technology for the future. In particular, when firms face an incentive to reduce their emissions, this simultaneously creates an incentive for them to find ways to reduce pollution at lower cost. The fact that the development of such technology will, over time, change the pollution benefit/cost calculus means that choosing efficient environmental policy requires an analysis of this dynamic interaction. The simple static model does not take into account the fact that new technology is itself not free.

To reach the point where pollution is being reduced or some other benefit is realized, two things must happen, both of which require the investment of resources. The first step—innovation—involves scientific or engineering research to establish a new technical idea and to develop that idea into a commercial product or process.[2] The second step—adoption (or diffusion)—is the process by which a new product or process gradually replaces older technology throughout many firms and applications. Adoption is also costly, because firms must learn about new technology, purchase new equipment, and adapt it to their particular circumstances. If technological change is not free, can we expect Adam Smith's "invisible hand" to choose the right level of investment in both innovation and diffusion of new technology?

[2] Schumpeter (1942) identified three steps in technological change: invention, innovation and diffusion. In the Schumpeterian trichotomy, invention is the first technical development, and innovation the first commercial introduction. For simplicity, we have collapsed these two steps into one and labeled it innovation.

The problem compounds, because independent of the externality associated with pollution, innovation and diffusion are both characterized by externalities as well as other market failures.

Knowledge Externalities. In the case of pollution as an externality, the polluter reaps the benefits derived from polluting while imposing the pollution costs on others. The polluter therefore lacks an incentive to reduce those costs. However, in the case of technology, the problem is reversed. 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. Pollution creates a negative externality, and so the invisible hand allows too much of it. Technology creates positive externalities, and so the invisible hand produces too little of it.[3]

The positive externality of innovation comes from the public-good nature of new knowledge—innovating firms cannot keep other firms from also benefiting from their new knowledge and therefore cannot capture for themselves all the benefits of the innovation. In addition, the process of competition will typically drive a firm to sell a new device at a price that captures only a portion of its full value, which means that consumers also reap some of the benefits from new technology. While patents and other institutions are employed to protect firms' investments in innovation, such protection is inherently imperfect. A successful innovator will capture some rewards, but those rewards will always be only a fraction—and sometimes a

[3] There is, however, an offsetting negative externality because R&D is a fixed cost that must, in equilibrium, be financed by the stream of quasi-rents it produces. The entry of another R&D competitor, or an increase in the R&D investment level of a competitor, reduces the expected quasi-rents earned by other R&D firms. This "rent-stealing" effect (Mankiw and Whinston 1986) could, as a theoretical matter, lead to over-investment in R&D. The empirical evidence suggests, however, that positive externalities associated with knowledge spillovers dominate the rent-stealing effect, leading to social rates of return to R&D substantially in excess of the private rates of return (Griliches 1992).

very small fraction—of the overall benefits to society of the innovation. Hence innovation creates positive externalities in the form of "knowledge spillovers" for other firms, and spillovers of value or consumer surplus for the users of the new technology.

Adoption Externalities. The environmental and knowledge externalities discussed above have long been at the center of economic debates about technology policy. More recently, we have come to understand some additional market failures that may operate in the adoption and diffusion of new technology. 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."

Dynamic increasing returns can be generated by learning-by-using, learning-by-doing, or network externalities.[4] While the image of the world beating a path to the door of the successful innovator may seem compelling, the diffusion of a new technology is typically gradual. It takes time for potential users to learn of the new technology, try it, adapt it to their circumstances, and become convinced of its superiority. An important mechanism in this learning process is the observation of the adoption of the new technology by others. Hence the adopter of a new technology creates a positive externality for others in the form of the generation of information about the existence, characteristics, and success of the new technology. This phenomenon is often called "learning-by-using."

The supply-side counterpart, "learning-by-doing," describes how production costs tend to fall as manufacturers gain production experience. If this learning spills over to benefit other

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[4] See Jaffe, Newell, and Stavins (2003, pp. 491-494) for a review of the literature on dynamic increasing returns.

manufacturers without compensation it can represent an additional adoption externality. Finally, network externalities exist if a product becomes technologically more valuable to an individual user as other users adopt a compatible product (as with telephone and computer networks, for example). 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.

Incomplete Information. Both innovation and diffusion of new technology are characterized by additional market failures related to incomplete information. While all investment is characterized by uncertainty, the uncertainty associated with the returns to investment in innovation is often particularly large. Further, information about the prospects for success of given technology research investments is asymmetric, in the sense that the developer of the technology is in a better position to assess its potential than outsiders. A firm attempting to raise investment capital to fund the development of new technology will therefore find such investors skeptical about promised returns, and likely to demand a premium for investment that carries such risks. This likely imperfection in the market for capital for funding technology development exacerbates the "spillover" problem and therefore contributes to our expectation that the invisible hand encourages too little research and development.

In the context of environmental problems such as climate change, the huge uncertainties surrounding the future impacts of climate change, the magnitude of the policy response, and thus the likely returns to R&D investment, would seem to exacerbate this problem further. In the extreme, for example, it is difficult to see how the technological solutions that would be required to address the possibility of catastrophic effects of climate change would be provided for by the market even if environmental policies sent appropriate signals about expected costs. In this sense, there may be considerable option value to the development of certain environmental technologies that would be difficult to capture solely through emissions policy.

With respect to technology adoption and diffusion, we have already noted that imperfect information can slow the diffusion of new technology. First, information has important “public good” attributes: once created it can be used by many people at little or no additional cost. It may be difficult or impossible for an individual or firm that invests in information creation to prevent others who do not pay for the information from using it. It is well known that such public goods will tend to be underprovided by ordinary market activity. Incomplete information can also foster 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).

Thus the interplay of technology and the environment involves the interaction of two analytically distinct but linked sets of market failures. The consequences of this interaction can be complex. The fact that markets under-invest in new technology strengthens the case for making sure that environmental policy is designed to foster, rather than inhibit innovation. It may mean that the social cost of environmental policy is less than it would otherwise appear, because part of the cost is in the form of investments in innovation that yield positive externalities outside the environmental arena. Whether this is true or not depends on, among other things, whether the increased investment in environmental innovation brought forth by environmental policy comes at the expense of innovation in other areas. If it does, the net effect on the costs of environmental policy will depend on the relative spillovers of environmental innovation compared to innovation that is displaced.[5] In practice, it may be difficult to sort out all of these effects, and very difficult to do so with quantitative reliability.

Thus, technological change is important for environmental policy, and analysis of energy and environmental policy can benefit from the perspective of the economics of technological change. Our general approach is to view technological change relative to the environment as occurring at the nexus of two distinct and important market failures: pollution represents a negative externality, and new technology generates positive externalities. Hence, in the absence of public policy, new technology for pollution reduction is, from an analytical perspective, doubly underprovided by markets. This suggests that the efficiency of environmental policy depends on its consequences for technological change, and also that there is a potential role for policy aimed directly at the stimulation of environmentally beneficial technological change.

3. ENVIRONMENTAL TECHNOLOGY POLICY

Given that the development of environmentally beneficial technology is subject to two interacting market failures, in cases where environmental externalities have not been fully internalized it is likely that the rate of investment in such technology is below the socially optimal level. And it is unlikely that environmental policy alone creates sufficient incentives. Hence the optimal set of public policies likely also includes instruments designed explicitly to foster innovation and possibly technology diffusion, as distinct from environmental policies that stimulate new technology as a side effect of internalizing environmental externalities.

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[5] See, for example, Goulder and Schneider (1999) on the importance of spillover assumptions for the cost of climate mitigation.

Of course, one way to foster environmental technology is to foster technology in general, and allow the market to determine what portion of the stimulated development will be in the environment area. The arguments for generally greater public investment in technology infrastructure are well known and have been the subject of numerous studies. We focus instead on the potential for policies aimed explicitly at the development and diffusion of environmentally benign and/or energy-saving technology.

There is a strong strain in the economic analysis of technology policy of *avoiding* choosing particular technical areas for support, that is “picking winners.” There are, however, several interrelated reasons why technology policy narrowly focused on energy and environment is likely to be socially desirable under certain circumstances. First is the public good nature of the environment itself, which makes environment, in effect, an area of government procurement like defense and space, and hence a suitable area for focused governmental technology efforts.

Another is a second-best argument related to the practical limitations of environmental policy. Most economists, present authors included, would argue that the most efficient single policy for addressing global climate change is an emissions policy that places a price on greenhouse gases (for example, through an emissions tax or cap-and-trade system). However, in the area of global climate change — arguably the most significant long-run environmental threat — the United States and much of the world has largely put off, for the moment, significant environmental policy intervention. Hence there is little environmental policy-induced incentive to develop technologies that reduce greenhouse gas emissions. In this second-best setting, policy to foster greenhouse-gas-reducing technology may be one of the main policy levers available and can be justified on economic grounds so long as it has positive net benefits. Technology policy can be a costly approach, however, if it is used as a substitute for, rather than complement, to environmental policy.[6]

One might reasonably ask, however, why governments who are unwilling to impose costs on the economy to reduce greenhouse gas emissions directly should be more willing to invest resources in improving energy technologies to reduce greenhouse gases? One reason is purely political: policies subsidizing technology do in fact receive considerable political support in most countries (see, for example, section 3.3). An explanation is that the benefits of such policies tend to be focused and the costs dispersed, giving rise to favorable political-economic conditions.

Another possible explanation may be found in the limitations of feasible environmental policies to address the dynamic nature of the problem.[7] If the social costs of climate change are considered modest at the present but are expected to rise considerably in the future, this may warrant current investment in R&D at the same time as it explains tempered interest in current mitigation. In principle, governments could announce a time path for future environmental policies that might induce the appropriate level of R&D investment in anticipation of future emissions policy. But there are many reasons, both practical and theoretical, why such advance policy commitments are unlikely to be forthcoming, and why they may not represent credible commitments if they were announced. This difficulty of setting appropriate dynamic environmental policies may warrant more reliance on technology policy, to which governments can commit now.

[6] See, for example, Fischer and Newell (2004) on the increasing cost of using certain focused technology policies to achieve greenhouse gas reduction goals. Note, however, that they do not address market imperfections in the innovation process, although these seem unlikely to substantially change their results.

[7] We thank an anonymous referee for emphasizing these additional features of the problem.

In the context of environmental problems having important international dimensions, such as global climate change, there can be additional reasons related to international cooperation for considering environmental and technology policies simultaneously. 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 Folmer and van Mouche 1993, Cesar and de Zeeuw 1996, Carraro and Egenhofer 2002, and Kemfert 2004).

3.1. Innovation Policies

Policies that internalize the cost of environmental harm stimulate the creation of environment-friendly technology by increasing the demand for low-cost pollution-reduction methods. Thus, so-called “demand-pull” increases the return to developing such technologies. The spillover problem implies that firms can expect to capture only a portion of that return, but a portion of a large return is still more of an incentive than a portion of a small return. Government can also stimulate innovation through the supply side, either by making it less expensive for firms to undertake research in this area, or by performing the research in public institutions.

Where research produces potentially large social benefits, but is so prone to the spillover problem that firms will not view it as profitable, there is an analytical basis for performing that research in the public sector or through direct private research contracts. In the United States, for example, there is a long tradition of performing such basic research at the U.S. National Energy Laboratories. The National Labs, such as Lawrence Berkeley, Brookhaven, Oak Ridge, Sandia, Lawrence Livermore, and the National Energy Technology Lab are owned by the U.S. Department of Energy (DOE), but operated by either a private firm or a university. Most of the research on energy and environment that is performed at these facilities is funded by the DOE and other U.S. federal agencies.

So long as firms see some potential for private return, public policy can counter-balance the spillover problem by subsidizing research in the private sector rather than performing it in the public sector. The advantage of this approach is that private firms may have better information than the government about the likely commercial feasibility of technologies, and hence be more successful at choosing which technologies to pursue. Subsidies can take the form of fairly general tax credits, or matching funds provided to firms for specific research proposals. In areas where the public research institutions have specific expertise, joint industry-government research can be undertaken via vehicles such as Cooperative Research and Development Agreements. Finally, because the supply of appropriately trained scientists and engineers is relatively inelastic in the short run, there is a danger that any increased expenditure on research in a given area will be at least partly consumed by an increase in wages (Goolsbee 1998), rather than going to more research effort. This tendency can be offset if subsidies to or expenditures on research are complemented by subsidies for education and training in the appropriate areas.[8]

It is generally the case with science and technology programs that systematic assessment efforts are woefully lacking. Because success is uncertain and difficult to measure, most agencies engaged in support of research and technology adoption have resisted efforts to measure their output against quantitative benchmarks, as is required in the United States by the Government Performance and Results Act (Jaffe 1998, 2002). Granted, such evaluation is very difficult, and there is a real danger that imperfect assessment methods will distort policy by encouraging

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[8] For a general discussion of support for training and education as a complement to research subsidies, see Romer (2000).

efforts that "look good" on evaluation, even if such efforts are not ideally suited to the program's mission. But continuous, systematic, quantitative assessment is the only way that the relative effectiveness of alternative policy approaches can be compared over time. In particular, collecting information in a standardized way as projects are begun, implemented, and terminated is the only way to amass the data necessary for a rigorous retrospective analysis.

Retrospective assessment must of course account for the considerable uncertainties that exist when projects are undertaken, so that projects that turn out to have low value ex post may still have been good investments given ex ante possibilities. Consideration of such uncertainties may be particularly problematic for problems such as climate mitigation, where timeframes are especially long, and considerable uncertainties exist with respect to environmental benefits and with respect to baseline energy market conditions (for example, natural gas prices). Such considerations underscore the need to go beyond simplistic ex post rate-of-return analyses that ignore ex ante information sets, changing conditions, and option value. It also reinforces the value of taking a portfolio approach to R&D investments, whereby investments are made in a set of projects that are likely to pay off under differing future conditions.

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 monumental waste represented by 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 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.

Perhaps more important than the question of the overall rate of return is what distinguishes the successful programs from the failures. While the small numbers and inherent randomness makes it difficult to draw strong conclusions, it seems that the successful programs are ones in which significant participation by industry—in the form of many firms or consortia rather than individual contractors—helped to ensure that the photovoltaics, building energy efficiency, and advanced engine programs produced outputs that are actually or potentially of real commercial value.

3.2. Adoption Policies

There is a long history of public support for research in the United States and other industrialized countries. There has been less policy consensus regarding the desirability of using public policy to speed the adoption of new technology. Because of the positive information externality associated with technology adoption, there is a valid analytical basis for considering such policy. Further, if learning curves or other sources of dynamic increasing returns are important, there could be social benefits associated with speeding diffusion of new energy-saving or otherwise environmentally beneficial technologies.

On the other hand, the possibility of technology "lock-in" makes this a potentially two-edged sword. If the government encourages the diffusion of a particular technology, it is possible that it could become so entrenched in the market place that it stifles, at least for a time, the development of some other, superior technology. This danger creates a tension in the design of policies to encourage adoption. To maximize the exploitation of dynamic increasing returns, it is desirable to focus on the development of a small number of promising technologies. Yet to avoid accidentally helping to entrench the wrong technology, it is desirable for policy to be "technology neutral," encouraging all efforts that achieve specified objectives *without* focusing on a particular approach.

Given limited public resources, the government clearly can not subsidize all new technologies, so there is a need to focus scarce resources on commercialization opportunities for which there is the clearest need for a public role. As stated earlier, this case will be more compelling the lower are the private incentives for adoption, as in the case of environmental problems that have not otherwise been fully priced into private decisions.

As with research, the government can encourage adoption both in its own operations and by subsidizing the efforts of others. As the government is a very large landlord, vehicle operator, and user of many other kinds of equipment, its decision to purchase certain technologies for its own use can have significant effects on the rate of diffusion.

Technology diffusion, and achievement of any associated benefits of dynamic increasing returns, can also be encouraged with tax credits that reduce the effective purchase price of new equipment that meets specified criteria. There is some literature analyzing the effectiveness of energy conservation tax credits at inducing conservation investment. The empirical evidence from this literature is mixed, with some early studies suggesting that tax credits are a very ineffective policy (for example, Dubin and Henson 1988 and Walsh 1989), while some later evidence points to some effectiveness (for example, Hassett and Metcalf 1995). Nonetheless, it is important to recognize some disadvantages of subsidy approaches. First, unlike policies that raise the price of emissions, adoption subsidies do not provide incentives to reduce utilization of polluting technology (Fischer and Newell 2004). Second, technology subsidies and tax credits can require large public expenditures per unit of effect, since consumers who would have purchased the product even in the absence of the subsidy (i.e., free-riders) still receive it. This free-rider effect is likely to be more of a problem for technologies that have already penetrated to a significant extent, and less so for very new technologies that are expensive compared with substitutes.

Since a major aspect of market failure in technology diffusion is imperfect information, another category of policy to encourage diffusion is information provision. With respect to technologies that appear cost-effective, but are not yet widely utilized, this kind of policy can help overcome the apparent market failure without putting the government in the position of betting on particular technologies. While analysis is limited, there is some evidence of success for information programs (Anderson and Newell 2004). For example, the DOE provides free energy audits to small and medium-sized companies using university-based engineering teams that recommend energy-saving projects that appear to be desirable. DOE has maintained an extensive database on the technology costs, projected energy savings, and which recommendations were adopted. Overall, about 50% of recommended projects are adopted. These programs are relatively inexpensive, and so are probably earning a reasonable social return. But firms' decisions to adopt only 50% of the projects recommended by engineering experts suggest that imperfect information is not the only reason for non-adoption; rate-of-return requirements and other economic considerations remain.

The early years of utility demand side management in the 1970s, which emphasized information and low-interest loans, also demonstrated to utilities that education alone produced limited energy savings. Thus utilities were led to consider programs that contained stronger financial incentives to convince consumers to make energy-saving choices (Nadel and Geller 1996).

Finally, command and control regulations can also be used to try to force the diffusion of particular technologies, if only by removing less expensive and less environmentally beneficial competing technologies from the market. The Corporate Average Fuel Economy ("CAFE") standards have been designed to force an improvement in auto efficiency.[9] Energy efficiency standards have also been implemented for major home appliances. Such standards can in principle be beneficial by conserving on the need for every individual to undertake the information and assessment process inherent in trading off capital and energy operating costs. However, they also raise the risk of going beyond an economically justified minimum, at which point they can impose limits to product choice and undesirable costs on what is a very heterogeneous population of adopters.

3.3. Current U.S. Climate Technology Policy Efforts

As an illustration of the range of technology policy initiatives related to energy and environment, Table 1 summarizes current U.S. Federal climate change initiatives. Based on the 2004 fiscal year budget request (OMB 2003), about $1.3 billion dollars will be spent on research, and a similar amount on technology diffusion. On the research side, about 40% relates to energy conservation, one-third for sources of renewable energy, and most of the remainder going to "clean coal" and other forms of carbon reduction from fossil fuels. On the diffusion side, a little over half is proposed to go toward tax credits for renewable energy production, cogeneration, hybrid/fuel cell autos, landfill gas production, and solar homes. About one-third of the money goes for state energy efficiency grants, and 9% for EPA information and voluntary initiatives, such as the "Green Lights" program.

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[9] For an assessment of the cost-effectiveness of the CAFE standards see National Research Council (2002) and the research it reviews.

While the level of proposed climate technology R&D funding is very close to past funding levels (for example, $1.4 billion in 2002), the proposed funding for adoption incentives reflects $288 million in proposed new tax incentives for hybrid/fuel cell cars, cogeneration of electricity, landfill gas, residential solar, and expansion of the existing renewables tax credit to include certain forest-related resources, agricultural, and other sources. While this paper has argued that there may be sound economic reasons for pursuing some of these programs, the net benefits of individual initiatives remains an open question and is the subject of more detailed analysis.

4. CONCLUDING REMARKS

When economists evaluate public policies that intervene in the market economy, they generally view it from the analytical perspective of market failure. When it comes to green technology, two mutually reinforcing sets of market failures are at work—which decrease the likelihood that the rate of investment in the development and diffusion of such technology would occur at the socially optimal level. The solutions fall into two categories of approaches. One approach is to foster the development and diffusion of new technology by designing environmental policies to increase the perceived market payoff and maximize flexibility in compliance. The other approach is to implement policies aimed directly at encouraging the development and diffusion of environmentally friendly technologies. Theory suggests and empirical research confirms that innovation and technology diffusion do respond to the incentives of the market, and that properly designed regulation can create such incentives.

The double market failure further clarifies the case for broad-based public support of technology innovation and diffusion. And for cases in which private incentives do not reflect the full costs of environmental externalities, for whatever reason, the efficiency of the policy mix will likely be improved by including public policies aimed directly at stimulating the development and diffusion of new environmentally benign technology. This argument is particularly strong with respect to those aspects of technology development that are most subject to market failure in the form of difficulty by private firms in appropriating the returns to innovation and adoption. Technology “infrastructure” such as data collection and dissemination, and training of scientists and engineers is likely to be seriously underprovided by market incentives alone.

Technology policy that goes beyond basic scientific research, toward the development and diffusion of specific technologies is politically controversial. There are good reasons for this controversy, including the question of whether the government is the appropriate arbiter for determining which aspects of technology should be supported, as well as concern over the effect of political momentum forming behind ill-advised initiatives, which then became difficult to stop. But problems such as global climate change are too important—and the potential positive technological externalities are too clear—to abandon policy efforts simply because they are difficult. Government must remain engaged in technology policy, but it should try a variety of ways to structure policy in this area to minimize the known policy problems. Models are already working, such as public-private partnerships that subsidize research but retain significant elements of market forces in determining which technologies to pursue. Failure of some policy initiatives should be expected, and those failures should be used to terminate or improve particular programs, not to rationalize total inaction.

Policy experimentation would logically work hand-in-hand with systematic policy evaluation. On the ground, however, policy success is very difficult to measure, because the output or effect is often intangible, the expected benefits of technologies change with changing conditions, and the evaluation period must take place over a long time period. This leads some advocates of public investment in technology to resist quantitative evaluation of technology programs on the grounds that measurements of such intangible outputs will understate the benefits and hence undermine political support for such programs. The danger of not even attempting to evaluate policies is that we perpetuate our ignorance in solving the problem, and thereby consign technology policy forever to the realm of ideology. Rather, we should embrace the fact that technological change is a long-term process, and we ought to be willing to take a long-term view. We should remain hopeful that on the time scale of years and decades, systematic evaluation will eventually allow the creation of a solid empirical base for the design of technology policy to maximize its social returns.

REFERENCES

Anderson, S. T. and R. G. Newell. 2004. "Information Programs for Technology Adoption: The Case of Energy-Efficiency Audits", *Resource and Energy Economics* 26(1): 27-50.

Carraro, C., B.C.C. van der Zwaan, and R. Gerlagh. 2003. Endogenous Technological Change in Economy-Environment Modeling, an Introduction, Resource and Energy Economics, 25, 1-10.

Carraro, C. and C. Egenhofer. 2002. Firms, Governments, and Climate Policy: Incentive-based Policies for Long-term Climate Change. Cheltenham: Edward Elgar.

Cesar H. and A. de Zeeuw. 1996. Issue Linkage in Global Environmental Problems. In Xepapadeas, A. (ed.) Economic Policy for the Environment and Natural Resources (197-216). Cheltenham: Edward Elgar.

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

Clarke, Leon, and John Weyant. 2002. Modeling Induced Technological Change: An Overview. In *Technological Change and the Environment*, edited by A. Grübler, N. Nakicenovic and W. Nordhaus. Washington, DC: Resources for the Future Press.

Dubin, J.A., and S.D. Henson. 1988. The Distributional Effects of the Federal Energy Tax Act. Resources and Energy 10:191-212.

Energy Modeling Forum, Stanford University. 1996. Markets for Energy Efficiency, EMF Report 13, Volume I.

Fischer, Carolyn, and Richard Newell 2004. "Environmental and Technology Policies for Climate Change," RFF Discussion Paper 04-05. Washington, DC: Resources for the Future.

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

Goolsbee, A. 1998. "Does Government R&D Policy Mainly Benefit Scientists and Engineers?" American Economic Review 88:298-302.

Goulder, Lawrence H., and Stephen H. Schneider. 1999. "Induced Technological Change and the Attractiveness of CO2 Emissions Abatement," Resource and Energy Economics, 21, 211-253.

Griliches, Z. 1992. "The Search for R&D Spillovers", Scandinavian Journal of Economics 94:S29-S47.

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.

Jaffe, Adam B., Richard G. Newell, Robert N. Stavins. 2003. Technological Change and the Environment. Chapter 11 in Handbook of Environmental Economics, Volume 1, K.-G. Mäler and J.R. Vincent, eds., pp. 461-516, Elsevier Science, Amsterdam.

Jaffe, Adam B. 2002. "Building Programme Evaluation into the Design of Public Research-Support Programmes," *Oxford Review of Economic Policy*.

Jaffe, Adam B. 1998. “Measurement Issues,” in Investing in Innovation, L. M. Branscomb & J. Keller, Editors, (MIT Press, Cambridge).

Jaffe, A.B. and R.N. Stavins. 1994. “The Energy Paradox and the Diffusion of Conservation Technology”, Resource and Energy Economics 16:91-122.

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

Mankiw, N.G. and M.D. Whinston. 1986. “Free Entry and Social Inefficiency”, Rand Journal of Economics 17:48-58.

National Research Council. 2001. Energy Research at DOE: Was it Worth It? National Academy Press, 2001.

National Research Council. 2002. Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards, National Academy Press.

OMB. 2003. Federal Climate Change Expenditures Report to Congress. Executive Office of the President, Washington, DC.

Pegram, William M., “The Photovoltaics Commercialization Program,” in Cohen and Noll, *op cit*, 1991

Romer, P. 2000. “Should the Government Subsidize Supply or Demand for Scientists and Engineers,” in A. Jaffe *et al*., eds. Innovation Policy and the Economy (MIT Press, Cambridge, MA).

Schumpeter, J. 1942. Capitalism, Socialism and Democracy (Harper, New York).

Walsh, Michael J. 1989. Energy Tax Credits and Housing Improvement. Energy Economics 11 (2): 274-284.

Table 1
Overview of U.S. Federal Climate Technology R&D and Adoption Initiatives
(Proposed for FY04)

Climate-Related Technology R&D Spending ($1.3 billion/year)	
Energy conservation	41%
Renewables supply	33%
Fossil fuel GHG reductions	14%
Carbon capture & sequestration	8%
Nuclear	2%
EPA science & technology	1%
Forest, range, agriculture	1%
Energy Information Admin.	<1%
Climate-Related Technology Adoption Spending ($1.0 billion/year)	
State energy efficiency grants	34%
Renewables production tax incentives	27%
Hybrid/fuel cell car tax credits	16%
Cogen. production tax incentives	10%
EPA information/voluntary programs	9%
Landfill gas production tax credit	3%
Solar homes tax credits	1%