Stimulating Innovation in Green Technology

Policy Alternatives and Opportunities

ROBERT P. ANEX
University of Oklahoma

Developing a sustainable form of industry based on green technology will require radical technological innovation by the private sector. Stimulating innovation in green technology through public policy requires an understanding of technology, the innovation process, and how policy affects the innovation behavior of firms. This article explores how to design public policy measures to stimulate green technology innovation. The potential of current environmental policy measures to stimulate green technology innovation is assessed. Opportunities are identified to improve our understanding of the innovation process, to use policy mechanisms to more effectively stimulate green technology development, and to direct the trajectories of key environmental technologies.

TECHNOLOGICAL CHANGE AND THE ENVIRONMENT

It is now generally accepted that the next large reduction of industrial emissions will require fundamental changes in production methods. Although "end-of-pipe" pollution controls have greatly reduced emissions from the largest polluters, it has grown increasingly clear that increased human industrial activity driven by population and economic growth will soon produce more waste than the supporting natural system can absorb. To sustain or improve living standards, we will need to greatly reduce or eliminate the production of waste. Conceptualizations of a more sustainable form of industry go by many names, including pollution prevention, ecoefficiency, product stewardship, design for environment (DFE), design for and within society (DFS), green technology, and industrial ecology. Although there are distinctions between these concepts in terms of scope and degree, they all suggest the need for a fundamental industrial change that will depend on radical technological innovation.[1]

Managing this technological innovation will require appreciation of the complex process of technological innovation. Technology, although often thought of as a physical artifact, is a mixture of social-behavioral and physical elements. Thus, technology cannot be fully understood in isolation from the social, political, and economic forces that shape it and are themselves shaped and altered by technology. Because environmental issues often involve explicit decisions

AMERICAN BEHAVIORAL SCIENTIST, Vol. 44 No. 2, October 2000 188-212

between different social goods, the desire and demand for green technologies are particularly a product of social choice. The development of green production technologies within the private firm depends in a similar way on the *corporate* culture, because environmental objectives often lie outside the traditional economic objectives of the firm. For many firms, incorporating environmental objectives *before* the design stage, in the innovation process, will require a major shift in management and culture. Thus, if it is to be successful, public policy intended to encourage innovation in green technologies must be designed with an understanding of how corporate culture and management respond to social and regulatory influence.

In addition to understanding the managerial behavior of the firm, inducing technological innovation through policy requires understanding the dynamic nature of the innovation process itself. Technological innovation within the firm is guided by external regulatory and market forces and internal strategic direction of management and has momentum provided by the technical experts and technology existing within the firm. Thus, the process of technology development is often specific to a technology, a region, an industry, or even an individual firm.

The above discussion addresses the leverage points within an industry or the supply chain that present opportunities for policy to influence technological innovation. There are also specific times in the life cycle of a technology that represent windows of opportunity for influencing the trajectory of technology development.

The industrial system evolves through a series of decentralized technology choices. Technologies selected are not necessarily chosen because they are best. The dominance of one technology over its competitors may occur through a series of small, perhaps random, events that conspire to "lock in" a technology. The subsequent technology development pathway may then be firmly entrenched for a long period, stabilized by the positive feedback of increasing returns to adoption of the standardized alternative. There are, however, occasionally periods of large social, economic, or political change during which an incumbent technology can be more easily supplanted. Society should anticipate these infrequent and brief windows of opportunity to redirect technology development and encourage the innovation of new technologies that can take advantage of these "inflection points" in technology pathways.

In this article, I argue that we are now entering a period when an unprecedented number of such opportunities to induce radical technological change will present themselves. In the United States, the restructuring of environmental key industries, reauthorization of many U.S. environmental regulations, international processes of economic globalization, and rapid social change are now occurring or are anticipated in the relatively near future. These phenomena create opportunities to change technology trajectories for the better or for the worse. If technologies are chosen without careful long-term assessment of future scenarios, we may lock ourselves into undesirable technological and social arrangements. Conversely, if we carefully design public policy to foster innovation in targeted technology areas, desirable, clean technologies will be available when the time comes to make technology changes, and markets and social structures will be able to adapt efficiently.

This article proceeds with a definition of green technological innovation. The role of government in technology policy is then discussed. This is followed by descriptions of the process of technology innovation and the effect of regulation on green innovation. Finally, I argue that current events are conspiring to create unique opportunities for public policy to guide key technology trajectories onto more sustainable and desirable paths.

GREEN TECHNOLOGICAL INNOVATION DEFINED

Technological innovation is a part of the larger process of technological change that comprises invention, innovation, and diffusion.[2] The customary definitions are that *invention* is the first demonstration of the feasibility of a proposed idea or device. *Innovation* is the first practical or commercial application of an invention, and *diffusion* is the adoption of an innovation by other firms or organizations. It is important to remember that innovation is a part of the process of social change as well as technical change. In this context, innovation is an unusual event during which a social organization changes what it does and how it does it. Often, technological change and social change are closely related and simultaneous. This article focuses on technological innovations, particularly in industrial processes, that reduce the production of waste. Such innovations are called "green" technological innovations.

The innovation literature also differentiates between *incremental* and *radical* innovation. One might view incremental and radical innovation as two ends of the same scale so that the difference between them is only a matter of degree. The more common view is that these are qualitatively different processes. The latter perspective, in which incremental and radical innovation require very different facilitating social contexts and that radical innovation yields new organizational structures, is that taken here.[3] It is radical green technological innovation that will be most beneficial in meeting the goals of a more sustainable form of industrial production as well as that which is most complex and disruptive to society.

It is common and useful to draw a further distinction between technological innovations that are products and those that are processes. Products are an end in themselves, whereas processes are means to another outcome. Diffusion of a new process requires systematic change involving machines, people, and social structures, whereas diffusion of a new product can be more a matter of marketing. Radical process innovation requires systematic change and thus tends to be extremely disruptive. Because process innovation is often more disruptive than

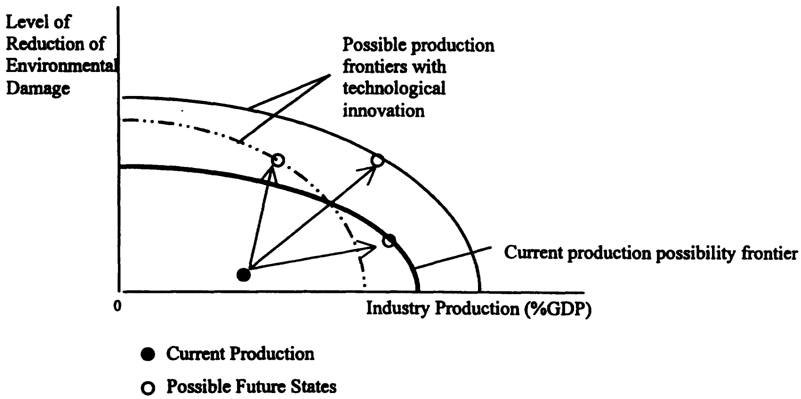

Figure 1: Technology Change Creates New Production Possibility Frontiers

product innovation, the conditions required to facilitate process change are different from those required for product innovation.

THE PROMISE OF GREEN TECHNOLOGY

The problem of reducing industrial emissions is often seen as a zero-sum game in which any environmental improvement comes at the cost of reduced industrial output. The promise of green technology innovation is that through new technologies we can enjoy environmental improvement while maintaining economic growth. This is shown conceptually in Figure 1. The current production possibility frontier represents the combinations of industrial production and reduction of environmental damage below some baseline that are possible if all of society's resources are efficiently employed. Although inefficiencies may keep us from ever reaching this boundary, we are always striving to move toward this frontier.

The other production possibility frontiers shown in Figure 1 illustrate two possible technological alternatives. The outer frontier represents a clearly superior technology because it lies outside the current production frontier at all points. That is, society can achieve both more environmental improvement and more production by switching to this technology. The frontier represented by the dashed line in Figure 1 represents a technology that for current (lower) levels of environmental improvement allows lower-than-current levels of industrial productivity. However, if society demanded greater reduction in environmental damage, this technology would allow greater industrial production than the current technology. These abstractions show that not only must society decide how to make the trade-off between environmental damage and productivity using current technology; it must anticipate future environmental objectives when choosing new technologies.

THE ROLE OF PUBLIC POLICY IN GREEN INNOVATION

Although technology can be viewed narrowly as tools that extend man's capabilities, technology is also one of the key elements that define a society, and the evolution of technology is critical to the evolution of a society. Thus, technology and technological innovation are naturally subjects of interest in public policy. Although technology is closely linked to productivity and therefore standard of living, it is also vital in the defense of the nation, maintaining public health, and improving the quality of life.

In addition to its desired impacts, innovations often affect quality of life in unpredictable and sometimes undesirable ways. Modern innovations such as the automobile, the personal computer, and the jet airliner have extended human capabilities in startling ways but also have had a profound impact on our culture and the way we live our daily lives. Technological innovations may displace workers by reducing the need for labor and may similarly shift the fortunes of private firms and nations. Thus, in addition to being vital to the development of a nation, technological innovation may be seen to cause the deterioration of personal well-being, to be a source of social inequities, and to lead to degradation of the natural environment (Cramer & Zegveld, 1991). It is the role of technology policy to try to manage technological innovation to reap the benefits and reduce the costs to society of new technologies.

Advocates of a strong technology policy usually feel an obligation to justify such policies' interference in the free market. The argument usually made is that private firms and institutions underinvest in basic research because they cannot capture the benefits of the generically applicable results. This represents a market failure because the free market does not provide the full measure of innovation that can result in a net benefit to society.[4] This argument is no less valid when applied to justify policy in support of green technological innovation.

Pollution creates a market failure because it is not priced by, or is "external" to, the market. It has been the role of environmental regulation to internalize pollution costs to the firm. Such regulations are typically not designed to encourage firms to be innovative in their product or process design to reduce the creation of pollution; rather, they tend to favor particular control technologies. Thus, a market imperfection that impedes the development of green technologies is created by the current environmental regulatory system that creates a de facto requirement for particular pollution control technologies.

The "end-of-pipe"-oriented environmental regulatory regime has eliminated the worst industrial pollution problems that this country has faced during the past 30 years. However, this approach is not applicable to many of the remaining pollution problems such as small business emissions and nonpoint sources, and in some cases it has simply shifted pollution between media. For example, scrubbers that remove sulfur dioxide from flue gasses create large quantities of gypsum that are often disposed as solid waste. Future reductions in emissions will require innovation in manufacturing processes, product design, and the way services are provided.

Government policy can promote technological innovation either through increasing the market for innovative technology or by stimulating the supply of innovation directly. Policy measures that affect the demand for technology innovation include information supply, government procurement, and performance standards. Supply-side policy measures include funding research directly, research tax credits, rate setting, patent and copyright protection, and antitrust and liability law relief. The most successful government efforts to promote technological innovation have been in the defense and space programs. Investigators examining these big programs have concluded that success has depended on the government influencing both supply and demand for technology (Dalpé, 1994; Mowery & Rosenberg, 1982; Rothwell & Zegveld, 1981).

Norberg-Bohm (1997) points out that green technological innovation is different from "big science" projects in three important ways. First, the goal of green technology policy is not to create a new type of technology but to incorporate environmental objectives into the development of all technologies. Second, government is not the primary customer for green technology nor can it guarantee markets for so many technologies. Third, there is no national consensus on the level of environmental protection that is appropriate or the need for government involvement in stimulating green technology development. Taken together, these characteristics significantly limit the success of government initiatives to create supply of, or demand for, green technologies. Green technological innovation policy will have more success targeting private-sector development of, and demand for, green technology.

THE INNOVATION PROCESS

To design policies that will stimulate private-sector technological innovation, we must understand how and why firms innovate. This section is not intended to present the definitive model of private-sector innovation or even to summarize the large body of research in this area but rather to emphasize that understanding firm behavior in response to regulation is critical to the design of successful technology policy.[5] Furthermore, it should become clear that there is still a great deal that is unknown about the behavior of the firm with regard to green technology innovation and that more empirical research is needed.

Technological innovation within the firm is a complicated phenomenon that is not easily predictable and does not have simple chains of causality. Innovation is influenced by the unique organizational, technological, and environmental context of the situation in which it occurs. Organizational factors that affect innovation include the organizational structure of the firm, management behaviors, human resources available, and informal linkages and communication internal and external to the firm. Environmental factors in innovation include industry and market characteristics such as competition, market uncertainty, and the industry life cycle, as well as government regulation. Because technology policy is often designed to target a specific industry, the roles of industry and market characteristics in innovation are important and worthy of closer examination.

The structure of some industries seems to be more conducive to innovation than that of others. Some industries are technologically stagnant, whereas others are marked by rapid technological change in both products and processes. Understanding the underlying cause for these differences could allow policy measures to alter the rate of innovation in an industry or at least allow targeting of industries that are more susceptible to change.

Empirical research supports three different but not incompatible hypotheses concerning the effect of industrial structure on innovation (Gort & Wall, 1986; Nordhaus, 1969; Scherer, 1982; Stoneman, 1979). The *technology push* hypothesis argues that the richness and complexity of an industry's technology base determine the likely effectiveness of further research and development (R&D). The *demand pull* hypothesis suggests rather that firms adjust their R&D effort and output in response to economic opportunities in their industry. The third view is that innovation in an industry follows a predictable industry life-cycle pattern. The first two positions are relatively self-explanatory, but the third may require more description.

According to Abernathy and Utterback (1978), the nature and amount of innovation will change over time as a market niche is born, matures, and finally grows into senescence. In this model, a market niche is created when a new, superior technology first comes to the market. Rapid product innovation occurs as the new technology is refined and improved. As the market niche matures and the product definition stabilizes, the market seeks production efficiency improvements and thus process innovation becomes more prevalent (Utterback, 1987). Finally, senescence of the market niche is characterized by a reduction in both product and process innovation rates.

In addition to industry structure, the role of market structure or patterns of competition has been empirically shown to strongly influence private-sector innovation. Empirical studies by Von Hippel (1988) and Nelson (1996) support the hypothesis that the inventive activity within an industry will be found where the ability to appropriate the returns of that activity is the greatest. This view provides insight into the differences between product and process innovation as well as the role of innovation by suppliers.

Nelson (1996) reports that the bulk of industrial R&D is directed toward new or improved products rather than processes because product innovation can result in a rapid increase in the market share. Because the market share in process industries tends to be less sensitive to short-run cost and price, the reduced costs associated with process innovation will increase the market share more slowly and may be less important than economies of scale achieved by larger firms. Thus, firms in process industries spend less on fostering innovation, particularly in less-concentrated industries.

Although process industries may spend less on R&D, this does not mean that process innovation is not taking place. In many such industries, innovation is being done by upstream suppliers of materials and equipment. An innovation by a firm in a fragmented process industry will gain that firm little, given the relative insensitivity of the market share to process innovation. However, innovation from an upstream firm in the form of new materials or equipment can be sold to the entire industry. Thus, this model predicts that process innovation is more likely to come from upstream suppliers, particularly in less-concentrated industries.[6] This view is consistent with the taxonomy of sectoral patterns of technological innovation developed by Pavitt (1984), which identifies a group of "supplier-dominated" industries populated by firms that are small and not idiosyncratic with regard to equipment needs and rely on upstream suppliers for new processes.

This short discussion of the innovation process indicates that policy to promote innovation should be most effective if targeted at the portion of the supply chain that is most inclined to innovate. Similarly, the life cycle of industries and the "natural" trajectories of technologies create windows of opportunity when technologies can be easily changed and other periods during which technologies can be dislodged only with great difficulty.[7] Therefore, where possible, policy should target technologies when their development trajectories make them susceptible to change. In addition to looking for opportunities afforded by industry and market structures, policy may also be able to induce innovation by modifying organizational context, for example, by fostering collaborative arrangements and creating networks of information transfer. Such networks, forged by social or commercial relationships, are often cited as determining factors of the form and spread of innovations.[8]

This discussion has been directed at technological innovation in general, but inasmuch as "green" technology is a type of technology, it is commonly assumed that insights into how industrial context affects technological innovation in general will apply to green technology innovation as well. However, little empirical work has been done to test to what extent this expectation holds.

It is also reasonable to expect that because of the unique characteristics of green technology within the firm, green technological innovation will occur under a somewhat different set of circumstances than other technological innovation. In particular, the returns from green technological innovation tend to be highly uncertain. Often, environmental improvements are made to avoid highly contingent costs such as future liability. Green technology development involves additional uncertainty because of the highly regulated and political nature of environmental issues. Response to risk, such as investment in research and technology development, is sensitive to level of uncertainty and is often very different in the realm of losses as opposed to gains (Tversky & Kahneman, 1992). Although there is a small but expanding literature of green technology innovation case studies, there is still little generalizable empirical study of green technology innovation in industry. Most policy prescriptions concerning green technological innovation have been based on "common sense" or hunches as to how the process of green innovation may be similar to, or different from, more general technological innovation. More empirical study of the process of green technology innovation in private industry is needed to inform and support policy prescriptions intended to promote green innovation.

REGULATION AND ITS EFFECT ON GREEN INNOVATION

The ability to develop more environmentally friendly industrial technologies lies primarily in the private sector. As described previously, private-sector innovation is driven by a wide range of industry, market, and firm-specific factors such as availability of human and technological resources, firm management, factor prices, industry structure, and market uncertainty. Public policy influences the rate and direction of private technological innovation by changing these innovation drivers. For example, by stimulating the provision of information on the true or "full cost" of managing waste and controlling emissions, the Environmental Protection Agency (EPA) encourages firms to identify and invest in technologies that reduce these costs by eliminating production of the wastes (EPA, 1992, 1996).

Several authors have identified desirable characteristics of regulatory initiatives intended to promote green technology innovation (Ashford, 1993; Banks & Heaton, 1995; Norberg-Bohm, 1997). The characteristics identified are the following:

- Provide economic or political incentives for innovation
- Allow flexibility in firms' response to regulation
- Control technological and economic uncertainty
- Stimulate the production and dissemination of information
- Address emissions into all media
- Consider the entire product life cycle

Additional desirable characteristics are the following:

- Consider the technological life cycle
- Serve as policy experiments

All policies must ultimately achieve their intended purpose by creating incentives. The justification for green technology innovation policy previously offered here is that there is insufficient incentive for such change provided by free markets. If policy is to induce green technology innovation in industry, clearly it must create an incentive for such behavior. Regulation can be used to create direct economic incentive through measures such as taxes, subsidies, or penalties for noncompliance.[9] Incentives can also be created indirectly through programs that sway public opinion such as those that disseminate positive or negative information with regard to the environmental performance of a firm. Regardless of the nature of the incentive, the incentive to innovate must be strong enough to induce an innovation response from firms rather than alternate responses such as political lobbying or end-of-pipe pollution controls.[10] The need for a sufficiently strong innovation incentive has been described by Ashford (1993) as "regulatory stringency." A regulation is stringent either because it requires significant emission reductions, because compliance using existing technology is expensive, or because it requires a significant technological change. Several authors have argued that stringent environmental regulation is actually good for a country's competitiveness precisely because it creates incentive for technological innovation, making firms fitter and more competitive (Banks & Heaton, 1995; Palmer & Simpson, 1993; Schmidheiny, 1992).

Unfortunately, technological innovation does not operate on a fixed timetable or proceed in predictable directions. As already discussed, technology and technological change are often specific to an industry, region, or individual firm. This creates a considerable challenge for policy makers who wish to promote technological innovation. Because the ability to innovate lies primarily within the firm, green technology policy must be flexible enough to accommodate the specific circumstances of an individual firm, while still achieving its environmental goals. Thus, flexibility is realized as an enforcement style that is collaborative and performance oriented, allowing firms to negotiate ways to achieve regulatory compliance.

Policy instruments can also encourage technological change by reducing the uncertainty associated with investing in new technology development. Technological innovation is, by definition, disruptive, and radical innovation is very disruptive. Because of the often high direct cost of technological development and the disruption that comes with innovation, technological change usually represents a significant financial investment. Because an investment represents an option that a firm may exercise or not, increased uncertainty raises the "hurdle rate" of return at which a firm will invest (Dixit & Pindyck, 1994).

Investments in green technology development are characterized by both technological and economic uncertainty. Technological uncertainty can be reduced by providing information such as through demonstration projects. Economic uncertainty is created both by markets and by policy itself. Market uncertainty can be reduced through direct government procurement. The uncertainty created by policy results from the political and nonpermanent nature of policy measures. Policies that communicate a long-term commitment by society to continued environmental improvement will create an environment in which firms will be more willing to make long-term investments in innovative waste-reducing technologies.

Policy measures that provide information or cause it to be provided reduce uncertainty, but they also can help firms to identify pollution reduction opportunities. Firms may not recognize opportunities for reducing waste production because accounting methods often hide environmental costs in overhead. Environmental costs are also difficult for firms to assess because they tend to be contingent and highly uncertain. Policies that require firms to perform "full-cost" accounting or implement environmental management systems (EMSs) can help firms identify waste reduction opportunities. As previously described, information can reduce uncertainty and through instruments such as green labels and product information can stimulate demand for environmentally friendly products.

Policies that limit total emissions by taking a multimedia approach will reduce the opportunity for firms to shift emissions between media and therefore provide more stimulus for green innovation. Emissions can often be traded off between media such as when liquid wastes are converted to air emissions through volatilization or air emissions become solid waste when captured in filter media. The objective of green technology innovation is to prevent the creation of waste, not to shift it between media. Thus, policy should be designed to create incentive for true pollution elimination, rather than relocation.

Just as emissions can be shifted between media, environmental impacts can be shifted between stages of the product life cycle. For example, a disposable product may result in much less waste during manufacture than a durable product but result in a much larger amount of postconsumer waste. Green technology innovation policy should create incentives for products and processes that result in lower life-cycle environmental impacts, not simply lower impacts due to manufacture or any one stage of the product life cycle.

As products have life cycles, so do technologies. As observed earlier, a policy aimed at fostering innovation when a product niche is new may not be appropriate as the market segment matures and manufacturers begin seeking production efficiencies rather than hoping to redefine the product. Thus, policy makers should consider the technology life cycle in determining how to structure an instrument to have the best effect. They should also recognize that as technologies age and policies become less effective, policy measures should be reformed or retired (Starling, 1988). In the same vein, each policy measure should be seen as an experiment that offers opportunities to gather data. A policy experiment not only teaches us what works (or does not work) in a specific case but helps us refine our models of firm innovation behavior so that we can design policy for future, different cases. The idea of policy as experiment is particularly appropriate with regard to green innovation policy for which large environmental and technological uncertainties make comprehensive planning extremely difficult (Frosch, 1996; Lindblom, 1959, 1979).

POLICY OPTIONS

Most of today's environmental policies have been promulgated in the past 30 years and have been designed with little consideration of their impact on technological innovation. The policy options that have been used include standards,

TABLE 1: Classes of Policy Options

Class of Mechanism	*Example*
Standards	Ambient standards, performance standards, material prohibitions
Direct incentives and disincentives	Incentives: research and development subsidies, research tax credits Disincentives: effluent fees, disposal fees
Liability	Joint and several liability, worker safety and health
Market mechanisms	Tradable emission permits, use taxes
Information	Firms: demonstration projects, technical assistance Consumers: green labeling, release inventories
Voluntary agreements	Voluntary emissions reductions, self-auditing

direct incentives and disincentives, market-based measures, information, liability, and voluntary agreements. Table 1 summarizes these policy mechanisms. The effectiveness of these policy options at promoting innovation has been discussed previously by several authors, and each class of instrument has been found to have both strengths and weaknesses. The impact of existing environmental regulations on technological innovation has been examined by Andrews (1994); Davies and Mazurek (1996); Heaton and Banks (1998); Newell and Jaffe (1996); Norberg-Bohm (1997); and Susskind, Secunda, and Krockmalnick (1997). The purpose of this discussion is to review these policy options and suggest that although generalizations concerning these classes' impacts on technological innovation are useful guides, details of implementation are vital in a policy's ability to foster technological innovation.

Standards

Standards are the most common form of environmental regulation in the United States, serving as the primary instruments of major environmental legislation such as the Clean Air Act (CAA), Clean Water Act, and the Resource Conservation and Recovery Act (RCRA). Standards are used to permit or prohibit the use of specific materials and to set ambient and emission standards for certain pollutants. Ambient standards are set to control the level of a pollutant within a particular environmental medium and geographic region to control health or ecosystem risk. Emission or "performance" standards are set to limit pollutant discharges from a particular industry and are often based on the "best" or "maximum" available control technology. Ambient and performance standards are sometimes used together as in the CAA with the performance standard setting a baseline emission limit. If the ambient standard is exceeded, emission reductions beyond the performance standard are required.

In general, standards do little to stimulate technological innovation because they are commonly based on existing technology. For example, Title III of the 1990 amendments to the CAA creates a permitting process that, although not specifying exactly how to reduce pollutant releases, requires that sources are to use maximum available control technology (MACT) to reduce pollutant releases (Bryner, 1993). This approach raises a barrier to technological innovation, creating a de facto technology standard by making it much easier to get a permit if a firm uses the MACT specified in the standard.

The CAA permit process also fails to create an incentive for technology innovation by calculating permit fees based on factors such as size of facility and extent of emission, rather than the environmental efficiency of a facility's technology. In this context, environmental efficiency is defined as the amount of product produced per unit of emissions. For example, the CAA permit process discourages innovation in generating combined heat and power in an industrial facility because that would increase facility emissions and raise the permit cost even though it would reduce total emissions because the average power plant supplying the grid uses older and dirtier technology (i.e., is less efficient but can absorb permit costs because its capital costs have been paid for over time).

Implementation issues have created barriers to innovation under other existing standards as well. Under the Toxic Substances Control Act (TSCA) and the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), new chemicals are subject to stringent review and testing, whereas those already on the market before regulation are not (Heaton & Banks, 1998). This type of "grandfathering" discourages the development of new products and also discourages the makers of currently registered chemicals from improving their products. See Sharfman, Meo, and Ellington (2000 [this issue]) for a case study of green insecticide development that overcame the grandfathering barrier through cooperation between regulators and the innovating firm.

Direct and Indirect Incentives

The traditional way for government to stimulate technological change is by creating direct incentives for innovation. Such measures can either attempt to create an incentive to develop new technologies, known as *technology push*, or can create demand for new technologies, which is called *market pull*. Technology-push programs create direct economic incentives for technology creation by paying research subsidies or providing research tax credits to firms. Incentive can also be created by penalizing undesired activities such as waste generation. Market-pull incentives can be created through government procurement. Under specific conditions, these approaches are practical for stimulating innovation in particular targeted technologies. Rothwell and Zegveld (1981) discuss the conditions under which subsidies and government procurement are potent tools for fostering technological innovation. In particular, they state that subsidies should be targeted at specific high payoff sectors. Such targeting would require better forecasting abilities than now available. They note that procurement works best under conditions of monopsony or oligopsony, but government is not the intended user of, and cannot be the primary purchaser of, green industrial technology. Therefore, because the policy objective assumed here is a more sustainable form of technology across a broad range of industries, government is not in a position to create significant direct incentives via traditional methods such as subsidies and procurement.

Liability

Another way that policy can influence innovation is by controlling liability. Liability is a source of uncertainty in many industrial ventures because it is determined by the courts and is subject to changing judicial and public opinion. Environmental liability is additionally uncertain because it incorporates the scientific uncertainty associated with the environment.

Whether environmental and product liability has positive or negative impacts on innovation is a matter of debate. One view is that the liability system, developed through statute and case law, is critical to creating efficient, durable, innovative, and safe products and processes because liability deters harmful products (Ide, 1998). Unlike government standards, the liability system enforces voluntary standards without prescribing precise compliance methods and allows individuals to pursue their own self-interests with minimal government involvement. The counterargument is that although the liability system demands safe products and processes, by not making clear how to be safe or how safe to be, liability introduces large uncertainty into every phase of planning for, and managing, the product cycle. This uncertainty and the potentially high cost of liability lead to the practice of "defensive design" and the stifling of technological innovation (Morrow, 1998). It is likely that both perspectives are somewhat valid and that liability can have various effects on innovation depending on how the law is interpreted and enforced. In either case, because controlling liability is a blunt tool with regard to innovation and because it serves other important social purposes, controlling liability is unlikely to be an effective method of promoting green technology innovation.

Market Mechanisms

Economic policy instruments such as environmental taxes or Tradable Emission Permit (TEP) systems are the most commonly suggested alternatives to standards. Such market-based mechanisms have been promoted because they can reduce pollution at the lowest cost and because they create incentives for technological innovation. However, recent experience with the U.S. SO_2 TEP program and more sophisticated economic analyses have shown that incentives for innovation are not necessarily improved by market-based mechanisms.

For instance, Malueg (1989) has shown through economic modeling that TEPs may increase or decrease firms' incentive to innovate depending on whether they are buyers or sellers of permits. Similarly, although the U.S. SO_2 TEP program (implemented as part of the CAA amendments) has shown much lower control costs than predicted (Burtraw, Krupnick, & Farrell, 1998; Schmalensee, Joskow, Ellerman, Montero, & Bailey, 1998), Burtraw (1996) has attributed these innovations more to flexibility provided by switching to performance standards than to the use of marketable permits. Wallace (1995) concludes of TEPs that "care must be taken that they are the appropriate choice and that their implementation does not negate the advantages they apparently offer" (p. 246).

Environmental taxes are even more sensitive to implementation issues than TEP systems. TEP systems provide a flexible way to achieve a chosen level of emissions, whereas under a tax, the level of emission reduction is determined by the amount of the tax. Regulators must therefore establish the proper tax rate to cause emissions to fall to a desired level. To promote innovation, the tax rate must be announced well in advance so that firms can develop technologies to allow them to avoid the financial burden of the tax. The tax rate should be certain so that firms are willing to invest in technological innovation. However, as firms innovate and emission reduction becomes less expensive, the tax rate needs to be reduced to prevent excessive (inefficient) emission reductions. Lowering the tax rate would create losses for the firms that had invested in innovation and destroy the market's confidence concerning the tax mechanism, precluding further innovation.

Differences between industries in innovation-determining factors such as competition, market uncertainty, and industry life cycle mean that different tax rates would be required to induce innovation in different industries. To complicate matters further, tax systems create incentives for the developers and users of green technology to deceive regulators about the costs of using the technologies, making the task of setting the tax rate more difficult (Milliman & Prince, 1989). Thus, the impact of environmental taxes on green technology innovation is confounded by the difficult task of setting the appropriate tax rate and understanding an industry's uncertain response to the tax.

Information

Controlling the flow of information between government and industry can also be used as a policy instrument. Information can flow from government to industry or from industry to government. Information flow from government to industry, often in the form of demonstration projects or technical data, is more useful in promoting diffusion of technology than innovation. Although such government information programs increase "information capital," they fail to create the trustful relationships associated with "social capital" that allow collaborative networks to screen information for accuracy and implication and thereby use informational capital in innovation (Fountain, 1998, p. 93). Information programs in which industry is asked to provide information to government for public dissemination can have a more significant impact on innovation.

The public dissemination of environmental information, such as through release inventories or green labeling, can create a significant incentive for firms to reduce emissions but does not create a direct incentive for green technology innovation because firms can respond with end-of-pipe pollution controls. The most widely studied U.S. program of this type is the Toxics Release Inventory (TRI). Authorized under the Emergency Planning and Community Right-to-Know Act (EPCRA), the TRI requires firms to provide annual data on releases of more than 600 toxic chemicals. Although the TRI has been criticized for containing inaccurate data and reporting only chemical waste rather than usage, it has been shown to have been effective in reducing the production of toxic waste (Hamilton, 1995; Khanna, Quimio, & Bojilova, 1998; Konar & Cohen, 1997).

Voluntary Agreements

Voluntary agreements are a broad range of instruments in which individual firms can choose to participate or not. Voluntary agreements vary significantly in how the industry-regulator relationship is structured. Some voluntary agreements are very similar to regulatory standards in which the government sets goals and constrains the ways in which industry may respond. Other programs are completely voluntary, and firms decide what they will do and how it will be done in exchange for positive publicity. Several studies have examined the impacts of the major U.S. voluntary programs: EPA's 33/50 Program (Davies & Mazurek, 1996; Norberg-Bohm, 1997), the EPA's Common Sense Initiative (Davies & Mazurek, 1996; Heaton & Banks, 1998; Norberg-Bohm, 1997), Occupational Safety and Health Administration's (OSHA) Voluntary Protection Programs (Davies & Mazurek, 1996), and EPA's Energy Star Program (Norberg-Bohm, 1997). International voluntary agreements have been reviewed by Andrews (1994) and Wallace (1995). There has been very little economic analysis of voluntary environmental agreements, and what has been done has used equilibrium models that do not consider technology change (Segerson & Miceli, 1998).

Several general conclusions concerning the use of voluntary agreements can be drawn from these studies. First, voluntary agreements do little to promote innovation without a background threat of regulatory action. For example, innovation could be motivated by a credible threat of industry-wide regulation if certain environmental goals are not met "voluntarily." Second, to gain significant industry cooperation, a program will probably need to address the "free rider" problem in which some firms are seen to benefit without paying the potentially high cost of participation. The perception of free riders will erode industry's willingness to cooperate and invest in innovation. This problem can be addressed by offering nonparticipants a strict regulatory option. Third, the success of voluntary agreements at encouraging technology innovation and reducing environmental damage depends on close, trustful relationships between government and industry.

The success of voluntary agreements is predicated on close cooperation between government and industry. Government cannot set or evaluate environmental goals without information from industry about markets and current and projected technologies. Industry will not voluntarily undertake costly efforts to develop new technology and reduce emissions unless it has confidence in the reliability and goodwill of regulators. Because the relationship between government and industry is instrumental in determining the success of voluntary agreements, the performance of such programs is highly context dependent. Voluntary agreements are therefore even more sensitive to details of implementation than more traditional environmental regulations (Wallace, 1995, p. 250).

Policy Option Recommendations

Despite their limitations, standards will remain important tools of regulators because standards create a baseline of environmental performance and are relatively easy to formulate and administer. However, standards should be implemented so that they create incentives for, rather than barriers to, green technology innovation. Reforms that make it easier to permit innovative technologies are needed. Incentives for innovation can be created through reduced monitoring or streamlined permitting for firms that exceed compliance standards, multimedia standards, and flexible enforcement. Uncertainty can be reduced by committing to standards that become more stringent over time and by clearly communicating the standards so that firms will make long-term investments in new technology. The anticipation of more stringent regulation under existing standards has resulted in technological innovation, even when that expectation is not fulfilled. See Sharfman et al. (2000) for case studies of green technology innovation during prepromulgation periods under the CAA and RCRA.

There have been several recent regulatory reforms introduced that are intended to promote innovation, to increase flexibility, and to consider multimedia impacts within the system of regulatory standards in the United States. Two particularly noteworthy federal reforms are Project XL (which stands for "Excellence in Leadership") and the Common Sense Initiative (CSI). Project XL encourages collaborative, innovative technology development by allowing firms that commit to achieving better environmental performance than required under existing regulation to enjoy greater flexibility in how they meet the standards. The CSI attempts to move away from media-specific regulation by eliminating conflicting or contradictory regulations that impede innovation in specific industry sectors and by allowing industry to develop holistic compliance strategies. Although these initiatives attempt to address important shortcomings of standards with regard to innovation, they have thus far had little impact. The primary reason cited for these programs' poor performance is that, as implemented within the media-specific, command-and-control culture of the EPA, these measures are unable to achieve their intended objectives.[11]

Although the policy instruments reviewed here have different strengths and weaknesses, in each case their ability to promote green technology innovation is sensitive to the manner and context in which the measure is employed. Policy instruments are selected to satisfy the many constraints of the legislative and regulatory processes. However, the choice of mechanism will frequently have less influence on the prospects for promoting technology innovation than the details of how the mechanism is implemented and the context in which it is employed. The characteristic that appears to encourage innovation regardless of the instrument used is the existence of a credible threat of stringent regulation.

POLICY OPPORTUNITIES

It was argued previously that the life cycle of industries and the natural trajectories of technologies result in periods during which technologies can be dislodged only with great difficulty and others when technologies can be easily changed. It appears that we are now entering a period when a large number of such opportunities to induce radical technological change will present themselves. In the United States, the restructuring of the electric power generation industry, reauthorization of many U.S. environmental regulations, as well as international processes of economic globalization are now occurring or are anticipated in the relatively near future. At the same time, a growing number of firms are recognizing that industrial environmental stewardship is a necessary condition for sustainability. Governments should take advantage of this window of opportunity to craft public policy that fosters innovation in appropriate technology areas so that desirable, clean technologies will be available when the time comes to make a change and the market will be able to adapt efficiently.

The current opportunity to influence green technology innovation is not created simply because capital expenditures are predicted to grow rapidly during the next few decades but rather because circumstances will require significant shifts in technology choice in environmentally important sectors. The coming changes in technology represent inflection points in technology trajectories that will allow society rare opportunities to make large improvements in the environmental performance of some of the most polluting technologies. The technology choices that are made are likely to then be locked in for many years by the economic advantage created by increasing returns from adopting the standardized technology.

One of the world's most persistent pollution problems has been the emission of the products of combustion from industrial and mobile sources. Although we have eliminated many of the worst pollution problems during the past 30 years, the world's hunger for energy has grown continuously, as has the environmental impact of burning fossil fuels. In the United States, two of the most important energy-consuming sectors, electric power generation and transportation, are expected to undergo significant changes in technology during the next 20 years.

Restructuring of electric power markets in the United States is resulting in large changes of ownership and is changing how power generation companies are compensated for their power. New large power plants that were attractive under regulation because of the way capital costs were incorporated in a utility's rate base are now unattractive because they have very long payback periods and cannot be operated as flexibly as smaller gas turbine plants. As a result of deregulation and demand growth, more than 400 gigawatts of new electric power generation capacity will be needed in the United States between 1996 and 2020.[12] This represents more than 50% of current capacity. The life span of an electric power plant is approximately 60 years, so it is rare that such a large amount of generation capacity is installed in such a short period. This large turnover in the installed power generation capability provides a unique opportunity to improve this environmentally important technology.

A similar but somewhat less certain opportunity may appear in the transportation industries in the next 20 years. Several prominent petroleum geologists have recently predicted that the world will face a permanent oil shortage beginning early in the next century (Campbell & Laherrère, 1998; Kerr, 1998). Such a shortage, if it occurs, will require profound changes in our transportation systems. Such changes may not only change the vehicles we use but may require a new infrastructure. When put in place, the new infrastructure will give large momentum to the technology trajectory we have chosen at that time, and the new technology may well be as hard to displace as the automobile has been. Therefore, it will be critical to choose a technology that will provide the flexibility to meet our future transportation and environmental needs.

If fuel availability does not force technology changes in transportation, environmental restrictions probably will. Already we are seeing automobile manufacturers being forced to abandon traditional internal combustion engine designs to meet the increasingly stringent emissions requirements in many developed countries. New technologies now coming to the market include a wide variety of electric, hybrid electric/internal combustion, and fuel-cell powerplants. The variety of automobile power plants currently available in the marketplace is unprecedented in the modern history of the automobile. The technology that wins the contest for dominance of the automobile power plant market will have profound effects on the automobile industry, transportation infrastructure, and the environment.

Economic globalization is another trend that is dramatically changing the way in which entire industries design, market, and distribute their goods. Economic globalization has far-reaching and uncertain effects on economic growth, resource use, environmental impacts of industrial production, and the structure of community. As a result, the debate about the economic, environmental, and social effects of globalization has grown loud and strident in recent years.[13] Whether globalization is, in sum, good or bad is unclear, but what is clear is that it is continuing apace and rapidly changing the face of the world's industries.

The changes that globalization brings to industries create opportunities for innovation. Although it is impossible without further study to identify and verify the opportunities for green technology innovation created by globalization, some possibilities present themselves.

One possibility is that economic globalization will help diffuse green technology innovations from more-developed to less-developed countries that in the past have not been able to afford the luxury of investing in environmental technologies. Because firms want to have a degree of uniformity in the products they sell around the world to benefit from returns to scale, there is an opportunity to "green" industries around the world through the innovation efforts of more developed countries. If innovation in developed countries results in green technologies that are cost-competitive, they will quickly spread around the world through globalized firms. Somewhat less cost-competitive technologies will also diffuse if firms benefit sufficiently from standardization and these technologies are required in the more developed countries. Therefore, through economic globalization, green technology innovation policy may be able to help control the large and rapidly growing sources of industrial pollution in the less-developed countries.

On a local scale, many of the major pieces of U.S. environmental legislation are now facing reauthorization in Congress. In light of the many critiques of how measures such as the CAA and the Clean Water Act create barriers to green technology innovation, reauthorization presents an opportunity to make important reforms. I have argued in this article that there is still a great deal that is unknown about how to design policy to promote green technology innovation. In addition, the effect of environmental regulation on innovation is highly sensitive to context and details of implementation. These conclusions suggest that policy makers should expand the use of local policy measures as carefully monitored policy experiments. The more successful mechanisms can be transferred to other regional programs or applied at the federal level if appropriate.[14]

SUMMARY

The questionable ability of the natural system to absorb wastes produced by the steadily increasing world population and economic growth has led to calls for a sustainable form of industry based on green technology. Developing such technology will require radical technological innovation throughout industry. The management of green technology innovation requires an understanding of technology, the dynamic process of innovation, and the innovation behavior of firms.

Thus far, there has been little empirical study of green technology innovation in the private sector. It is likely that the process of green technology innovation in industry will differ from innovation of technology in general because environmental objectives often lie outside the traditional economic objectives of the firm. In addition, green technology development involves large uncertainties because of the highly regulated and political nature of environmental issues and our poor understanding of environmental processes. Because uncertainty increases the hurdle rate at which a risk-neutral firm is willing to invest and because firms tend to be risk seeking in the realm of losses, such as is associated with environmental costs, the process of green technology innovation is likely to be quite different from that of other types of technology. More empirical study of the process of green technology innovation in private industry is needed to inform and support policy prescriptions intended to promote green innovation.

Guidelines for crafting green technology policy are now starting to emerge from our experiences with different regulatory instruments. A review of the effects of different policy mechanisms suggests that the choice of the mechanism will frequently have less influence on the prospects for promoting green technology innovation than the details of how the mechanism is implemented and the context in which it is employed. However, two characteristics that appear to encourage innovation regardless of the instrument used are the existence or credible threat of stringent regulation and flexible implementation that facilitates industry-government cooperation.

Our limited understanding of the process of green technology innovation in the private sector and the highly context-dependent nature of policy's impact on innovation support the expanded use of local policy measures as policy experiments. Regional and sectoral policy measures will be more responsive to local characteristics of green technology innovation processes, and the more policy experiments that we perform, the more we will learn about green technology innovation and how it can best be managed.

Finally, it appears that we are approaching a time of great technological change and of environmental crisis. These phenomena create both the opportunities and the need to move industrial technology trajectories in a less-polluting and more efficient direction. If technologies are chosen without careful long-term assessment of future scenarios, we may lock ourselves into undesirable technological and social arrangements. Conversely, if we carefully design public policy to foster innovation in targeted technology areas, desirable, clean technologies will be available when the time comes to make changes, and our markets and social structures will be able to adapt efficiently.

NOTES

1. Pollution prevention and ecoefficiency are both primarily concerned with modifying production methods to eliminate the production of pollution, with ecoefficiency also stressing economic efficiency. Product stewardship adds consideration of the environmental impact of products during use and as postconsumer waste. Design for Environment (DFE) takes a full life-cycle perspective, including environmental impacts from resource extraction to disposal or reuse. Design for and

within society (DFS) adds to DFE a particular emphasis on the role of social norms and behavior in the environmental impacts of our use of artifacts. Industrial ecology has many definitions but is often described to include all of the other concepts listed here.

2. This distinction is now customary in the innovation literature. It appears as early as the work of Australian economist Joseph Schumpeter (1939).

3. Ettlie, Bridges, and O'Keefe (1984) found that very different types of social contexts facilitate incremental and radical innovation. Nord and Tucker (1987) found that incremental innovation tends to take place within existing organizational structures but that radical innovation tends to yield new organizational forms.

4. This argument views benefit to society in the sense of a potential Pareto optimum, that is, the case where the net benefit to society is positive, but that benefit is not necessarily distributed such that each individual is better off. This market failure argument can be found in Branscomb (1997, p. 42) and Rothwell and Zegveld (1981, p. 49), among others.

5. For a comprehensive summary of the literature on the process of technological innovation, see Tornatzky and Fleischer (1990).

6. The results of many studies of industry concentration as a predictor of R&D intensity are inconclusive. It is more likely that concentration mediates the effects of appropriability in predicting innovation effort. For a discussion of this, see Tornatzky and Fleischer (1990, p. 89).

7. Technology innovation is said to exhibit "natural" trajectories that are the result of previous developments as well as management, market, and social forces (Arthur, 1988; Kemp, 1994).

8. For discussions of the importance of social networks in the technological innovation and diffusion processes, see Grübler (1996), Fountain (1998), and Clarke (1998).

9. The effectiveness of economic incentives versus direct regulation has been the subject of a great deal of economic analysis. See Freeman (1990, pp. 155-164); Wallace (1995, pp. 19-22); Jung, Krutilla, and Boyd (1996); and Dosi and Moretto (1997).

10. Oliver (1991) has developed a typology of firm strategic responses to institutional processes and identifies 10 institutional factors that are hypothesized to predict the occurrence of the alternative strategies and degree of institutional conformity or resistance to institutional pressures.

11. The successes and failures of Project XL and the Common Sense Initiative have been analyzed by Davies and Mazurek (1996); Susskind, Secunda, and Krockmalnic (1997); and Heaton and Banks (1998), with particular attention paid to the role of implementation in these outcomes.

12. The 405.2 gigawatts of new electric power generation capacity represent 54.14% of 1996 capacity, of which 138.8 gigawatts (18.56% of 1996 capacity) will be replacing retired capacity. See Energy Information Administration (1998).

13. For a summary of the debate about the effects of economic globalization and a broad sampling of published work, see Gladwin (1998).

14. The Environmental Protection Agency has been using some regional environmental programs as policy experiments (e.g., the Merit Partnership for Pollution Prevention in Region 9). See Buelow and Jacques (1996) and Asmus (1998).

REFERENCES

Abernathy, W., & Utterback, J. M. (1978). Patterns of industrial innovation. *Technology Review, 80*, 40-47.

Andrews, C. (1994). Policies to encourage clean technology. In R. Socolow, C. Andrews, F. Berkhout, & V. Thomas (Eds.), *Industrial ecology and global change* (pp. 405-422). Cambridge: MIT Press.

Arthur, W. B. (1988). Competing technologies: An overview. In G. Dosi, C. Freeman, R. Nelson, G. Silverberg, & L. Soete (Eds.), *Technical change and economic theory* (pp. 590-607). London: Pinter.

Ashford, N. A. (1993). Understanding technological responses of industrial firms to environmental problems: Implications for government policy. In K. Fischer & J. Shot (Eds.), *Environmental strategies for industry: International perspectives on research needs and policy implications* (pp. 277-307). Washington, DC: Island Press.

Asmus, P. (1998). The greening of corporate California. *California Journal, 29*(9), 18-22.

Banks, R. D., & Heaton, G.R.J. (1995). An innovation-driven environmental policy. *Issues in Science and Technology, 12*(1), 43-51.

Branscomb, L. M. (1997). From technology politics to technology policy. *Issues in Science and Technology, 13*(3), 41-48.

Bryner, G. C. (1993). *Blue skies, green politics: The Clean Air Act of 1990*. Washington, DC: Congressional Quarterly.

Buelow, C., & Jacques, M. A. (1996). *Characteristics of innovative state pollution prevention programs and their potential application to EPA programs*. Durham, NC: Duke University, Nicholas School of the Environment.

Burtraw, D. (1996). The SO_2 emissions trading program: Cost savings without allowance trades. *Contemporary Economic Policy, 14*(2), 79-93.

Burtraw, D., Krupnick, A., & Farrell, D. (1998). Costs and benefits of reducing air pollutants related to acid rain. *Contemporary Economic Policy, 16*(4), 379-396.

Campbell, C. J., & Laherrère, J. H. (1998, March). The end of cheap oil. *Scientific American*, pp. 78-83.

Clarke, S. F. (1998). Sustainable technology management: The role of networks of learning. In N. Roome (Ed.), *Sustainability strategies for industry* (pp. 145-167). Washington, DC: Island Press.

Cramer, J., & Zegveld, W.C.L. (1991). The future role of technology in environmental management. *Futures, 23*(5), 451-468.

Dalpé, R. (1994). Effects of government procurement on industrial innovation. *Technology in Society, 16*(1), 65-83.

Davies, J. C., & Mazurek, J. (1996). *Industry incentives for environmental improvement: Evaluation of U.S. federal initiatives*. Washington, DC: Resources for the Future, Global Environmental Management Initiative.

Dixit, A. K., & Pindyck, R. S. (1994). *Investment under uncertainty*. Princeton, NJ: Princeton University Press.

Dosi, C., & Moretto, M. (1997). Pollution accumulation and firm incentives to accelerate technological change under uncertain private benefits. *Environmental and Resource Economics, 10*(3), 285-299.

Energy Information Administration. (1998). *Annual energy outlook 1998* (DOE/EIA-0383[98]). Washington, DC: U.S. Department of Energy, Office of Integrated Analysis and Forecasting.

Environmental Protection Agency. (1992). *Total cost assessment: Accelerating industrial pollution prevention through innovative project financial analysis* (EPA 741-R-92-002). Washington, DC: Author, Office of Pollution Prevention and Toxics.

Environmental Protection Agency. (1996). *Valuing potential environmental liabilities for managerial decision-making: A review of techniques* (EPA 742-R-96-003). Washington, DC: Author, Office of Pollution Prevention and Toxics.

Ettlie, J. E., Bridges, W. P., & O'Keefe, R. D. (1984). Organizational strategy and structural differences for radical versus incremental innovation. *Management Science, 30*, 682-695.

Fountain, J. E. (1998). Social capital: The key enabler of innovation. In L. M. Branscomb & J. H. Keller (Eds.), *Investing in innovation* (pp. 85-111). Cambridge: MIT Press.

Freeman, A. M. (1990). Economics, incentives, and environmental regulation. In N. J. Vig & M. E. Kraft (Eds.), *Environmental policy in the 1990s* (pp. 203-228). Washington, DC: Congressional Quarterly.

Frosch, R. A. (1996). Toward the end of waste: Reflections on a new ecology of industry. *Daedalus, Proceedings of the American Academy of Arts and Sciences, 125*(3), 199-212.

Gladwin, T. N. (1998). Economic globalization and ecological sustainability: Searching for truth and reconciliation. In N. J. Roome (Ed.), *Sustainability strategies for industry: The future of corporate practice* (pp. 27-54). Washington, DC: Island Press.

Gort, M., & Wall, R. A. (1986). The evolution of technologies and investment in innovation. *Economic Journal, 96*, 741-757.

Grübler, A. (1996). Time for a change: On the patterns of diffusion of innovation. *Daedalus, Proceedings of the American Academy of Arts and Sciences, 125*(3), 19-42.

Hamilton, J. T. (1995). Pollution as news: Media and stock market reactions to the toxics release data. *Journal of Environmental Economics and Management, 28*(1), 98-113.

Heaton, G. R., & Banks, R. D. (1998). Toward a new generation of environmental technology. In L. M. Branscomb & J. H. Keller (Eds.), *Investing in innovation* (pp. 276-298). Cambridge: MIT Press.

Ide, R. W. (1998). The role of the justice system in the product liability debate. In J. R. Hunziker & T. O. Jones (Eds.), *Product liability and innovation: Managing risk in an uncertain environment*. Washington, DC: National Academy Press.

Jung, C., Krutilla, K., & Boyd, R. (1996). Incentives for advanced pollution abatement technology at the industry level: An evaluation of policy alternatives. *Journal of Environmental Economics and Management, 30*(1), 95-111.

Kemp, R. (1994). Technology and the transition to environmental sustainability: The problem of technological regime shifts. *Futures, 26*(10), 1023-1046.

Kerr, R. A. (1998). The next oil crisis looms large—and perhaps close. *Science, 281*, 1128-1131.

Khanna, M., Quimio, W., & Bojilova, D. (1998). Toxics release information: A policy tool for environmental protection. *Journal of Environmental Economics and Management, 36*(2), 243-266.

Konar, S., & Cohen, M. A. (1997). Information as regulation: The effect of community right to know laws on toxic emissions. *Journal of Environmental Economics and Management, 32*(1), 109-124.

Lindblom, C. E. (1959). The science of "muddling through." *Public Administration Review, 19*(1), 79-88.

Lindblom, C. E. (1979). Still muddling, not yet through. *Public Administration Review, 39*(8), 517-526.

Malueg, D. A. (1989). Emission credit trading and the incentive to adopt new pollution abatement technology. *Journal of Environmental Economics and Management, 16*(1), 52-57.

Milliman, S. R., & Prince, R. J. (1989). Firm incentives to promote technological change in pollution control. *Journal of Environmental Economics and Management, 17*(2), 247-265.

Morrow, R. M. (1998). Technology issues and product liability. In J. R. Hunziker & T. O. Jones (Eds.), *Product liability and innovation: Managing risk in an uncertain environment* (pp. 23-29). Washington, DC: National Academy Press.

Mowery, D., & Rosenberg, N. (1982). The commercial aircraft industry. In R. R. Nelson (Ed.), *Government and technical progress: A cross-industry analysis* (pp. 101-161). New York: Pergamon.

Nelson, R. R. (1996). *The sources of economic growth*. Cambridge, MA: Harvard University Press.

Newell, R. G., & Jaffe, A. B. (1996). *Environmental policy and technological change: The effect of economic incentives and direct regulation on energy-saving innovation*. Cambridge, MA: Harvard University, Kennedy School of Government.

Norberg-Bohm, V. (1997). *Stimulating "green" technological innovation: An analysis of alternative policy mechanisms* (Working Paper ETP97-01). Cambridge: MIT, Environmental Technology and Public Policy Program.

Nord, W. R., & Tucker, S. (1987). *Implementing routine and radical innovations*. Lexington, MA: Lexington Books.

Nordhaus, W. (1969). *Invention growth and welfare*. Cambridge: MIT Press.

Oliver, C. (1991). Strategic responses to institutional processes. *Academy of Management Review, 16*(1), 145-179.

Palmer, K. L., & Simpson, R. D. (1993). Environmental policy as industrial policy. In *Resources* (No. 112). Washington, DC: Resources for the Future.

Pavitt, K. (1984). Sectoral patterns of technical change: Towards a taxonomy and a theory. *Research Policy, 13*(6), 343-373.

Rothwell, R., & Zegveld, W. (1981). *Industrial innovation and public policy.* Westport CT: Greenwood.

Scherer, F. M. (1982). Demand-pull and technological invention: Schmookler revisited. *Journal of Industrial Economics, 30*(3), 225-237.

Schmalensee, R., Joskow, P. L., Ellerman, A. D., Montero, J. P., & Bailey, E. M. (1998). SO^2 trading—An interim evaluation of sulfur dioxide emissions trading. *Journal of Economic Perspectives, 12*(3), 53-62.

Schmidheiny, S. (1992). *Changing course: A global business perspective on development and the environment.* Cambridge: MIT Press.

Schumpeter, J. A. (1939). *Business cycles, a theoretical, historical, and statistical analysis of the capitalist process* (Vols. 1-2). New York: McGraw-Hill.

Segerson, K., & Miceli, T. J. (1998). Voluntary environmental agreements: Good or bad news for environmental protection? *Journal of Environmental Economics and Management, 36*(1), 109-130.

Starling, G. (1988). *Strategies for policy making.* Chicago: Dorsey.

Stoneman, P. (1979). Patenting activity: A re-evaluation of the influence of demand pressures. *Journal of Industrial Economics, 27*(4), 385-401.

Susskind, L., Secunda, J., & Krockmalnic, G. (1997). *The risks and advantages of agency discretion: Evidence from EPA's Project XL* (Working Paper ETP97-02). Cambridge: MIT, Environmental Technology and Public Policy Program.

Tornatzky, L. G., & Fleischer, M. (1990). *The process of technological innovation.* Lexington, MA: Lexington Books.

Tversky, A., & Kahneman, D. (1992). Advances in prospect theory: Cumulative representation of uncertainty. *Journal of Risk and Uncertainty, 5*(4), 297-323.

Utterback, J. M. (1987). Innovation and industrial evolution in manufacturing industries. In B. R. Guiles & H. Brooks (Eds.), *Technology and global industry: Companies and nations in the world economy* (pp. 16-48). Washington, DC: National Academy Press.

Von Hippel, E. (1988). *The source of innovation.* Oxford, UK: Oxford University Press.

Wallace, D. (1995). *Environmental policy and industrial innovation.* London: Earthscan.