Chapter 11

TECHNOLOGICAL CHANGE AND THE ENVIRONMENT

ADAM B. JAFFE

Department of Economics, Brandeis University and
National Bureau of Economic Research, Waltham, MA 02454-9110, USA

RICHARD G. NEWELL

Resources for the Future, Washington, DC 20036, USA

ROBERT N. STAVINS

John F. Kennedy School of Government, Harvard University, Cambridge, MA 02138, USA and
Resources for the Future, Washington, DC 20036, USA

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Abstract

Environmental policy discussions increasingly focus on issues related to technological change. This is partly because the environmental consequences of social activity are frequently affected by the rate and direction of technological change, and partly because environmental policy interventions can themselves create constraints and incentives that have significant effects on the path of technological progress. This chapter summarizes current thinking on technological change in the broader economics literature, surveys the growing economic literature on the interaction between technology and the environment, and explores the normative implications of these analyses. We begin with a brief overview of the economics of technological change, and then examine theory and empirical evidence on invention, innovation, and diffusion and the related literature on the effects of environmental policy on the creation of new, environmentally friendly technology. We conclude with suggestions for further research on technological change and the environment.

Keywords

technological change, induced innovation, environmental policy, invention, diffusion

JEL classification: D24, D83, O14, O3, Q25, Q28, Q4

1. Introduction

In the last decade, discussions of environmental economics and policy have become increasingly permeated by issues related to technological change. An understanding of the process of technological change is important for two broad reasons. First, the environmental impact of social and economic activity is profoundly affected by the rate and direction of technological change. New technologies may create or facilitate increased pollution, or may mitigate or replace existing polluting activities. Further, because many environmental problems and policy responses thereto are evaluated over time horizons of decades or centuries, the cumulative impact of technological changes is likely to be large. Indeed, uncertainty about the future rate and direction of technological change is often an important sensitivity in "baseline" forecasts of the severity of environmental problems. In global climate change modeling, for example, different assumptions about autonomous improvements in energy efficiency are often the single largest source of difference among predictions of the cost of achieving given policy objectives [Weyant (1993), Energy Modeling Forum (1996)].

Second, environmental policy interventions themselves create new constraints and incentives that affect the process of technological change. These induced effects of environmental policy on technology may have substantial implications for the normative analysis of policy decisions. They may have quantitatively important consequences in the context of cost-benefit or cost-effectiveness analyses of such policies. They may also have broader implications for welfare analyses, because the process of technological change is characterized by externalities and market failures with important welfare consequences beyond those associated with environmental issues.

Our goals in this chapter are to summarize for environmental economists current thinking on technological change in the broader economics literature; to survey the growing literature on the interaction between technology and the environment; and to explore the normative implications of these analyses. This is a large task, inevitably requiring unfortunate but necessary omissions. In particular, we confine ourselves to the relationship between technology and problems of environmental pollution, leaving aside a large literature on technological change in agriculture and natural resources more broadly.[1] Because of the significant environmental implications of fossil fuel combustion, we include in our review some of the relevant literature on technological change and energy use.[2]

Section 2 provides a brief overview of the general literature on the economics of technological change. It is intended less as a true survey than as a checklist of issues

[1] See the recent surveys by Sunding and Zilberman (2000) and Ruttan (2000).

[2] Because our focus is *technological* change, we also exclude the growing literature on political and policy innovation and the evolution of social norms. See Chapters 8 ("The Political Economy of Environmental Policy") and 3 ("Property Rights, Public Goods, and the Environment").

that the interested reader can use to find entry points into the literature.[3] Section 3 discusses invention and innovation, including the idea of "induced innovation" whereby environmental policy can stimulate the creation of new environmentally friendly technology. Section 4 focuses on issues related to technology diffusion. Section 5 provides concluding observations and suggestions for future research.

2. Fundamental concepts in the economics of technological change

The literature pertaining to the economics of technological change is large and diverse. Major sub-areas (with references to surveys related to those areas) include: the theory of incentives for research and development [Tirole (1988), Reinganum (1989), Geroski (1995)]; the measurement of innovative inputs and outputs [Griliches (1984, 1998)]; analysis and measurement of externalities resulting from the research process [Griliches (1992), Jaffe (1998a)]; the measurement and analysis of productivity growth [Jorgenson (1990), Griliches (1998), Jorgenson and Stiroh (2000)]; diffusion of new technology [Karshenas and Stoneman (1995), Geroski (2000)]; the effect of market structure on innovation [Scherer (1986), Sutton (1998)]; market failures related to innovation and appropriate policy responses [Martin and Scott (2000)]; the economic effects of publicly funded research [David, Hall and Toole (2000)]; the economic effects of the patent system [Jaffe (2000)]; and the role of technological change in endogenous macroeconomic growth [Romer (1994), Grossman and Helpman (1994)]. In this section, we present a selective overview designed to provide entry points into this large literature.

2.1. Schumpeter and the gale of creative destruction

The modern theory of the process of technological change can be traced to the ideas of Josef Schumpeter (1942), who saw innovation as the hallmark of the modern capitalist system. Entrepreneurs, enticed by the vision of the temporary market power that a successful new product or process could offer, continually introduce such products. They may enjoy excess profits for some period of time, until they are displaced by subsequent successful innovators, in a continuing process that Schumpeter called "creative destruction".

Schumpeter distinguished three steps or stages in the process by which a new, superior technology permeates the marketplace. *Invention* constitutes the first development of a scientifically or technically new product or process.[4] Inventions may be patented,

[3] For surveys of other aspects of the economics of technological change, see Solow (1999) on neoclassical growth theory, Grossman and Helpman (1995) on technology and trade, Evenson (1995) on technology and development, and Reinganum (1989) on industrial organization theory of innovation and diffusion.

[4] The Schumpeterian "trichotomy" focuses on the commercial aspects of technological change. As discussed in Section 3.1.2 below, the public sector also plays an important role. In addition, a non-trivial amount of basic research – which one might think of as prior even to the invention stage – is carried out by private firms [Rosenberg (1990)].

though many are not. Either way, most inventions never actually develop into an *innovation*, which is accomplished only when the new product or process is commercialized, that is, made available on the market.[5] A firm can innovate without ever inventing, if it identifies a previously existing technical idea that was never commercialized, and brings a product or process based on that idea to market. The invention and innovation stages are carried out primarily in private firms through a process that is broadly characterized as "research and development" (R&D). [6] Finally, a successful innovation gradually comes to be widely available for use in relevant applications through adoption by firms or individuals, a process labeled *diffusion*. The cumulative economic or environmental impact of new technology results from all three of these stages,[7] which we refer to collectively as the process of technological change.

2.2. Production functions, productivity growth, and biased technological change

The measurement of the rate and direction of technological change rests fundamentally on the concept of the transformation function,

$$T(Y, I, t) \leqslant 0, \tag{1}$$

where Y represents a vector of outputs, I represents a vector of inputs, and t is time. Equation (1) describes a production possibility frontier, that is, a set of combinations of inputs and outputs that are technically feasible at a point in time. Technological change is represented by movement of this frontier that makes it possible over time to use given input vectors to produce output vectors that were not previously feasible.

[5] More precisely, an invention may form the basis of a *technological* innovation. Economically important innovations need not be based on new technology, but can be new organizational or managerial forms, new marketing methods, and so forth. In this chapter, we use the word *innovation* as short-hand for the more precise *technological innovation*.

[6] Data regarding R&D expenditures of firms are available from the financial statements of publicly traded firms, if the expenditure is deemed "material" by the firm's auditors, or if the firm chooses for strategic reasons to report the expenditure [Bound et al. (1984)]. In the United States, the government carries out a "census" of R&D activity, and reports totals for broad industry groups [National Science Board (1998)]. Many industrialized countries now collect similar statistics, which are available through the Organization of Economic Cooperation and Development [OECD (2000)].

[7] Typically, for there to be environmental impacts of a new technology, a fourth step is required – utilization, but that is not part of the process of technological change *per se*. Thus, for example, a new type of hybrid motor vehicle engine might be *invented*, which emits fewer pollutants per mile; the same or another firm might commercialize this engine and place the *innovation* in new cars available for purchase on the market; individuals might purchase (or adopt) these cars, leading to *diffusion* of the new technology; and finally, by driving these cars instead of others (*utilization*), aggregate pollutant emissions might be reduced. Conversely, if higher efficiency and the resulting reduced marginal cost causes users to increase utilization, then the emissions reduction associated with higher efficiency may be partially or totally offset by higher utilization.

In most applications, separability and aggregation assumptions are made that make it possible to represent the economy's production technology with a production function,

$$Y = f(K, L, E; t), \tag{2}$$

where Y is now a scalar measure of aggregate output (for example, gross domestic product), and the list of inputs on the right-hand side of the production function can be made arbitrarily long. For illustrative purposes, we conceive of output as being made from a single composite of capital goods, K, a single composite of labor inputs, L, and a single composite of environmental inputs, E (for example, waste assimilation). Again, technological change means that the relationship between these inputs and possible output levels changes over time.

Logarithmic differentiation of Equation (2) with respect to time yields

$$y_t = A_t + \beta_{Lt} l_t + \beta_{Kt} k_t + \beta_{Et} e_t, \tag{3}$$

in which lower case letters represent the percentage growth rates of the corresponding upper case variable; the β's represent the corresponding logarithmic partial derivatives from Equation (2); and the t indicate that all quantities and parameters may change over time.[8] The term A_t corresponds to "neutral" technological change, in the sense that it represents the rate of growth of output if the growth rates of all inputs were zero. But the possibility that the β's can change over time allows for "biased" technological change, that is, changes over time in *relative* productivity of the various inputs.

Equations (2) and (3) are most easily interpreted in the case of process innovation, in which firms figure out more efficient ways to make existing products, allowing output to grow at a rate faster than inputs are growing. In principle, these equations also apply to product innovation. Y is a composite or aggregate output measure, in which the distinct outputs of the economy are each weighted by their relative value, as measured by their market price. Improved products will typically sell at a price premium, relative to lower quality products, meaning that their introduction will increase measured output even if the physical quantity of the new goods does not exceed the physical quantity of the old goods they replaced. In practice, however, product improvement will be included in measured productivity only to the extent that the price indices used to convert nominal GDP or other nominal output measures to real output measures are purged of the effects of product innovation. In general, official price indices and the corresponding real output measures achieve this objective only to a limited extent.

On its face, Equation (3) says nothing about the *source* of the productivity improvement associated with the neutral technological change term, A_t. If, however, all inputs and outputs are properly measured, and inputs (including R&D) yield only normal investment returns, then all endogenous contributions to output should be captured by

[8] This formulation can be considered a first-order approximation to an arbitrary functional form for Equation (2). Higher-order approximations can also be implemented.

returns to inputs, and there should be no "residual" difference between the weighted growth rates of inputs and the growth rate of output. The observation that the residual has been typically positive is therefore interpreted as evidence of some source of exogenous technological change.[9]

There is now a large literature on the measurement and explanation of the productivity residual. There are two basic approaches to the measurement of productivity. The "growth accounting" approach relies on neoclassical production theory under constant returns to scale for the proposition that the β's in Equation (3) are equal to the corresponding factor shares, and thereby calculates the A_t as an *arithmetic* residual after share-weighted input growth rates are subtracted from the growth rate of output [Denison (1979), U.S. Bureau of Labor Statistics (2000)]. The "econometric" approach estimates the parameters of Equation (3) from time series data and infers the magnitude of A_t as an *econometric* residual after the estimated effects of all measurable inputs on output have been allowed for [Jorgenson and Griliches (1967), Jorgenson and Stiroh (2000)]. In both of these approaches, much attention has focused on the difficulties of appropriately measuring both inputs and outputs [Jorgenson and Griliches (1967), Griliches (1994)]. This issue can be particularly problematic for the measurement of natural capital stocks, which can lead to bias in the productivity residual if they are ignored or mismeasured [see Dasgupta and Mäler (2000) and the chapter "National Income Accounts and the Environment" in this volume)]. A particular focus has been understanding the slowdown in productivity growth in the 1970s and 1980s relative to the earlier postwar period, including the role played by rising energy prices in that slowdown [Berndt and Wood (1986), Jorgenson (1984)].

In many contexts, it is difficult to distinguish the effects of innovation and diffusion. We observe improvements in productivity (or other measures of performance) but do not have the underlying information necessary to separate such improvements into movements of the production frontier and movements of existing firms towards the frontier. A related issue, and one that is often significant for environment-related technological change, is that innovation can be undertaken either by the manufacturers or the users of industrial equipment. In the former case, the innovation must typically be *embodied* in new capital goods, and must then diffuse through the population of users via the purchase of these goods, in order to affect productivity or environmental performance. In the latter case, the innovation may take the form of changes in practices that are implemented with existing equipment. Alternatively, firms may develop new equipment for their own use, which they then may or may not undertake to sell to other firms. The fact that the locus of activity generating environment-related technological change can

[9] Fabricant (1954) was the first to observe that the growth of conventional inputs explained little of the observed growth in output in the twentieth century. This observation was elaborated by Abramowitz (1956), Kendrick (1956) and Solow (1957). The early writers were clear that the large "residual" of unexplained growth was "a measure of our ignorance" [Abramowitz (1956)] rather than a meaningful measure of the rate of technological progress. See Solow (1999) for a survey of neoclassical growth theory.

be supplying firms, using firms, or both, has important consequences for modeling the interaction of technological change and environmental policy.

The embodiment of new technology in new capital goods creates an ambiguity regarding the role played by technology *diffusion* with respect to Equations (2) and (3). One interpretation is that these equations represent "best practice," that is, what the economy would produce if all innovations made to date had fully diffused. In this interpretation, innovation would drive technological change captured in Equation (3); the issue of diffusion would then arise in the form of the presence of firms producing at points inside the production possibility frontier. Frontier estimation techniques [Aigner and Schmidt (1980)] or data envelopment methods [Fare, Grosskopf and Lovell (1994)] would be needed to measure the extent to which such sub-frontier behavior is occurring.[10] Alternatively, one can assume that the users of older equipment make optimal, informed decisions regarding when to scrap old machines and purchase newer ones that embody better technology. In this formulation, observed movements of the frontier – measured technological change – comprise the combined impacts of the invention, innovation and diffusion processes.

2.3. Technological change and endogenous economic growth

In the last two decades there has emerged a large macroeconomic literature that builds on the above concepts to produce models of overall economic growth based on technological change [Romer (1990, 1994), Grossman and Helpman (1994), Solow (2000)]. In these models, R&D is an *endogenous* equilibrium response to Schumpeterian profit incentives. Spillovers associated with this R&D generate a form of dynamic increasing returns, which allows an economy endogenously investing in R&D to grow indefinitely.[11] This stands in contrast to the older neoclassical growth model, in which *exogenous* technological change, in the presence of decreasing returns to investment in physical capital, typically yields an economy that tends towards a steady state in which income per capita does not grow.[12]

Endogenous growth theory has played an important role in re-introducing technological change – and the associated policy issues deriving from R&D market failures

[10] Boyd and McClelland (1999) and Boyd and Pang (2000) employ data envelopment analysis to evaluate the potential for improvements at paper and glass plants that increase productivity and reduce pollution.

[11] It is also possible to generate such endogenous growth through human capital investment [Lucas (1988)].

[12] Thus, in the literature, "endogenous technological change" and "induced technological change" refer to different concepts, even though the opposite of each is often described by the same phrase, that is, exogenous technological change. Endogenous technological change refers to the broad concept that technological change is the result of activities within the economic system, which are presumed to respond to the economic incentives of the system. Induced technological change refers to the more specific idea that changes in relative factor prices affect the rate and direction of innovation. In practice, papers that use the phrase "endogenous technological change" tend to focus on aggregate R&D expenditure and neutral technological change. Papers that used the phrase "induced technological change" or "induced innovation" tend to focus on the direction of R&D efforts and biases in technological change.

– into discussions about economic growth.[13] Modeling growth as a process driven by the endogenous creation and diffusion of new technology ought to have implications for important environmental issues such as sustainable development and global climate change. Its policy utility has been limited, however, by its relative lack of empirical foundation, and by the difficulty of linking the macroeconomic endogenous growth models to the microeconomic foundations of technological innovation and diffusion [Caballero and Jaffe (1993), Aghion and Howitt (1998)]. This remains an important area for future research.

3. Invention and innovation

As discussed in the introduction, if the imposition of environmental requirements can stimulate invention and innovation that reduces the (static) cost of complying with those requirements, this has profound implications for both the setting of environmental policy goals and the choice of policy instruments. Nonetheless, there has been some tendency to treat technology as a "black box" [Rosenberg (1982)]. For example, the production function/productivity growth paradigm described in Section 2 says little about what generates technological change. But following Schumpeter, there has been a line of theoretical and empirical analysis that has cast invention and innovation as a purposive economic activity, and has attempted to discern its determinants and effects. Milestones in this line of research are: Schmookler (1966), Mansfield (1968), Rosenberg (1982), Griliches (1984), Nelson and Winter (1982) and Scherer (1986).[14]

It is useful to identify two major strands of thought regarding the determinants of innovative activity. We call these two broad categories of modeling approaches the "induced innovation" approach and the "evolutionary" approach.[15] We now describe the induced innovation approach, while the evolutionary approach is discussed in Section 3.4.

3.1. The induced innovation approach

3.1.1. Neoclassical induced innovation

The recognition that R&D is a profit-motivated investment activity leads to the hypothesis that the rate and direction of innovation are likely to respond to changes in relative prices. Since environmental policy implicitly or explicitly makes environmental inputs

[13] See, for example, Jones and Williams (1998), and the symposium on "New Growth Theory" in the Winter 1994 issue of the *Journal of Economic Perspectives*.

[14] See also the survey by Thirtle and Ruttan (1987).

[15] In this section and Section 4, we focus separately on induced innovation and the economic forces driving diffusion. As noted above, however, the analytical distinction between innovation and diffusion is blurred in practice.

more expensive, the "induced innovation" hypothesis suggests an important pathway for the interaction of environmental policy and technology, and for the introduction of impacts on technological change as a criterion for evaluation of different policy instruments.

The induced-innovation hypothesis was first articulated by Sir John Hicks:

> "a change in the relative prices of the factors of production is itself a spur to invention, and to invention of a particular kind – directed to economizing the use of a factor which has become relatively expensive" [Hicks (1932, p. 124)].[16]

Analysis of this hypothesis has a long and somewhat tortured history in economics. Early empirical work was largely confined to aggregate data, and focused primarily on questions such as whether historical cross-country differences in wage levels could explain the location of development of labor-saving inventions [Thirtle and Ruttan (1987)].

Hicks did not link the induced-innovation hypothesis in a formal way to the research process, or to profit-maximizing R&D decisions by firms. This link was formalized in the 1960s by Ahmad (1966) and Kamien and Schwartz (1968), and developed further by Binswanger (1974). Binswanger and Ruttan (1978) summarize this literature. The general approach is to postulate a "meta" production function according to which investing in R&D changes the parameters of a production function such as Equation (2). Unfortunately, theoretical conclusions regarding the induced affect of changes in factor prices on the parameters of the production function are sensitive to the specification of the "meta" production function governing the research process.

Although formulated in terms of the R&D decisions of firms, this theory is nonetheless aggregate, because the result of the research process is change in the parameters of the aggregate production function. That is, "labor-saving" innovation in these models means a change in the parameters of Equation (2) that results in less labor being used. The model abstracts entirely from what kinds of new machines or processes might be yielding these changes. Further, because of the ambiguity described in Section 2.2 as to whether the production frontier does or does not encompass technology diffusion, there is really no distinction in these models between induced *innovation* and the effect of factor prices on the rate of technology *diffusion*.

A natural way to move the modeling of induced innovation to the microeconomic level is to recognize that factor-saving technological change comes about largely through the introduction of new capital goods that embody different input ratios. These input ratios can then be thought of as attributes or characteristics of the capital goods in the sense of Lancaster (1971). Thirtle and Ruttan (1987) provided a review of the non-environmental literature on induced innovation. Much of this work is in the agricultural

[16] Writing before Schumpeter, Hicks does not appear to use the word "invention" in the specific sense used by Schumpeter and adopted by later authors. Rather, Hicks uses it in a general sense encompassing both invention and innovation, as used today.

area in which excellent microdata has long provided fertile ground for empirical work on innovation and diffusion.[17] In general, available empirical analyses confirm that factor price changes are associated with factor-saving technological change.

3.1.2. Market failures and policy responses

Within the induced innovation approach, firms undertake an investment activity called "R&D" with the intention of producing profitable new products and processes. Decisions regarding the magnitude and nature of R&D activities are governed by firms' efforts to maximize their value, or, equivalently, to maximize the expected discounted present value of cash flows. In some applications, the output of R&D is explicitly modeled as "knowledge capital", an intangible asset that firms use together with other assets and other inputs to generate revenues.[18]

When viewed as an investment activity, R&D has important characteristics that distinguish it from investment in equipment or other tangible assets. First, although the outcome of any investment is uncertain to some extent, R&D investment appears to be qualitatively different. Not only is the variance of the distribution of expected returns much larger than for other investments, but much or even most of the value may be associated with very low-probability but very high value outcomes [Scherer, Harhoff and Kukies (2000)]. This skewness in the distribution of the outcomes of the research process has important implications for modeling firms' R&D decision making [Scherer and Harhoff (2000)]. In addition, the asset produced by the R&D investment process is specialized, sunk and intangible, so that it cannot be mortgaged or used as collateral. The combination of great uncertainty and intangible outcomes makes financing of research through capital market mechanisms much more difficult than for traditional investment. The difficulty of securing financing for research from outside sources may lead to under-investment in research, particularly for small firms that have less internally generated cash and/or less access to financial markets.

In addition to these financing difficulties, research investment differs from physical investment because the asset produced by the research process – new knowledge about how to make and do things – is difficult to exclude others from using. As first noted in the classic paper by Arrow (1962a), this means that the creator of this asset will typically fail to appropriate all or perhaps most of the social returns it generates. Much of this social return will accrue as "spillovers" to competing firms, to downstream firms that purchase the innovator's products, or to consumers [Griliches (1979, 1992), Jaffe (1986, 1998a)]. This "appropriability problem" is likely to lead to significant underinvestment by private firms in R&D, relative to the social optimum [Spence (1984)].[19]

[17] More recently, the availability of computerized firm-level data on R&D and patents has led to an increase in parallel analyses in the industrial sector.

[18] See Griliches (1979) for the seminal statement of this research approach. An example of a recent application measuring the knowledge capital of firms is Hall, Jaffe and Trajtenberg (2000).

[19] The recognition that the costs and benefits of R&D for the firm are affected by the appropriability problem and financing issues has led to a large literature on the effects of market structure on innovation. In the older

An important special case of the appropriability problem is created by "general purpose technologies" [Bresnahan and Trajtenberg (1995)]. GPTs are technologies that find use in many distinct application sectors within the economy, such as the electric motor, the steam engine, the internal combustion engine and now, the semiconductor and possibly the Internet. The development of such technologies increases the returns to R&D designed to incorporate them into the different applications sectors; development of such applications in turn increases the return to improving the GPT. Because of these dynamic feedback effects, GPTs may be an important factor in economic growth [Helpman (1998)]. The dynamic feedback between a GPT and its applications sectors also creates an important example of "path dependence", discussed in Section 4 below. With respect to the environment, whether the GPTs that drive a particular era are pollution-intensive or pollution-saving may have profound implications for the long-term environmental prognosis.

As a profit-motivated activity, R&D investment decisions are governed by the cost of R&D and its expected return. Theory and evidence suggest that the most important factors affecting the optimal level of R&D are the after-tax cost of R&D [Hall and Van Reenen (2000)], the size of the market [Schmookler (1966)], technological opportunity [Rosenberg (1982)], and appropriability conditions [Jaffe (1988)]. Each of these varies intrinsically across time, markets, and technologies, and also is affected by government policy. In particular, patents and other forms of intellectual property are used by firms to overcome the appropriability problem, although the effect of these institutions on investment in R&D or inventive activity has not been clearly demonstrated empirically [Jaffe (2000), Cohen, Nelson and Walsh (2000)].

As noted above, both the appropriability problem and the possibility of capital market failures in the financing of R&D lead to a presumption that laissez-faire levels of investment in innovation will be too low from a social perspective. There is, however, an offsetting *negative* externality that suggests that private R&D incentives may be *too*

literature, it was argued that both these problems would be overcome more easily by large firms and/or firms operating in concentrated industries characterized by market power. From these observations, it was hypothesized that innovation comes disproportionately from large firms and concentrated industries. This conjecture is known as the "Schumpeterian Hypothesis". After much debate about what the Schumpeterian Hypothesis really means, the volume of evidence seems to show that: (1) much innovation comes from large firms in moderately concentrated industries, if only because much economic activity comes from such firms; (2) truly competitive industries (for example, construction) perform little R&D; (3) beyond minimal size and concentration, there is little evidence of any monotonic relationship between innovation intensity and either size or concentration; and (4) innovation and market structure interact dynamically in a way that is not captured by an alleged causal influence of firm size and market concentration on innovation. For an extensive survey of this literature, see Cohen and Levin (1989). More recently, a large game-theoretic literature related to strategic R&D incentives has emerged [surveyed by Reinganum (1989)]. This literature has two strands. One views R&D or other innovative activities in a context of *continuous competition* in which, for example, marginal R&D investments result in marginal cost reductions or product improvements [for example, Dasgupta and Stiglitz (1980a), Levin and Reiss (1988), Spence (1984)]. The other R&D theory literature focuses on *patent races*, where firms compete to be the first to achieve a specific innovation goal [for example, Dasgupta and Stiglitz (1980b), Reinganum (1982), Fudenberg et al. (1983)].

great. 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. This is analogous to the over-fishing of an open-access fishery by a competitive fishing industry.[20]

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)]. In practice, virtually all industrialized countries engage in policies designed to encourage investment in innovation [Guellec and van Pottelsberghe (2000), Mowery and Rosenberg (1989)]. It is difficult to determine how well these policies do in moving R&D toward optimal levels. There is some evidence that social rates of return remain well above private levels [Griliches (1992), Jones and Williams (1998)], but there is also evidence that R&D subsidies drive up the wages of scientists enough to prevent significant increases in real R&D [Goolsbee (1998)]. This implies that the supply of scientists and engineers is relatively inelastic; whether such inelasticity could hold in the long run remains unresolved.

Policy can try to increase social investment in R&D by engaging in R&D in the public (and/or nonprofit) sector, or by trying to reduce the after-tax cost of R&D for private firms. R&D in the public sector and in universities is an important, though declining component of the overall research effort in the U.S. and other developed nations.[21] The evidence on the effectiveness of public research is mixed, partly because of the difficulty of measuring the output of the basic research process [Jaffe (1998b)], and partially because of the difficulty of determining the extent of complementarity or substitutability between public research investment and private investment [David, Hall and Toole (2000)]. Examples of successful government technology development (as opposed to research) have been particularly few [Cohen and Noll (1991)]. Nonetheless, public R&D may well play a particularly important role with respect to environment-related science and technology, since the external social benefits of environmentally benign technology are unlikely to be fully captured by private innovators.

[20] There is also a dynamic analogue to the tension between spillovers and rent-stealing. Over time, innovation may become cumulatively easier because subsequent inventors "stand on the shoulders" of those who came before; or it may become harder, because the pool of potential inventions is "fished out". In the 1980s, there was considerable interest in the idea that "fishing out" of invention potential may explain the productivity slowdown of the 1970s [Evenson (1991)]. But the surge in patenting and productivity growth rates in the 1990s has led to a fading of the fishing-out idea [Jaffe (2000)].

[21] Research performed in government labs, universities and other non-profit institutions is currently about one-fourth of all research performed in the U.S., versus three-quarters performed in the for-profit sector. In addition, some of the research *performed* by firms is *funded* by public money; altogether, over one-third of all R&D is funded by public sources [National Science Board (1998)]. This estimate excludes the implicit public subsidy for private research represented by the Research and Experimentation Tax Credit.

Government policy affects the after-tax cost of R&D via tax incentives [Hall and Van Reenen (2000)],[22] direct subsidies and grants for research [Klette, Møen and Griliches (2000), Trajtenberg (2000)], and also via educational policies that affect the supply of scientists and engineers [Romer (2000)]. Public policies can affect the market for new technologies via direct government purchase, subsidies for purchase or installation of products incorporating particular technologies, [Stoneman (1987)], and also disincentives against the adoption of competing technologies (pollution fees, for example). Finally, policies can affect the extent to which firms can successfully appropriate the returns to their research, by establishing the institutional environment of patent systems, employment relations, and antitrust or other competition policies.[23]

3.1.3. Empirical evidence on induced innovation in pollution abatment and energy conservation

The greatest challenge in testing the induced innovation hypothesis specifically with respect to environmental inducement is the difficulty of measuring the extent or intensity of inducement across firms or industries [Jaffe et al. (1995)]. Ideally, one would like to look at the relationship between innovation and the shadow price of pollution or environmental inputs. In practice, such shadow prices are not easily observed. Consequently, one must use proxies for this shadow price, such as characteristics of environmental regulations, expenditures on pollution abatement, or prices of polluting inputs (for example, energy). In the following paragraphs, we review, in turn, studies that have used each of these approaches.

There is a large literature on the impact of environmental regulation on productivity and investment.[24] To the extent that regulation inhibits investment and/or slows productivity growth, this can be viewed as indirect evidence suggesting that induced innovation effects are either small or are outweighed by other costs of regulation. Results of this type seem to be industry and methodology dependent. For measuring the characteristics of environmental regulations, studies have used expert judgements about relative regulatory stringency in different states [Gray and Shadbegian (1998)], number of enforcement actions [Gray and Shadbegian (1995)], attainment status with respect to environmental laws and regulations [Greenstone (2002)], and specific regulatory events

[22] The effect of taxation on R&D incentives is theoretically complex. On the one hand, any tax on profits derived from R&D drives a wedge between the before- and after-tax returns and hence discourages R&D investment. On the other hand, returns from R&D are taxed much more lightly than returns from investment in equipment and structures, both because of explicit R&D incentives, and also because R&D can be expensed rather than amortized. Thus *relative* to traditional investment, R&D is strongly tax-preferred.

[23] The primary explicit non-fiscal mechanism for encouraging innovation in industrialized countries is the patent system. Empirical evidence on the impact of patent protection on the rate of innovation is ambiguous. For a survey, see Jaffe (2000).

[24] See, for example, Gollop and Roberts (1983), Kolstad and Turnovsky (1998) and Yaisawarng and Klein (1994).

[Berman and Bui (1998)].[25] For example, Berman and Bui (1998) found significant productivity increases associated with air pollution regulation in the oil refining industry, but Gray and Shadbegian (1998) found that pollution abatement investment "crowds out" productive investment almost entirely in the pulp and paper industry. Greenstone (2002) found overall that air pollution regulation has a statistically significant but very small impact on overall costs, implying a small negative productivity impact.

Lanjouw and Mody (1996) showed a strong association between pollution abatement expenditures and the rate of patenting in related technology fields. Jaffe and Palmer (1997) examined the correlation between pollution expenditures by industry and indicators of innovation more broadly. They found that there is a significant correlation within industries over time between the rate of expenditure on pollution abatement and the level of R&D spending. They did not, however, find evidence of an effect of pollution control expenditure on overall patenting.

Evidence of inducement has also been sought by examining the response to changing energy prices. Newell (1997, Chapter 2) and Newell, Jaffe and Stavins (1999) examined the extent to which the energy efficiency of the menu of home appliances available for sale changed in response to energy prices between 1958 and 1993, using a model of induced innovation as changing characteristics of capital goods. Hicks formulated the induced innovation hypothesis in terms of factor prices. Newell, Jaffe and Stavins (1999) generalized this concept to include inducement by regulatory standards, such as labeling requirements that might increase the value of certain product characteristics by making consumers more aware of them. More generally, non-price regulatory constraints can fit within the inducement framework if they can be modeled as changing the shadow or implicit price that firms face in emitting pollutants. In their framework, the existing technology for making a given type of equipment at a point in time is identified in terms of vectors of characteristics (including cost of manufacture) that are feasible. The process of invention makes it possible to manufacture "models" (characteristics vectors) that were previously infeasible. Innovation means the offering for commercial sale of a model that was not previously offered for sale. Induced innovation is then represented as movements in the frontier of feasible models that reduce the cost of energy efficiency in terms of other attributes.

By constructing a series of dynamic simulations, they examined the effects of energy price changes and efficiency standards on average efficiency of the menu of products over time. They found that a substantial amount of the improvement was what may be described as autonomous (that is, associated with the passage of time), but significant amounts of innovation were also due to changes in energy prices and changes in energy-efficiency standards. They found that technological change in air conditioners was actually biased against energy efficiency in the 1960s (when real energy prices were falling), but that this bias was reversed after the two energy shocks of the 1970s.

[25] Of course, there is a parallel problem with respect to measurement of the rate of invention or innovation. See Griliches (1990) and Lanjouw and Schankerman (1999).

In terms of the efficiency of the average model offered, they found that energy efficiency in 1993 would have been about one-quarter to one-half lower in air conditioners and gas water heaters, if energy prices had stayed at their 1973 levels, rather than following their historical path. Most of the response to energy price changes came within less than five years of those changes.

Popp (2001, 2002) looked more broadly at energy prices and energy-related innovation. In the first paper, he found that patenting in energy-related fields increases in response to increased energy prices, with most of the effect occurring within a few years, and then fading over time. Popp attributed this fading to diminishing returns to R&D. In the second paper, he attempted to decompose the overall reduction in energy use that is associated with changing energy prices between the substitution effect – movements along a given production frontier – and the induced innovation effect – movement *of* the production frontier itself induced by the change in energy prices. Using energy-related patents as a proxy for energy innovation, he found that approximately one-third of the overall response of energy use to prices is associated with induced innovation, with the remaining two-thirds associated with factor substitution. Because energy patents are likely to measure energy innovation only with substantial error, one might interpret this result as placing a lower bound on the fraction of the overall response of energy use to changing prices that is associated with innovation.

3.2. Effects of instrument choice on invention and innovation

The effect of environmental policies on the development and spread of new technologies may, in the long run, be among the most important determinants of success or failure in environmental protection [Kneese and Schultze (1975)].[26] It has long been recognized that alternative types of environmental policy instruments can have significantly different effects on the rate and direction of technological change [Orr (1976)]. Environmental policies, particularly those with large economic impacts (for example, those intended to address global climate change) can be designed to foster rather than inhibit technological invention, innovation, and diffusion [Kemp and Soete (1990)].

3.2.1. Categories of environmental policy instruments and criteria for comparison

For purposes of examining the link between environmental policy instruments and technological change, policies can be characterized as either command-and-control or market-based approaches. Market-based instruments are mechanisms that encourage

[26] Whereas we focus in this section of the chapter on the effects of environmental policy instruments on technological change, it is also the case that exogenous technological change can differentially affect the performance of alternative environmental policy instruments. For example, technological change in monitoring and enforcement, such as improvements in remote-sensing of motor vehicle emissions, could render particular policy instruments that focus on emissions, rather than abatement equipment, more attractive.

behavior through market signals rather than through explicit directives regarding pollution control levels or methods. These policy instruments – such as pollution charges, subsidies, tradeable permits, and some types of information programs – have been described as "harnessing market forces". This is because if they are well designed and implemented, they encourage firms (and/or individuals) to undertake pollution control efforts that are in their own interests and that collectively meet policy goals.[27]

Conventional approaches to regulating the environment are often referred to as "command-and-control" regulations, since they allow relatively little flexibility in the means of achieving goals. Such regulations tend to force firms to take on similar shares of the pollution-control burden, regardless of the cost. Command-and-control regulations do this by setting uniform standards for firms, the most prevalent of which are performance- and technology-based standards. A performance standard sets a uniform control target for firms (emissions per unit of output, for example), while allowing some latitude in how this target is met. Technology-based standards specify the method, and sometimes the actual equipment, that firms must use to comply with a particular regulation. While even technology-based standards provide an incentive for innovation that reduces the cost of using specific technologies, performance standards allow a wider range of innovation, as long as standards are met at the plant level. In contrast, market-based instruments allow even greatter flexibility in innovation possibilities, including flexibility in plant-level emissions.

Holding all firms to the same target can be expensive and, in some circumstances, counterproductive. While standards may effectively limit emissions of pollutants, they typically exact relatively high costs in the process, by forcing some firms to resort to unduly expensive means of controlling pollution. Because the costs of controlling emissions may vary greatly among firms, and even among sources within the same firm,[28] the appropriate technology in one situation may not be appropriate (cost-effective) in another.

All of these forms of intervention have the potential for inducing or forcing some amount of technological change, because by their very nature they induce or require firms to do things they would not otherwise do. Performance and technology standards can be explicitly designed to be "technology forcing", mandating performance levels that are not currently viewed as technologically feasible or mandating technologies that are not fully developed. One problem with these approaches, however, is that while regulators can typically assume that *some* amount of improvement over existing technology will always be feasible, it is impossible to know how much. Standards must either be made unambitious, or else run the risk of being ultimately unachievable, leading to great political and economic disruption [Freeman and Haveman (1972)].

Technology standards are particularly problematic, since they tend to freeze the development of technologies that might otherwise result in greater levels of control. Under

[27] See Chapter 9 ("Experience with Market-Based Environmental Policy Instruments").

[28] Control costs can vary enormously due to a firm's production design, physical configuration, inputs, age of assets, and other factors.

regulations that are targeted at technologies, as opposed to emissions levels, no financial incentive exists for businesses to exceed control targets, and the adoption of new technologies is discouraged. Under a "Best Available Control Technology" (BACT) standard, a business that adopts a new method of pollution abatement may be "rewarded" by being held to a higher standard of performance and thereby not benefit financially from its investment, except to the extent that its competitors have even more difficulty reaching the new standard [Hahn and Stavins (1991)]. On the other hand, if third parties can invent and patent better equipment, they can – in theory – have a ready market. Under such conditions, a BACT type of standard can provide a positive incentive for technology innovation. Unfortunately, as we note below, there has been very little theoretical or empirical analysis of such technology-forcing regulations.

In contrast with such command-and-control regulations, market-based instruments can provide powerful incentives for companies to adopt cheaper and better pollution-control technologies. This is because with market-based instruments, it pays firms to clean up a bit more if a sufficiently low-cost method (technology or process) of doing so can be identified and adopted.

In theory, the relative importance of the dynamic effects of alternative policy instruments on technological change (and hence long-term compliance costs) is greater in the case of those environmental problems which are of great magnitude (in terms of anticipated abatement costs) and/or very long time horizon.[29] Hence, the increased attention that is being given by scholars and by policy makers to the problem of global climate change[30] has greatly increased the prominence of the issues that are considered in this part of the chapter.

There are two principal ways in which environmental policy instruments can be compared with regard to their effects on technological change. First and foremost, scholars have asked – both with theoretical models and with empirical analyses – the most direct question: what effects do particular instruments have on the rate and direction of relevant technological change? In keeping with the Schumpeterian trichotomy identified above, such investigations can be carried out with reference to the pace of invention, innovation, or diffusion of new technologies.

It is also possible to ask whether environmental policies encourage *efficient* rates (and directions) of technological change, or more broadly, whether such policies result in overall economic efficiency (that is, whether the efficient degree of environmental protection is achieved). This second principal mode for comparison is linked more directly with criteria associated with welfare economics, but such comparisons have been

[29] Parry, Pizer and Fischer (forthcoming) showed that the importance of the welfare gains from cost-reducing technological change relative to the welfare gains from optimal pollution control using existing technology tends to be higher when marginal benefits are flatter, marginal costs are steeper (and optimal abatement is lower), the discount rate is lower, the rate of technological change is faster, and research costs are lower.

[30] For particular attention to the links between technological change and global climate policy, see: Jaffe, Newell and Stavins (1999).

made much less frequently than have direct assessments of technology effects. Within the limits of the existing literature, we consider both sets of criteria.[31]

Most of the work in the economics literature on the dynamic effects of environmental policy instruments on technological change has been theoretical, rather than empirical, and so we consider the theoretical literature first.

3.2.2. Theoretical analyses

Although, as we suggested above, decisions about technology commercialization are partly a demand-side function of anticipated sales (adoption), the relevant literature comparing the effects of alternative environmental policy instruments has given greater attention to the supply side, focusing on incentives for firm-level decisions to incur R&D costs in the face of uncertain outcomes.[32] Such R&D can be either inventive or innovative, but the theoretical literature in this area makes no particular distinction.

The earliest work that is directly relevant was by Magat (1978), who compared effluent taxes and CAC standards using an innovation possibilities frontier (IPF) model of induced innovation, where research can be used to augment capital or labor in a standard production function. He compared the output rate, effluent rate, output-effluent ratio, and bias (in terms of labor or capital augmenting technical change), but produced ambiguous results. Subsequently, Magat (1979) compared taxes, subsidies, permits, effluent standards, and technology standards, and showed that all but technology standards would induce innovation biased toward emissions reduction.[33] In Magat's model, if taxes and permits are set so that they lead to the same reduction in emissions as an effluent standard at all points in time, then the three instruments provide the same incentives to innovate.

A considerable amount of theoretical work followed in the 1980s. Although much of that work characterized its topic as the effects of alternative policy instruments on technology innovation, the focus was in fact on effects of policy on technology diffusion. Hence, we defer consideration of those studies to Section 4.3.1 of this chapter.

Taking a somewhat broader view than most economic studies, Carraro and Siniscalco (1994) suggested that environmental policy instruments should be viewed jointly with traditional industrial policy instruments in determining the optimal way to attain a given degree of pollution abatement. They showed that innovation subsidies can be used to attain the same environmental target, but without the output reductions that result from pollution taxes. Laffont and Tirole (1996a) examined how a tradeable permit system could – in theory – be modified to achieve desired incentive effects for technological change. They demonstrated that although spot markets for permits cannot induce the

[31] Enforceability of environmental regulations is another criteria for policy choice that it is rarely emphasized in the technology literature. See Macauley and Brennan (2001) for an evaluation of the potential role of remote sensing technology in the enforcement of environmental regulations.

[32] See Kemp (1997) for an overview of theoretical models of technology innovation.

[33] Technology standards provided no incentives for innovation whatsoever.

socially optimal degree of innovation, futures markets can improve the situation [Laffont and Tirole (1996a)].[34]

Cadot and Sinclair-Desgagne (1996) posed the following question: if a potentially regulated industry has private information on the costs of technological advances in pollution control (frequently a reasonable assumption), then since the industry has an incentive to claim that such technologies are prohibitively expensive (even if that is not the case), can the government somehow design an incentive scheme that will avoid the problems of this information asymmetry? The authors developed a solution to this game-theoretic problem. Not surprisingly, the scheme involves government issued threats of regulation (which diminish over time as the firm completes stages of technology development).

It was only recently that theoretical work followed up on Magat's attempt in the late 1970's to rank policy instruments according to their innovation-stimulating effects. Fischer, Parry and Pizer (forthcoming) found that an unambiguous ranking of market-based policy instruments was not possible. Rather, the ranking of policy instruments was shown by the authors to depend on the innovator's ability to appropriate spillover benefits of new technologies to other firms, the costs of innovation, environmental benefit functions, and the number of firms producing emissions.

The basic model consists of three stages. First, an innovating firm decides how much to invest in R&D by setting its marginal cost of innovation equal to the expected marginal benefits. Second, polluting firms decide whether or not to adopt the new technology, use an (inferior) imitation of it, or do nothing. Finally, firms minimize pollution control expenditures by setting their marginal costs equal to the price of pollution. Policy instruments affect the innovation incentives primarily through three effects: (1) an abatement cost affect, reflecting the extent to which innovation reduces the costs of pollution control; (2) an imitation effect, which weakens innovation incentives due to imperfect appropriability; and (3) an emissions payment effect, which can weaken incentives if innovation reduces firms' payments for residual emissions. There is some variation in this pattern depending on the instrument, as shown in Table 1, which summarizes the direction of the three effects under three alternative policy instruments. The ranking of instruments depends on the relative strength of these effects.

Table 1
Theoretical determinants of the incentives for innovation [Fischer, Parry and Pizer (forthcoming)]

Determinant	Emissions tax	Freely-allocated tradeable permits	Auctioned tradeable permits
Abatement cost effect	(+)	(+)	(+)
Imitation effect	(−)	(−)	(−)
Emissions payment effect	none	none	(+)

[34] In a subsequent analysis, Laffont and Tirole (1996b) examined the government's ability to influence the degree of innovative activity by setting the number of permits (and permit prices) in various ways in a dynamic setting.

In an analysis that is quite similar in its results to the study by Fischer, Parry and Pizer (forthcoming), Ulph (1998) compared the effects of pollution taxes and command-and-control standards, and found that increases in the stringency of the standard or tax had ambiguous effects on the level of R&D, because environmental regulations have two competing effects: a direct effect of increasing costs, which increases the incentives to invest in R&D in order to develop cost-saving pollution-abatement methods; and an indirect effect of reducing product output, which reduces the incentive to engage in R&D.[35] Carraro and Soubeyran (1996) compared an emission tax and an R&D subsidy, and found that an R&D subsidy is desirable if the output contractions induced by the tax are small or if the government finds output contractions undesirable for other reasons. Addressing the same trade-off, Katsoulacos and Xepapadeas (1996) found that a simultaneous tax on pollution emissions and subsidy to environmental R&D may be better suited to overcoming the joint market failure (negative externality from pollution and positive externality or spillover effects of R&D).[36]

Finally, Montero (2002) compared instruments under non-competitive circumstances, and found that the results are less clear than when perfect competition is assumed. He modeled a two-firm oligopoly facing environmental regulation in the form of emissions standards, freely-allocated permits, auctioned permits, and taxes. Firms can invest in R&D to lower their marginal abatement costs, and they can also benefit from spillover effects from the other firm's R&D efforts. In choosing whether and how much to invest in R&D in order to maximize profits, a firm must consider two effects of its investment choice: (1) the increase in profits due to a decrease in its abatement costs (less the R&D cost); and (2) the decrease in profits due to changes in the other firm's output, as a result of spillover from the first firm's R&D. The result is that standards and taxes yield higher incentives for R&D when the market is characterized by Cournot competition, but the opposite holds when the market is characterized by Bertrand competition.

3.2.3. Empirical analyses

There has been exceptionally little empirical analysis of the effects of alternative policy instruments on technology innovation in pollution abatement, principally because of the paucity of available data. One study by Bellas (1998) carried out a statistical analysis of the costs of flue gas desulfurization (scrubbing) installed at coal-fired power plants in the United States under the new-source performance standards of the 1970 and 1977 Clean Air Acts. Bellas failed to find any evidence of effects of scrubber vintage on cost, suggesting little technological change had taken place under this regulatory regime.

Although there has been very little analysis in the context of pollution-abatement technologies, there is a more extensive literature on the effects of alternative policy

[35] In addition, Ulph (1998) examined a situation where two firms produce identical products with two characteristics. If both firms innovate on the same characteristic, price competition will eliminate any gains from R&D; but consumer pressure can affect the direction of R&D by influencing the characteristic that firms focus on improving. See also: Ulph and Ulph (1996).

[36] See, also, Conrad (2000).

instruments on the innovation of energy-efficiency technologies, because data have been available. As described in Section 3.1.3, above, the innovation process can be thought of as affecting improvements in the characteristics of products on the market, and the process can be framed as the shifting inward over time of a frontier representing the tradeoffs between different product characteristics for the range of models available on the market. If one axis is the cost of the product and another axis is the energy flow associated with a product, that is, its energy intensity, then innovation is represented by inward shifts of the curve – greater energy efficiency at the same cost, or lower cost for given energy efficiency. With this approach, Newell, Jaffe and Stavins (1999) assessed the effects of changes in energy prices and in energy-efficiency standards in stimulating innovation. Energy price changes induced both commercialization of new models and elimination of old models. Regulations, however, worked largely through energy-inefficient models being dropped, since that is the intended effect of the energy-efficiency standards (models below a certain energy efficiency level may not be offered for sale).

A closely related approach to investigating the same phenomena is that of hedonic price functions. One hedonic study examined the effects of public policies in the context of home appliances. Greening, Sanstad and McMahon (1997) estimated the impacts of the 1990 and 1993 national efficiency standards on the quality-adjusted price of household refrigerator/freezer units. They found that quality-adjusted prices fell after the implementation of the energy efficiency standards, but such quality-adjusted price decreases are consistent with historical trends in refrigerator/freezer prices. Hence, one cannot rule out the possibility that the imposition of efficiency standards slowed the rate of quality-adjusted price decline.

Greene (1990) used data on fuel prices and fuel economy of automobiles from 1978 to 1989 to test the relative effectiveness of Corporate Average Fuel Economy (CAFE) Standards and gasoline prices in increasing fuel economy. He found that the big three U.S. firms faced a binding CAFE constraint, and for these firms compliance with CAFE standards had roughly twice the impact on fuel economy as did fuel prices. Japanese firms, however, did not face a binding CAFE constraint, and fuel prices had only a small effect. Luxury European manufactures seemed to base their fuel efficiency largely on market demand and often exceeded CAFE requirements. For these firms, neither the standards nor prices seemed to have much effects.

More recently, Pakes, Berry and Levinsohn (1993) investigated the effects of gasoline prices on the fuel economy of motor vehicles offered for sale, and found that the observed increase in miles per gallon (mpg) from 1977 onward was largely due to the consequent change in the mix of vehicles on the market. Fewer low-mpg cars were marketed, and more high-mpg cars were marketed. Subsequently, Berry, Kortum and Pakes (1996) combined plant-level cost data for the automobile industry and information on the characteristics of models that were produced at each plant to estimate a hedonic cost function – the supply-side component of the hedonic price function – finding that quality-adjusted costs generally *increased* over the period 1972–1982, thus coinciding with rising gasoline prices and emission standards.

Finally, Goldberg (1998) combined a demand-side model of discrete vehicle choice and utilization with a supply-side model of oligopoly and product differentiation to estimate the effects of CAFE standards on the fuel economy of the new car fleet. She found that automobile fuel operating costs have had a significant effect, although a gasoline tax of a magnitude that could match the effect of CAFE on fuel economy would have to be very large.

3.3. Induced innovation and optimal environmental policy

Though the magnitude of induced innovation effects remains uncertain, a few researchers have begun to explore the consequences of induced innovation for environmental policy. Section 3.2, above, addressed the important question of how considerations related to induced innovation affect the normative choice among different policy *instruments*. In this section, we consider the larger question of whether the possibility of induced innovation ought to change environmental policy *targets*, or the pace at which we seek to achieve them.

Intuitively, it seems logical that if environmental policy intervention induces innovation, this in some sense reduces the social cost of environmental intervention, suggesting that the optimal policy is more stringent than it would be if there were no induced innovation. This intuition contains an element of truth, but a number of complexities arise. First, one has to be careful what is meant by "reducing the cost of intervention". As shown by Goulder and Schneider (1999), if the policy intervention induces a reduction in the marginal cost of abatement, then any given policy target (for example, a particular aggregate emission rate or a particular ambient concentration) will be achieved at lower cost than it would without induced innovation. On the other hand, the lower marginal abatement cost schedule arising from induced innovation makes it socially optimal to achieve a greater level of pollution abatement. For a flat marginal social benefit function evaluated at the social optimum, or for any emission tax, this results in greater *total* expenditure on abatement even as the *marginal* abatement cost falls.

Another important issue is the general equilibrium effect of induced environmental innovation on innovation elsewhere in the economy [Schmalensee (1994)]. If inducement operates through increased R&D expenditure, then an issue arises as to the elasticity of supply of R&D inputs. To the extent that this supply is inelastic, then any induced innovation must come at the expense of other forms of innovation, creating an opportunity cost that may negate the "innovation offsets" observed in the regulated portion of the economy.[37] The general equilibrium consequences of these effects for welfare analysis depend on the extent of R&D spillovers or other market failures, and the magnitude of these distortions in the regulated firms or sectors relative to the rest of the economy [Goulder and Schneider (1999)].

[37] Goldberg (1998) provided evidence that the supply of R&D inputs (scientists and engineers) is relatively inelastic in the short run. It seems less likely that this supply is inelastic in the long run. See Romer (2000).

Goulder and Mathai (2000) looked at optimal carbon abatement in a dynamic setting, considering not only the optimal overall amount of abatement but also its timing.[38] In addition to R&D-induced innovation, they considered (in a separate model) reductions in abatement costs that come about via learning-by-doing. In the R&D model, there are two effects of induced innovation on optimal abatement: it reduces marginal abatement costs, which increases the optimal amount of abatement. But it also increases the cost of abatement today relative to the future, because of lower abatement costs in the future. The combination of these effects implies that with R&D-induced innovation, optimal abatement is lower in early years and higher in later years than it would otherwise be. In the learning-by-doing model, there is a third effect: abatement today lowers the cost of abatement in the future. This reinforces the tendency for cumulative optimal abatement to be higher in the presence of induced innovation, but makes the effect on optimal near-term abatement ambiguous.

Goulder and Mathai also considered the impact of innovation on the optimal tax rate. One might suppose that the potential for induced technological change justifies a higher environmental tax rate (or higher time-profile for an environmental tax), since in this setting environmental taxes have a dual role: discouraging emissions and triggering new technologies. Goulder and Mathai showed, however, that under typical conditions (a downward-sloping marginal damages curve) the presence of induced innovation implies a *lower* time-profile for the optimal environmental tax. The reason is that with induced innovation, a lower tax is all that is needed to achieve the desired abatement, even when the desired extent of abatement is higher.

Nordhaus (2000) introduced induced technological change into the “DICE” model of global climate change and associated economic activities. To calibrate the model, he needed parametric estimates of the private and social returns to fossil-fuel-related R&D. Using the existing R&D intensity of the fossil sector to derive these parameters, he found that the impact of induced innovation is modest. Essentially, the existing share of R&D investment in this sector is so small that even with large social returns the overall impact is modest. Indeed, comparing a model with induced innovation (but no factor substitution) with a model that has factor substitution but no induced innovation, he concluded that induced innovation has less effect than factor substitution on optimal emissions levels.

Overall, there is considerable ambiguity regarding the importance of induced innovation for the optimal stringency of environmental policy. Partly, this is because predictions depend on the magnitudes of parameters that are hard to measure. But, more fundamentally, if environmental policy affects the innovation process, and the innovation process is itself characterized by market failure, then this is a classic problem of the “second best”. We know that robust results are generally hard to come by with respect to such problems. It will typically make a big difference whether we imagine optimizing R&D policy first, and then environmental policy, or vice versa, or if we imagine

[38] On the role of induced technological change in climate change modeling, see also Wigley, Richels and Edmonds (1996), Ha-Duong, Grubb and Hourcade (1997), and Grubb (1997).

simultaneous optimization in both realms, or if we assume that we are designing optimal environmental policy taking non-optimal R&D policy as given. Theory may be able to indicate the considerations that come into play, but is unlikely to provide robust prescriptions for policy.

3.4. The evolutionary approach to innovation

While viewing R&D as a profit-motivated investment activity comes naturally to most economists, the large uncertainties surrounding the outcomes of R&D investments make it very difficult for firms to make optimizing R&D decisions. Accordingly, Nelson and Winter (1982) used Herbert Simon's idea of boundedly rational firms that engage in "satisficing" rather than optimizing behavior [Simon (1947)] to build an alternative model of the R&D process. In this "evolutionary" model, firms use "rules of thumb" and "routines" to determine how much to invest in R&D, and how to search for new technologies. The empirical predictions of this model depend on the nature of the rules of thumb that firms actually use [Nelson and Winter (1982), Winter, Kaniovski and Dosi (2000)].

Because firms are not optimizing, a logical consequence of the evolutionary model is that it cannot be presumed that the imposition of a new external constraint (for example, a new environmental rule) necessarily reduces profits. There is at least the theoretical possibility that the imposition of such a constraint could be an event that forces a satisficing firm to rethink its strategy, with the possible outcome being the discovery of a new way of operating that is actually more profitable for the firm. This possibility of environmental regulation leading to a "win-win" outcome in which pollution is reduced and profits increased is discussed below.

3.4.1. Porter's "win-win" hypothesis

The evolutionary approach replaces optimizing firms with satisficing firms, and thereby admits greater scope for a variety of consequences when the firm's environment is modified. Satisficing firms may miss opportunities for increased profits simply because they do not look very hard for such opportunities as long as things are going reasonably well. An external shock such as a new environmental constraint can therefore constitute a stimulus to new search, possibly leading to discovery of previously undetected profit opportunities. This observation forms the basis for the normative observation that environmental regulation may not be as costly as we expect, because the imposition of the new constraint may lead to the discovery of new ways of doing things. In the limit, these new ways of doing things might actually be *more* profitable than the old ways, leading to an asserted "win-win" outcome.[39]

[39] Another related idea is that of "X-inefficiency" [Leibenstein (1966)].

In general, advocates of the "win-win" view of the consequences of environmental regulation seem unaware of the connection between their argument and the evolutionary school of technological change.[40] But the ideas are similar:

> It is sometimes argued that companies must, by the very notion of profit seeking, be pursuing all profitable innovation ... In this view, if complying with environmental regulation can be profitable, in the sense that a company can more than offset the cost of compliance, then why is such regulation necessary?
>
> The possibility that regulation might act as a spur to [profitable] innovation arises because the world does not fit the Panglossian belief that firms always make optimal choices ... [T]he actual process of dynamic competition is characterized by changing technological opportunities coupled with highly incomplete information, organizational inertia and control problems reflecting the difficulty of aligning individual, group and corporate incentives. Companies have numerous avenues for technological improvement, and limited attention [Porter and van der Linde (1995, pp. 98–99)].

Porter and other "win-win" theorists argued that in this non-optimizing world, regulation may lead to "innovation offsets" that "can not only lower the net cost of meeting environmental regulations, but can even lead to absolute advantages over firms in foreign countries not subject to similar regulations" [Porter and van der Linde (1995, p. 98)]. Of course, the fact that firms engage in non-optimizing behavior creates a *possibility* for profit improvements, without suggesting that such improvements would be the norm, would be systematic, or even likely. But win-win theorists propose several reasons why innovation offsets are likely to be common.

First, they argue that regulation provides a signal to companies about likely resource inefficiencies and potential technological improvements; that pollution is, by its very nature, indicative of resources being wasted, or at least not fully utilized. Regulation focuses attention on pollution, and such attention is likely to lead to the saving of resources, which will often lower costs. Second, regulation provides or requires the generation of information; since information is a public good it may be underprovided without such incentives. Third, regulation reduces uncertainty about the payoffs to investments in environmental innovation. There may be potential investments that are believed to be profitable in an expected value sense, and also deliver environmental benefits, but which are highly risky in the absence of regulation that ensures that the environmental benefits

[40] Neither Simon (1947) nor Nelson and Winter (1982) appear in the references of Porter and van der Linde (1995). Interestingly, Nelson and Winter themselves anticipated the connection. In their 1982 book, they say "In a regime in which technical advance is occurring and organizational structure is evolving in response to changing patterns of demand and supply, new nonmarket interactions that are not contained adequately by prevailing laws and policies are almost certain to appear, and old ones may disappear ... The canonical 'externality' problem of evolutionary theory is the generation by new technologies of benefits and costs that old institutional structures ignore" (p. 368). See also Kemp and Soete (1990).

are also privately valuable. Regulation, in effect, provides "insurance" against the risk of investing in new technology, part of whose benefit cannot be internalized. Fourth, new technology that is initially more costly may produce long-run competitive advantage, because of learning-by-doing or other "first-mover" advantages, if other countries eventually impose similarly strict standards. Finally, regulation simply creates pressure. Such pressure plays an important role in the innovation process, "to overcome inertia, foster creative thinking and mitigate agency problems" [Porter and van der Linde (1995, p. 100)].

Porter and van der Linde (1995) provided numerous case studies of particular firms who developed or adopted new technology in response to regulation, and appear to have benefited as a result. It should be emphasized, however, that win-win theorists do not claim that all environmental regulations generate significant innovation offsets. Indeed, they emphasize that regulation must be properly designed in order to maximize the chances for encouraging innovation. Quantitative evidence is limited. Boyd and McClelland (1999) and Boyd and Pang (2000) employ data envelopment analysis to evaluate the potential at paper and glass plants for "win-win" improvements that increase productivity and reduce energy use or pollution. They find that the paper industry could reduce inputs and pollution by 2–8% without reducing productivity.

Generally, economists have been skeptical of the win-win theory [Palmer, Oates and Portney (1995)]. From a theoretical perspective, it is possible to model apparently inefficient firm behavior as the (second-best) efficient outcome of imperfect information and divergent incentives among managers or between owners and managers in a principal/agent framework.[41] From this perspective, the *apparent* inefficiency does not have normative implications. Since firms are doing the best they can given their information environment, it is unlikely that the additional constraints represented by environmental policy interventions would be beneficial.

On a more concrete level, it is not clear that pollution generally signals "waste"; most physical and biological processes have by-products of some sort, and whether the extent of such by-products is "wasteful" or not is inherently a question of prices and costs. More generally, firms' rationality is surely bounded, but that does not mean that unexploited profit opportunities are frequent. Palmer, Oates and Portney (1995) surveyed firms affected by regulation – including those cited by Porter and van der Linde as success stories – and found that most firms say that the net cost to them of regulation is, in fact, positive.

For regulation to have important informational effects, the government must have better information than firms have about the nature of environmental problems and their potential solutions. This seems questionable. Of course, the government may have better information about which environmental problems *it* considers most important, but it is not clear how conveying this type of information would produce win-win outcomes.

41 For a survey, see Holmström and Tirole (1987).

As to overcoming inertia, most firms in today's world feel a lot of pressure, so it seems unlikely that the additional pressure of regulation is going to have beneficial stimulating effects on innovation. Finally, while it seems likely that environmental regulation will stimulate the innovation and diffusion of technologies that facilitate compliance, creation and adoption of new technology will typically require real resources, and have significant opportunity costs. The observation that the new technology is cost-saving on a forward-looking basis is not sufficient to conclude that the firm was made better off by being induced to develop and/or adopt the new technology.

Overall, the evidence on induced innovation and the win-win hypothesis seems to be a case of a "partially full glass" that analysts see as mostly full or mostly empty, depending on their perspective. This balance is summarized in Table 2.

Table 2
Overview of conclusions on induced innovation and the "win-win" hypothesis

Areas of agreement	
Historical evidence indicates that a significant but not necessarily predominant fraction of innovation in the energy and environment area is induced.	
Environmental regulation is likely to stimulate innovation and technology adoption that will facilitate environmental compliance.	
Much existing environmental regulation uses inflexible mechanisms likely to stifle innovation; "incentive-based" mechanisms are likely to be more conducive to innovation.	
Firms are boundedly rational so that external constraints can sometimes stimulate innovation that will leave the firm better off.	
First-mover advantages may result from domestic regulation that correctly anticipates world-wide trends.	
Areas of disagreement	
Win-win theory	*Neoclassical economics*
Widespread case-study evidence indicates significant "innovation offsets" are common.	Case studies are highly selective. Firms believe regulation is costly.
Innovation in response to regulation is evidence of offsets that significantly reduce or eliminate the cost of regulation.	When cost-reducing innovation occurs, the opportunity cost of R&D and management effort makes a true "win-win" outcome unlikely.
Pollution is evidence of waste, suggesting why cost-reducing innovation in response to regulation might be the norm.	Costs are costs; even if firms are not at the frontier, side-effects of pollution reduction could just as easily be bad as good.
Existing productivity or cost studies do not capture innovation offsets.	Existing productivity and cost studies suggest that innovation offsets have been very small.
There is much evidence of innovation offsets even though existing regulations are badly designed. This suggests that offsets from good regulation would be large.	Since there is agreement that bad regulations stifle innovation, the apparent beneficial effects of existing regulation only show that case studies can be very misleading.

4. Diffusion

4.1. Microeconomics of diffusion

From the mechanical reaper of the nineteenth century [David (1966)], through hybrid corn seed [Griliches (1957)], steel furnaces [Oster (1982)], optical scanners [Levin, Levin and Meisel (1987)] and industrial robots [Mansfield (1989)], research has consistently shown that the diffusion of new, economically superior technologies is a gradual process.[42] Typically, the fraction of potential users that has adopted a new technology follows a sigmoid or "S-shaped" path over time, rising only slowly at first, then entering a period of very rapid growth, followed by a slowdown in growth as the technology reaches maturity and most potential adopters have switched [Geroski (2000)].

The explanation for the apparent slowness of the technology diffusion process has been a subject of research in a variety of disciplines. Two main forces have been emphasized. First, potential technology adopters are heterogeneous, so that a technology that is generally superior will not be equally superior for all potential users, and may remain inferior to existing technology for some users for an extended period of time after its introduction. Second, adopting a new technology is a risky undertaking, requiring considerable information, both about the generic attributes of the new technology and about the details of its use in the particular application being considered. It takes time for information to diffuse sufficiently, and the diffusion of the technology is limited by this process of diffusion of information.

The two main models of the diffusion process each emphasize one of these two aspects of the process.[43] The *probit* or *rank* model, first articulated in an unpublished paper by Paul David (1969), posits that potential adopters are characterized by a distribution of value or returns associated with the new technology.[44] Because adoption is costly, at any moment in time there is a threshold point on this distribution, such that potential users with values at or above this threshold will want to adopt, and users for whom the value of the new technology is below this threshold will not want to adopt. Because the new technology will typically get cheaper and better as time passes after its initial introduction, this threshold will gradually move to the right, and eventually sweep out the entire distribution. If the distribution of underlying values is normal (or another single-peaked distribution with similar shape), this gradual movement of the threshold across the distribution will produce the typical S-shaped diffusion curve.

The other widely-used model is called the *epidemic* model [Griliches (1957), Stoneman (1983)]. The epidemic model presumes that the primary factor limiting diffusion is information, and that the most important *source* of information about a new technology is people or firms who have tried it. Thus technology spreads like a disease, with the

[42] See, also, Kemp (1997) for an overview of theoretical models of technology diffusion.

[43] For empirical examples that integrate the two models, see Trajtenberg (1990) and Kerr and Newell (forthcoming).

[44] This has sometimes been called the *rank* model since potential adopters can be ranked in terms of their potential benefits from adoption [Karshenas and Stoneman (1995)].

instigation of adoption being contact between the "infected" population (people who have already adopted) and the uninfected population. Denoting the fraction of the potential using population that has adopted as f, this leads to the differential equation $\mathrm{d}f/\mathrm{d}t = \beta f(1 - f)$. Solution of this equation yields a logistic function, which has the characteristic S-shape. The parameter β captures the "contagiousness" of the disease, presumably related to the cost of the new technology and the degree of its superiority over the technology it replaces [Griliches (1957)].[45]

The probit model emphasizes adoption as the result of value-maximizing decisions by heterogeneous adopters. As such, at least in its basic form, it does not suggest that the slow diffusion of new technology is anything but optimal. In contrast, in the epidemic model each adopter generates a positive externality by transferring information to other potential adopters. This suggests that laissez-faire adoption rates may indeed be socially suboptimal. We return to this issue in Section 4.2.2 below.

Finally, we note an important issue of feedback from the diffusion process to the earlier stages of invention and innovation. The rate at which a technology diffuses determines in large part the rate at which its production volume grows. And as stated earlier, market size tends to be an important determinant of R&D effort and innovative activity, so that growing use increases the incentive for R&D to improve the product. Furthermore, if the production process is characterized by *learning by doing*, then quality may rise and production costs fall as production experience is accumulated. This possibility creates an additional source of positive externality associated with technology adoption, and may introduce dynamic increasing returns to scale for individual technologies. This issue is also discussed below in Section 4.1.1.

In the literature unrelated to environmental technology, both theory and empirical evidence are clear that technology diffusion rates depend on the strength of economic incentives for technology adoption. Both of the models discussed above predict that the present value of benefits from adoption and the initial adoption cost enter into decisions affecting the diffusion rate.[46] In the probit model, this net present value comparison determines the location of the adoption threshold that determines what fraction of potential adopters will adopt at a moment in time. In the epidemic model, this net present

[45] Both the probit and epidemic models typically focus on the fraction of the population that had adopted at a point in time. If one has individual-level data on adopters, one can take as the dependent variable the individual time until adoption. This leads to a duration or hazard model [Karshenas and Stoneman (1995), Rose and Joskow (1990)]. Kerr and Newell (forthcoming) employed a duration model to analyze technology adoption decisions by petroleum refineries during the phasedown of lead in gasoline, as discussed in Section 4.2.1 below.

[46] The fact that technology costs enter into the adoption decision demonstrates the close link between technology innovation and diffusion in both theory and reality. A key mechanism of diffusion is the gradual adoption of a new technology as its cost falls (and/or quality improves). Such cost and quality improvements represent innovation. Likewise, incentives for innovation will depend on the eventual demand for a new or improved product, that is, diffusion. This linkage also points to the difficulty of empirically distinguishing between technology innovation and diffusion since they depend on one another and also both depend on similar external incentives such as relative price changes.

value comparison determines the magnitude of the "contagiousness" parameter, which in turn determines the speed at which the technology spreads from adopters to previous non-adopters.

Empirical studies have addressed the influence on diffusion of factors such as firm size, R&D expenditure, market share, market structure, input prices, technology costs, firm ownership, and other institutional factors. The classic empirical study is by Griliches (1957), who showed that the rate of adoption of hybrid corn seed in different regions depended on the economic superiority of the new seed in that region. David (1966) showed that the first adopters of the mechanical reaper were larger farms, who benefited more from the decreased variable cost it permitted. Mansfield (1968) also found the rate of diffusion to depend on firm size (as do most studies), as well as the riskiness of the new technology and the magnitude of the investment required for adoption. [47]

4.1.1. Increasing returns and technology lock-in

Increasing returns to adoption – in the form of learning curves and positive adoption externalities – are a significant feature of market penetration processes for many technologies. Learning-by-doing describes how cumulative production experience with a product leads to reduced production costs, while learning-by-using captures how the value of a good increases for consumers as they gain experience using it. Positive adoption externalities arise when a non-user's probability of adoption is increased the greater the number of potential users who have already adopted [Berndt and Pindyck (2000)]. This could occur because of fad or herding effects, or because of "network externalities". Network externalities exist if a product is technologically more valuable to an individual user as other users adopt a compatible product (for example, telephone and computer networks). 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.

Furthermore, increasing returns to adopting a particular technology or system have been linked with so-called technology "lock-in", in which a particular product, technical standard, production process, or service is produced by a market, and it is difficult to move to an alternative competing technology. Lock-in implies that, once led down a particular technological path, the barriers to switching may be prohibitive. This can be problematic if it would have been in the broader social interest to adopt a fundamentally different pattern of technological capacity. In turn, it raises the question of whether policy interventions – possibly involving central coordination and information assessment, direct technology subsidies, or publicly funded research, development, demonstration, and procurement programs – might avoid undesirable cases of technology lock-in by guiding technological paths in directions superior to those that would be taken by the free market.

[47] For further evidence and discussion, see the survey by Karshenas and Stoneman (1995).

A classic, although somewhat controversial, example given is the QWERTY keyboard layout [David (1985)]. As the story goes, the so-called Dvorak keyboard system is ergonomically more efficient than the standard layout. In other words, we could all type faster and better if we learned the Dvorak system. Unfortunately, the QWERTY system got there first, so to speak, and we may be stuck with it, due in part to network externalities and learning-by-doing.

Increasing returns are necessary but not sufficient conditions for persistent and undesirable lock-in. There must also be costs associated with maintaining parallel rival networks or "switching costs" associated with moving between systems (for example, cost of buying a new keyboard or learning to type on a new keyboard layout). The presence of these factors, however, in theory has the potential to lead to a market equilibrium in which a socially suboptimal standard or technology is employed. Nonetheless, an inefficient outcome need not necessarily result, and if it does it may not be lasting. Market forces will eventually tend to challenge the predominance of an inferior technology [see Ruttan (1997)].

A related characteristic of products or systems subject to increasing returns or "positive feedbacks" is that history can be critical. While other markets can often be explained by current demand and supply, markets subject to increasing returns may not be fully understandable without knowing the pattern of historical technology adoption. Work by Arthur (1989, 1990, 1994), David (1985, 1997) and others [Foray (1997)] on the importance of such "path dependence" have focused on the lasting role that chance historical events can play in leading market outcomes down one rather than another possible path. It is important to note that increasing returns and technology lock-in do not necessarily imply market failure. In cases where they may, the question becomes what policies, markets, or institutions, if any, can ameliorate undesirable technological paths or eventual lock-in.

We are far from having a well-established theoretical or empirical basis for when intervention is preferable to an unregulated market outcome or the form that intervention should take. (See Section 4.2.3 for applications to environmental and energy issues.) David (1997, p. 36) suggested that perhaps the most productive question to ask is "how can we identify situations in which it is likely that at some future time individuals really would be better off had another equilibria been selected" from the beginning. One thing that public policy can do, David suggested, is try to delay the market from irreversible commitments before enough information has been obtained about the likely implications of an early, precedent-setting decision.[48] One could construe current policy discussions surrounding certain biotechnology developments as potentially doing just that.

[48] See Majd and Pindyck (1989) for an analysis that explicitly treats learning-by-doing as an irreversible investment decision.

Network externalities. Besen and Farrell (1994), Katz and Shapiro (1994), and Liebowitz and Margolis (1994) together provide an overview of issues surrounding network effects. Several properties of "network markets" distinguish them from other markets, influence the strategies firms pursue, and may lead to market inefficiencies including oligopoly or monopoly. Network markets tend to tip; that is, the coexistence of incompatible products may be unstable, resulting in a single standard dominating the market. Two potential inefficiencies can also arise due to demand side coordination difficulties in the presence of network externalities: excess inertia (users wait too long to adopt a new technology) or excess momentum (users rush to an inferior technology to avoid being stranded) [see Farrell and Saloner (1985)]. The role of information is central; the possibility of locking into an inferior technology is greater when users have incomplete information, and it is expectations about the ultimate size of a network that is crucial to which technology dominates. The root problem is the difficulty of collective coordination in a decentralized process [David (1997)].

One way to address this coordination problem is through standards – that is, a particular technology chosen for universal adoption – which are often adopted by government or industry associations when network externalities are present (telephone signals, for example).[49] While standards may help avoid excess inertia and reduce users' search and coordination costs, they can also reduce diversity and may be subject to the strategy of a dominant firm. Katz and Shapiro (1994) point out that while network effects can lead to market inefficiencies, there are many possible market responses to these problems that do not necessarily involve government intervention. Furthermore, there is a question about whether the government has the proper incentives and information to improve the situation.

Learning-by-doing and learning-by-using. In early production stages, the manufacture of technologically complex products is fraught with difficulties. As a firm produces more and more of the product, however, it learns to produce it more efficiently and with higher levels of quality. Production experience leads to the rationalization of processes, reduced waste, and greater labor force expertise. When this is so, average production costs will tend to decrease over time and with increases in the firm's cumulative output, albeit at a decreasing rate. Alternative terms used to denote this characteristic learning pattern and related phenomena include "learning curve", "experience curve", "learning-by-doing", and "progress function". Learning-by-using, the demand-side counterpart of learning-by-doing, can complement and reinforce these learning effects as adoption increases with greater experience in use and increased productivity over time by the user [see Sunding and Zilberman (2000)].

A technology with an initial cost advantage can allow for pricing that increases market share. In turn, increased market share can lead to even greater learning, cost reductions, and competitive advantage – a virtuous circle for the firms producing the technology. Unfortunately, as with network effects, this persistent cost advantage can create

[49] See, for example, Katz and Shapiro (1986, 1994).

a kind of entry barrier if knowledge spillovers are incomplete. In the extreme, the cost advantage may completely deter or "lock out" the entry of new technologies or rival systems, at least for a time. Spence (1981) showed that the main factors affecting costs and competition in the presence of learning are the rate of learning, the extent of learning-induced cost decline relative to the market, the intertemporal pattern of demand (that is, demand elasticity and growth), and the degree of spillovers of learning to other firms.[50]

4.2. Diffusion of green technology

While the induced innovation literature focuses on the potential for environmental policy to bring forth new technology through innovation, there is also a widely-held view that significant reductions in environmental impacts could be achieved through more widespread diffusion of *existing* economically-attractive technologies, particularly ones that increase energy efficiency and thereby reduce emissions associated with fossil fuel combustion. For example, the report of the Interlaboratory Working Group (1997) compiled a comprehensive analysis of existing technologies that reportedly could reduce energy use and hence CO_2 emissions at low or even negative net cost to users. The observation that energy-efficient technologies that are cost-effective at current prices are diffusing only slowly dates back to the 1970s, having been identified as a "paradox" at least as far back as Shama (1983).

As discussed in Section 4.1, above, the observation of apparently slow diffusion of superior technology is not a surprise when viewed in historical context. Nonetheless, the apparent potential for emissions reductions associated with faster diffusion of existing technology raises two important questions. First, what is the theoretical and empirical potential for "induced diffusion" of lower-emissions technologies? Specifically, how do environmental policy instruments that implicitly or explicitly increase the economic incentive to reduce emissions affect the diffusion rate of these technologies?

A second and related question is the degree to which historical diffusion rates have been limited by market failures in the energy and equipment markets themselves [Jaffe and Stavins (1994)]. To the extent that diffusion has been and is limited by market failures, it is less clear that policies that operate by increasing the economic incentive to adopt such technology will be effective. On the other hand, if such market failures are important, then policies focused directly on correction of such market failures provide, at least in principle, opportunities for policy interventions that are social-welfare increasing, even without regard to any environmental benefit. Table 3 summarizes the potential influence on technology diffusion of many of the factors discussed in this section.

[50] See also Fudenberg and Tirole (1983) on strategic aspects of learning-by-doing and early work by Arrow (1962b). Yelle (1979), Dutton and Thomas (1984), Day and Montgomery (1983), and Argote and Epple (1990) together provide an excellent overview of the fairly large empirical literature on learning curves, which spans the fields of economics, marketing, and business administration.

Table 3
Factors influencing technology diffusion

Factor	Likely direction of effect on technology diffusion	Potential policy/ Institutional instrument
Increased relative price of resource conserved by the technology	(+)	tax on the resource
Decreased cost and/or increased quality of technology	(+)	technology subsidy
Inadequate information, uncertainty, and agency problems regarding benefits and costs of technology adoption	(−)	information dissemination, technology demonstration
Learning-by-doing and learning-by-using	(+)	technology demonstration and deployment, tax/subsidy
Network externalities	(?)	standards, planning, coordination
Characteristics of potential adopters	varied	flexible regulation

4.2.1. Effects of resource prices and technology costs

Kerr and Newell (forthcoming) used a duration model to analyze the influence of plant characteristics and the stringency and the form of regulation on technology adoption decisions by petroleum refineries during the leaded gasoline phasedown. They found that increased stringency (which raised the effective price of lead) encouraged greater adoption of lead-reducing technology. They also found that larger and more technically sophisticated refineries, which had lower costs of adoption, were more likely to adopt the new technology.

Rose and Joskow (1990) found a positive effect of fuel price increases on the adoption of a new fuel-saving technology in the U.S. electricity-generation sector, with the statistical significance of the effect depending on the year of the fuel price. In a tobit analysis of steel plant adoption of different furnace technologies, Boyd and Karlson (1993) found a significant positive effect of increases in a fuel's price on the adoption of technology that saves that fuel, although the magnitude of the effect was modest. For a sample of industrial plants in four heavily polluting sectors (petroleum refining, plastics, pulp and paper, and steel), Pizer et al. (2001) found that both energy prices and financial health were positively related to the adoption of energy-saving technologies.

Jaffe and Stavins (1995) carried out econometric analyses of the factors affecting the adoption of thermal insulation technologies in new residential construction in the United States between 1979 and 1988. They examined the dynamic effects of energy prices and technology adoption costs on average residential energy-efficiency technologies in new home construction.[51] They found that the response of mean energy efficiency to

[51] The effects of energy prices can be interpreted as suggesting what the likely effects of taxes on energy use would be, and the effects of changes in adoption costs can be interpreted as indicating what the effects of technology adoption subsidies would be. See Section 4.3.2.

energy price changes was positive and significant, both statistically and economically. Interestingly, they also found that equivalent percentage adoption cost changes were about three times as effective as energy price changes in encouraging adoption, although standard financial analysis would suggest they ought to be about equal in percentage terms. This finding offers confirmation for the conventional wisdom that technology adoption decisions are more sensitive to up-front cost considerations than to longer-term operating expenses.

Hassett and Metcalf (1995) found an even larger discrepancy between the effect of changes in installation cost (here coming through tax credits) and changes in energy prices. There are three interrelated possible explanations for this. One possibility is a behavioral bias that causes purchasers to focus more on up-front cost than they do on the lifetime operating costs of an investment. An alternative (but probably indistinguishable) view is that purchasers focus equally on both, but uncertainty about future energy prices makes them give less weight to the current energy price (which is only an indicator of future prices) than they do to the capital cost, which is known. A final interpretation might be that consumers actually have reasonably accurate expectations about future energy prices, and their decisions reflect those expectations, but our empirical proxies for their expectations are not correct.

For households and small firms, adoption of new technologies with significant capital costs may be constrained by inadequate access to financing. And in some countries, import barriers may inhibit the adoption of technology embodied in foreign-produced goods [Reppelin-Hill (1999)].

On the other hand, it must be acknowledged that it is impossible to generalize, particularly across countries. Nijkamp, Rodenburg and Verhoef (2001) presented the qualitative results of a survey of Dutch firms regarding their decisions on how much to invest in energy-efficient technologies. They found that general "barriers" to energy-efficient technology adoption – including the existence of alternative investments, low energy costs, and a desire to replace capital only when is fully depreciated – are more important than financial barriers and uncertainty about future technologies and prices.

4.2.2. Effects of inadequate information, agency problems, and uncertainty

As discussed in Section 4.1, above, information plays an important role in the technology diffusion process. There are two reasons why the importance of information may result in market failure. First, information is a public good that may be expected in general to be underprovided by markets. Second, to the extent that the adoption of the technology by some users is itself an important mode of information transfer to other parties, adoption creates a positive externality and is therefore likely to proceed at a socially suboptimal rate.[52] Howarth, Haddad and Paton (2000) explored the significance

[52] Transfer of useful information via technology adoption is a special case of the more general phenomenon of consumption externalities in technology adoption [Berndt and Pindyck (2000)]. If early adopters act randomly rather than on the basis of better information, then consumption externalities can result in socially excessive adoption or "herding" effects.

of inadequate information in inhibiting the diffusion of more efficient lighting equipment. Metcalf and Hassett (1999) compared available estimates of energy savings from new equipment to actual savings realized by users who have installed the equipment. They found that actual savings, while significant, were less than those promised by engineers and product manufacturers. Their estimate of the median realized rate of return is about 12%, which they found to be close to a discount rate for this investment implied by a CAPM analysis.

Also related to imperfect information are a variety of agency problems that can inhibit the adoption of superior technology. The agency problem can be either external or internal to organizations. An example of an external agency problem would be a landlord/tenant relationship, in which a tenant pays for utilities but the landlord makes decisions regarding which appliances to purchase, or vice versa. Internal agency problems can arise in organizations where the individual or department responsible for equipment purchase or maintenance differs from the individual or department whose budget covers utility costs.[53] DeCanio (1998) explored the significance of organizational factors in explaining firms' perceived returns to installation of energy-efficient lighting.[54]

Uncertainty is another factor that may limit the adoption of new technology [Geroski (2000)]. Such uncertainty is not a market failure, merely a fact of economic life. Uncertainty can be inherent in the technology itself, in the sense that its newness means that users are not sure how it will be perform [Mansfield (1968)]. For resource-saving technology, there is the additional uncertainty that the economic value of such savings depends on future resource prices, which are themselves uncertain. This uncertainty about future returns means that there is an "option value" associated with postponing the adoption of new technology [Pindyck (1991), Hassett and Metcalf (1995, 1996)].

Closely related to the issue of uncertainty is the issue of the discount rate or investment hurdle rate used by purchasers in evaluating the desirability of new technology, particularly resource-conserving technology. A large body of research demonstrates that purchasers *appear* to use relatively high discount rates in evaluating energy-efficiency investments [Hausman (1979), Ruderman, Levine and McMahon (1987), Ross (1990)]. The implicit or explicit use of relatively high discount rates for energy savings does not represent a market failure in itself; it is rather the manifestation of underlying aspects of the decision process including those just discussed. At least some portion of the discount rate premium is likely to be related to uncertainty, although the extent to which

53 For a discussion of the implications of the separation of environmental decision-making in major firms from relevant economic signals, see: Hockenstein, Stavins and Whitehead (1997). A series of related case studies are provided by Reinhardt (2000).

54 Agency problems are probably part of the basis for the hypothesis that energy-saving investments are ignored simply because energy is too small a fraction of overall costs to justify management attention and decisionmaking. This idea actually dates back to Alfred Marshall; one of his four laws of demand was "the importance of being unimportant". Marshall (1922) argued that inputs with small factor shares would receive little attention from firms and hence face inelastic factor demand curves.

the premium can be explained by uncertainty and option value is subject to debate [Hassett and Metcalf (1995, 1996), Sanstad, Blumstein and Stoft (1995)].[55] Capital market failures that make it difficult to secure external financing for these investments may also play a role.[56]

4.2.3. *Effects of increasing returns*

As described in Section 4.1, above, the presence of increasing returns in the form of learning effects, network externalities, or other positive adoption externalities presents the possibility that market outcomes for technologies exhibiting these features, including those with environmental consequences, may be inefficient. For example, the idea that we are "locked into" a fossil-fuel-based energy system is a recurring theme in policy discussions regarding climate change and other energy-related environmental problems. At a more aggregate level, there has been much discussion of the question of whether it is possible for developing countries to take less environmentally-damaging paths of development than have currently industrialized countries, for example by relying less on fossil fuels.[57]

While the empirical literature is quite thin, some studies have explored the issue of increasing returns and technology lock-in for competing technologies within the energy and environment arenas, including analysis of renewable energy and fossil fuels [Cowan and Kline (1996)], the internal combustion engine and alternatively-fueled vehicles [Cowan and Hulten (1996)], pesticides and integrated pest management [Cowan and Gunby (1996)], technologies for electricity generation [Islas (1997)], nuclear power reactor designs [Cowan (1990)], and the transition from hydrocarbon-based fuels [Kemp (1997)].

Energy and environment-related examples of empirical estimation of learning curves include work related to renewable energy and climate modeling [Nakicenovic (1996), Neij (1997), Grübler and Messner (1999), Grübler, Nakicenovic and Victor (1999)], nuclear reactors [Joskow and Rozanski (1979), Zimmerman (1982), Lester and McCabe (1993)], and electricity supply [Sharp and Price (1990)]. Although network externalities can be an important element of increasing returns, especially for information and communication technologies, their role in environmental technologies is less evident.

[55] Option values can arise for investments that can be postponed, and unless explicit account is taken of the option value, it will result in an increased effective hurdle rate for the investment.

[56] Shrestha and Karmacharya (1998) carried out an empirical analysis of the relative importance of various potential barriers to the adoption of fluorescent lighting in Nepal. They found that product information predicted adoption, but owner-occupancy and discount rates did not.

[57] See the survey by Evenson (1995) on technology and development. Also Chapter 5 ("Population, Poverty, and the Natural Environment") for a discussion of related issues, including the "environmental Kuznets curve".

4.3. Effects of instrument choice on diffusion

4.3.1. Theoretical analyses

The predominant theoretical framework for analyses of diffusion effects has been what could be called the "discrete technology choice" model: firms contemplate the use of a certain technology which reduces marginal costs of pollution abatement and which has a known fixed cost associated with it. While some authors have presented this approach as a model of "innovation",[58] it is more appropriately viewed as a model of adoption.

With such models, several theoretical studies have found that the incentive for the adoption of new technologies is greater under market-based instruments than under direct regulation [Zerbe (1970)],[59] Downing and White (1986), Milliman and Prince (1989), Jung, Krutilla and Boyd (1996). With the exception of Downing and White (1986), all of these studies examined the gross impacts of alternative policy instruments on the quantity of technology adoption.[60]

Theoretical comparisons *among* market-based instruments have produced only limited agreement. In a frequently-cited article, Milliman and Prince (1989) examined firm-level incentives for technology diffusion provided by five instruments: command-and-control; emission taxes; abatement subsidies; freely-allocated emission permits, and auctioned emission permits. Firm-level incentives for adoption in this representative-firm model were pictured as the consequent change in producer surplus. They found that auctioned permits would provide the largest adoption incentive of any instrument, with emissions taxes and subsidies second, and freely allocated permits and direct controls last. The Milliman and Prince (1989) study was criticized by Marin (1991) because of its assumption of identical firms, but it was subsequently shown that the results remain largely unchanged with heterogeneous abatement costs [Milliman and Prince (1992)].

In 1996, Jung, Krutilla and Boyd built on Milliman and Prince's basic framework for comparing the effects of alternative policy instruments, but rather than focusing on firm-level changes in producer surplus, they considered heterogeneous firms, and modeled the "market-level incentive" created by various instruments.[61] Their rankings echoed

[58] Downing and White (1986) and Malueg (1989) framed their work in terms of "innovation". Milliman and Prince (1989) used one model to discuss both diffusion and "innovation", the latter being defined essentially as the initial use of the technology by an "innovating" firm.

[59] Zerbe (1970) compared taxes, subsidies, and direct regulation (emissions standards). If a technology reduces emissions levels, rather than costs, taxes are still superior to direct regulation, but subsidies are not.

[60] Downing and White (1986) compared market-based instruments and command-and-control standards, and found for the case of small changes in emissions (so that the optimal pollution tax or permit quantity is unchanged) that all of the instruments except CAC standards would induce the socially optimal level of adoption. But for non-marginal emission changes, where the control authority does not modify the policy (tax or quantity of available permits), market-based instruments would induce too much diffusion, relative to the social optimum. Keohane (2001) demonstrated that the cost savings from adoption will always be greater under a market-based instrument than under an emissions rate standard that induces the same emissions.

[61] This measure is simply the aggregate cost savings to the industry as a whole from adopting the technology.

those of Milliman and Prince (1989): auctioned permits provided the greatest incentive, followed by taxes and subsidies, free permits, and performance standards.

Subsequent theoretical analyses [Parry (1998), Denicolò (1999), Keohane (1999)] clarified several aspects of these rankings. First, there is the question of relative firm-level incentives to adopt a new, cost-saving technology when the price of pollution (permit price or tax level) is endogenous. Milliman and Prince (1989), as well as Jung, Krutilla and Boyd (1996), argued that auctioned permits would provide greater incentives for diffusion than freely-allocated permits, because technology diffusion lowers the equilibrium permit price, bringing greater aggregate benefits of adoption in a regime where all sources are permit buyers (that is, auctions). But when technology diffusion lowers the market price for tradeable permits, all firms benefit from this lower price regardless of whether or not they adopt the given technology [Keohane (1999)]. Thus, if firms are price takers in the permit market, auctioned permits provide no more adoption incentive than freely-allocated permits.

The overall result is that both auctioned and freely-allocated permits are inferior in their diffusion incentives to emission tax systems (but superior to command-and-control instruments). Under tradeable permits, technology diffusion lowers the equilibrium permit price, thereby reducing the incentive for participating firms to adopt. Thus, a permit system provides a lower adoption incentive than a tax, assuming the two instruments are equivalent before diffusion occurs [Denicolò (1999), Keohane (1999)].[62]

More broadly, it appears that an unambiguous exhaustive ranking of instruments is not possible on the basis of theory alone. Parry (1998) found that the welfare gain induced by an emissions tax is *significantly* greater than that induced by tradable permits only in the case of very major innovations. Similarly, Requate (1998) included an explicit model of the final output market, and finds that whether (auctioned) permits or taxes provide stronger incentives to adopt an improved technology depends upon empirical values of relevant parameters.[63]

Furthermore, complete theoretical analysis of the effects of alternative policy instruments on the rate of technological change must include modeling of the government's response to technological change, because the degree to which regulators respond to technologically-induced changes in abatement costs affects the magnitude of the adoption incentive associated with alternative policy instruments.[64] Because technology diffusion presumably lowers the aggregate marginal abatement cost function, it results in a change in the efficient level of control. Hence, following diffusion, the optimal agency response is to set a more ambitious target. Milliman and Prince (1989) examined the incentives facing private industry, under alternative policy instruments, to oppose such

[62] The difference between diffusion incentives of permits and taxes/subsidies depends upon four conditions: (1) some diffusion occurs; (2) firms have rational expectations and recognize that diffusion lowers the permit price; (3) taxes and permits are equivalent *ex ante*; and (4) the level of regulation is fixed over the time horizon considered.

[63] See, also Parry (1995).

[64] See our discussion, above, of "Induced innovation and optimal environmental policy" in Section 3.3.

policy changes. Their conclusion was that firms would oppose optimal agency adjustment of the policy under all instruments *except taxes*. Under an emissions tax, the optimal agency response to cost-reducing technological change is to lower the tax rate (assuming convex damages); under a subsidy, the optimal response is to lower the subsidy; under tradeable permit systems, the optimal response is to decrease the number of available permits, and thereby drive up the permit price. Thus, firms have clear incentives to support the optimal agency response only under an emissions tax regime.

In a comparison of tradeable permits and pollution taxes, Biglaiser, Horowitz and Quiggin (1995) examined these instruments' ability to achieve the first-best outcome in a dynamic setting.[65] They found that effluent taxes can do so, but permits cannot. With an effluent tax, the optimal tax is presumably determined by marginal damages (which the authors assume to be constant), yielding a policy which is time consistent. Whether or not firms adopt a cost-saving technology, the government has no incentive to change the tax rate. From this perspective, however, tradeable permits are not time consistent, because the optimal number of permits in each period depends on both firms' costs, which are determined by all previous investments, and marginal damages. With constant marginal damages, and marginal abatement costs decreasing over time, the optimal number of permits should also be decreasing over time. Firms may internalize this, and thereby invest less than optimally in pollution control technology.

The result of Biglaiser, Horowitz and Quiggin (1995) depends, however, on the assumption of constant marginal damages. If marginal damages are not constant, then the optimal policy is determined by the interaction of marginal damages and marginal abatement costs for both taxes and permits. The result appears to be analogous to Weitzman's (1974) rule: if the marginal damage curve is relatively flat and there is uncertainty in marginal costs (from the regulator's perspective) due to potential innovation at the firm level, then a price instrument is more efficient.

4.3.2. Empirical analyses

Unlike the case of empirical analysis of the effects of alternative policy instruments on technology innovation (Section 3.2.3), where nearly all of the analysis focuses on energy-efficiency technologies, in the case of technology diffusion, there is a small, but significant literature of empirical analyses focused on pollution-abatement technologies *per se*.

One of the great successes during the modern era of environmental policy was the phasedown of lead in gasoline, which took place in the United States principally during the decade of the 1980s. The phasedown was accomplished through a tradeable permit system among refineries, whereby lead rights could be exchanged and/or banked for later use.[66] As noted in Section 4.2.1, Kerr and Newell (forthcoming) used a duration model to assess the effects of the phasedown program on technology diffusion.

[65] See, also, Biglaiser and Horowitz (1995).

[66] The tradeable permit system was also a great success. See Chapter 9 ("Experience with Market-Based Environmental Policy Instruments").

As theory suggests [Malueg (1989)], they found that the tradeable permit system provided incentives for more *efficient* technology adoption decisions, as evidenced by a significant divergence in the adoption behavior of refineries with low versus high compliance costs. Namely, the positive differential in the adoption propensity of expected permit sellers (i.e., low-cost refineries) relative to expected permit buyers (i.e., high-cost refineries) was significantly greater under market-based lead regulation compared to under individually binding performance standards.

Another prominent application of tradeable permit systems which has provided an opportunity for empirical analysis of the effects of policy instruments on technology diffusion is the sulfur dioxide allowance trading program, initiated under the U.S. Clean Air Act amendments of 1990. In an econometric analysis, Keohane (2001) found evidence of the way in which the increased flexibility of a market-based instrument can provide greater incentives for technology adoption. In particular, he found that the choice of whether or not to adopt a "scrubber" to remove sulfur dioxide – rather than purchasing (more costly) low-sulfur coal – was more sensitive to cost differences (between scrubbing and fuel-switching) under the tradeable permit system than under the earlier emissions rate standard.[67]

In an examination of the effects of alternative policy instruments for reducing oxygen-demanding water pollutants, Kemp (1998) found that effluent charges were a significant predictor of adoption of biological treatment by facilities. In earlier work, Purvis and Outlaw (1995) carried out a case study of EPA's permitting process for acceptable water-pollution control technologies in the U.S. livestock production sector. Those authors concluded that the relevant regulations encouraged the use of "time-tested" technologies that provided lower levels of environmental protection than other more innovative ones, simply because producers knew that EPA was more likely to approve a permit that employed the established approach.

Another body of research has examined the effects on technology diffusion of command-and-control environmental standards when they are combined with "differential environmental regulations". In many situations where command-and-control standards have been used, the required level of pollution abatement has been set at a far more stringent level for new sources than for existing ones.[68] There is empirical evidence that such differential environmental regulations have lengthened the time before plants were retired [Maloney and Brady (1988), Nelson, Tietenberg and Donihue (1993)]. Further, this dual system can actually worsen pollution by encouraging firms to keep older, dirtier plants in operation [Stewart (1981), Gollop and Roberts (1983), McCubbins, Noll and Weingast (1989)].

[67] Several additional research efforts on the sulfur dioxide allowance trading program are underway; a number of relevant hypotheses are described by Stavins (1998).

[68] It could be argued that new plants ought to have somewhat more stringent standards if their abatement costs are lower, although such standards should obviously be linked with actual abatement costs, not with the proxy of plant vintage.

In addition to economic incentives, direct regulation, and information provision, some research has emphasized the role that "informal regulation" or community pressure can play in encouraging the adoption of environmentally clean technologies. For example, in an analysis of fuel adoption decisions for traditional brick kilns in Mexico, Blackman and Bannister (1998) suggested that community pressure applied by competing firms and local non-governmental organizations was associated with increased adoption of cleaner fuels, even when those fuels had relatively high variable costs.

Turning from pollution abatement to energy efficiency, the analysis by Jaffe and Stavins (1995), described above in Section 4.2.1, provided evidence of the likely effects of energy taxes and technology adoption subsidies on the adoption of thermal insulation technologies in new residential construction in the United States. Their findings suggest the response to energy taxes would be positive and significant, and that equivalent percentage technology cost subsidies would be about three times as effective as taxes in encouraging adoption, although standard financial analysis would suggest they ought to be about equal in percentage terms. These results were corroborated by the study of residential energy conservation investments by Hassett and Metcalf (1995), also described in Section 4.2.1, which suggested that tax credits for adoption would be up to eight times more effective than "equivalent" energy taxes.

Although empirical evidence from these two studies indicate that subsidies may be more effective than "equivalent" taxes in encouraging technology diffusion, it is important to recognize some disadvantages of such subsidy approaches. First, unlike energy prices, (energy-efficiency) adoption subsidies do not provide incentives to reduce utilization. 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 still receive it. In the presence of fiscal constraints on public spending, this raises questions about the feasibility of subsidies that would be sizable enough to have desired effects.[69]

Given the attention paid to automobile fuel economy over the past two decades, it is not surprising that several hedonic studies of automobiles have addressed or focused on energy-efficiency, including Ohta and Griliches (1976) and Goodman (1983). Atkinson and Halvorsen (1984) found that the fuel efficiency of the new car fleet responds more than proportionally to changes in expected fuel prices. Using an analogue to the hedonic price technique, Wilcox (1984) constructed a quality-adjusted measure of automobile fuel economy over the period 1952–1980, finding that it was positively related to oil prices. Ohta and Griliches (1986) found that gasoline price changes over the period 1970–1981 could alone explain much of the observed change in related automobile characteristics.

[69] Mountain, Stipdonk and Warren (1989) attempted to assess the effects of relative prices on relevant technology diffusion in the Ontario manufacturing sector from 1962 to 1984. They found that fuel choices changed in response to changes in fuel prices, but given the nature of their analysis, they could not distinguish between product substitution and technology diffusion.

What about conventional command-and-control approaches? Jaffe and Stavins (1995) also examined the effects of more conventional regulations on technology diffusion, in the form of state building codes. They found no discernable effects. It is unclear to what extent this is due to inability to measure the true variation across states in the effectiveness of codes, or to codes that were in many cases not binding relative to typical practice. This is a reminder, however, that although price-based policies will always have some effect, typical command-and-control may have little effect if they are set below existing standards of practice.

In a separate analysis of thermal home insulation, this one in the Netherlands, Kemp (1997) found that a threshold model of diffusion (based on a rational choice approach) could not explain observed diffusion patterns. Instead, epidemic models provided a better fit to the data. Kemp also found that there was no significant effect of government subsidies on the adoption of thermal insulation by households.

Attention has also been given to the effects on energy-efficiency technology diffusion of voluntary environmental programs. Howarth, Haddad and Paton (2000) examined two voluntary programs of the U.S. Environmental Protection Agency, the Green Lights and Energy Star programs, both of which are intended to encourage greater private industry use of energy-saving technologies. A natural question from economics is why would firms carry out *additional* technology investments as part of a voluntary agreement? The authors respond that there are a set of agency problems that inhibit economically wise adoption of some technologies (see discussion of these issues in Section 4.2.2). For example, most energy-saving investments are small, and senior staff may rationally choose to restrict funds for small projects that cannot be perfectly monitored. The Green Lights program may be said to attempt to address this type of agency problem by providing information on savings opportunities at the level of the firm where decisions are made.[70]

Although the empirical literature on the effects of policy instruments on technology diffusion by no means settles all of the issues that emerge from the related theoretical studies, a consistent theme that runs through both the pollution-abatement and energy-efficiency empirical analyses is that market-based instruments are decidedly more effective than command-and-control instruments in encouraging the cost-effective adoption and diffusion of relevant new technologies.

5. Conclusion

In opening this chapter, we suggested that an understanding of the process of technological change is important for economic analysis of environmental issues for two broad

[70] Another potential explanation arises where the benefits and costs of a project are born by different units of a firm. Under such circumstances, projects that are good for the firm may not be undertaken. See discussion of this phenomenon in Chapter 9 (“Experience with Market-Based Environmental Policy Instruments”).

reasons. First, the environmental impact of social and economic activity is greatly affected by the rate and direction of technological change. This linkage occurs because new technologies may either create or mitigate pollution, and because many environmental problems and policy responses are evaluated over timeframes in which the cumulative impact of technological changes is likely to be large.

The importance of the first link is manifest in determining the economic and environmental "baseline" against which to measure the impacts of proposed policies. That is, before we can discuss what we should or should not do about some environmental problem, we need to forecast how severe the problem will be in the absence of any action. Such forecasts are always based, in some way, on extrapolation of historical experience. Within that historical experience, the processes of technological change have been operating, often with significant consequences for the severity of environmental impacts. Forecasts for the future based on this historical experience depend profoundly on the relative magnitude of the effects of price-induced technological change, learning-by-doing and learning-by-using, public sector R&D, and exogenous technical progress. Sorting out these influences with respect to environmentally relevant technologies and sectors poses a major modeling and empirical challenge.

A particularly important aspect of this set of issues is the historical significance of "lock-in" phenomena for environmentally significant technologies. We understand the theory of increasing returns and other sources of path dependence, but we have little evidence regarding their quantitative importance. We know that it is theoretically possible, for example, that the dominant place of the internal combustion engine in our economy results from a combination of historical accidents and path dependence. But the actual magnitude of such effects, relative to the role played by the superior attractiveness of the technology to individual users, has enormous consequences for the question of whether developing nations will be able or likely to find a different path.

Another important area is in the conceptual and empirical modeling of how the various stages of technological change are interrelated, how they unfold over time, and the differential impact that various policies (for example, public-sector R&D, R&D subsidies to the private sector, environmental taxes, information programs) may have on each phase of technological change. We have reviewed the existing literature on various aspects of technology policy, but there has been relatively little empirical analysis of these policy options directed specifically at the development of environmentally beneficial technology.

There has been much debate surrounding the "win-win" hypothesis. Much of this debate has been explicitly or implicitly ideological or political. More useful would be detailed examinations regarding the kinds of policies and the kinds of private-sector institutions that are most likely to generate innovative, low-cost solutions to environmental problems.

This observation is a natural bridge to the second broad linkage between technology and environment, the effect of environmental policy interventions on the process of technological change. The empirical evidence to date is generally consistent with theoretical findings that market-based instruments for environmental protection provide better incentives than command-and-control approaches for the cost-effective diffusion of desirable, environmentally-friendly technologies. Further, empirical studies suggest that the response of technological change to relevant price changes can be surprisingly swift in terms of patenting activity and introduction of new model offerings – on the order of five years or less. Substantial diffusion can sometimes take considerably longer, depending on the rate of retirement of previously installed equipment. The longevity of much equipment reinforces the importance of taking a longer-term view toward improvements – on the order of decades. Existing empirical studies have also produced some results that may not be consistent with theoretical expectations, such as the finding from two independent analyses that the diffusion of energy-efficiency technologies is more sensitive to variation in adoption-cost than to commensurate energy price changes. Further theoretical and/or empirical work may resolve this apparent anomaly.

A variety of refutable hypotheses that emerge from theoretical models of alternative instruments have not been tested rigorously with empirical data. For example, the predictions from theory regarding the ranking of alternative environmental policy instruments is well-developed but much of the empirical analysis has focused on energy-efficient technologies, rather than pollution abatement technologies *per se*. The increased use of market-based instruments and performance-based standards has brought with it considerably more data with which hypotheses regarding the effects of policy instruments on technology innovation and diffusion can be tested.

The potential long-run consequences of today's policy choices create a high priority for broadening and deepening our understanding of the effects of environmental policy on innovation and diffusion of new technology. Unfortunately, these issues cannot be resolved at a purely theoretical level, or on the basis of aggregate empirical analyses. For both benefit-cost and cost-effectiveness analysis, we need to know the *magnitudes* of these effects, and these magnitudes are likely to differ across markets, technologies, and institutional settings. Thus, taking seriously the notion of induced technological change and its consequences for environmental policy requires going beyond demonstration studies that test whether or not such effects exist, to carry out detailed analyses in a variety of sectors in order to understand the circumstances under which they are large or small. This will require significant research attention from multiple methodological viewpoints over an extended period of time. But the alternative is continuing to formulate public policies with significant economic and environmental consequences without being able to take into account what is going on "inside the black box" of technological change.

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References

Abramowitz, M. (1956), "Resource and output trends in the U.S. since 1870", American Economic Review Papers and Proceedings 46:5–23.

Aghion, P., and P. Howitt (1998), Endogenous Growth Theory (MIT Press, Cambridge, MA).

Ahmad, S. (1966), "On the theory of induced innovation", Economic Journal 76:344–357.

Aigner D.J., and P. Schmidt (1980), "Specification and estimation of frontier production, profit and cost functions", Journal of Econometrics 13:1–138.

Argote, L., and D. Epple (1990), "Learning curves in manufacturing", Science 247:920–924.

Arrow, K.J. (1962a), "Economic welfare and the allocation of resources for invention", in: R. Nelson, ed., The Rate and Direction of Inventive Activity (Princeton University Press, Princeton, NJ).

Arrow, K.J. (1962b), "The economic implications of learning by doing", Review of Economic Studies 29:155–173.

Arthur, W.B. (1989), "Competing technologies, increasing returns, and lock-in by historical events", Economic Journal 99:116–131.

Arthur, W.B. (1990), "Positive feedbacks in the economy", Scientific American 262:92–95, 98–99.

Arthur, W.B. (1994), Increasing Returns and Path Dependence in the Economy, Economics, Cognition, and Society Series (University of Michigan Press, Ann Arbor, MI).

Atkinson, S.E., and R. Halvorsen (1984), "A new hedonic technique for estimating attribute demand: an application to the demand for automobile fuel efficiency", Review of Economics and Statistics 66:417–426.

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

Berman, E., and L. Bui (1998), "Environmental regulation and labor demand: evidence from the South Coast air basin", Working Paper No. 6776 (National Bureau of Economic Research, Cambridge, MA).

Berndt, E.R., and D.O. Wood (1986), "Energy rice shocks and productivity growth in US and UK manufacturing", Oxford Review of Economic Policy 2:1–31.

Berndt, E.R., and R.S. Pindyck (2000), "Consumption externalities and diffusion in pharmaceutical markets: antiulcer drugs," Working Paper No. 7772 (National Bureau of Economic Research, Cambridge, MA).

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

Besen, S.M., and J. Farrell (1994), "Choosing how to compete: Strategies and tactics in standardization", Journal of Economic Perspectives 8:117–131.

Biglaiser, G., and J.K. Horowitz (1995), "Pollution regulation and incentives for pollution-control research", Journal of Economics and Management Strategy 3:663–684.

Biglaiser, G., J.K. Horowitz and J. Quiggin (1995), "Dynamic pollution regulation", Journal of Regulatory Economics 8:33–44.

Binswanger, H.P. (1974), "A microeconomic approach to innovation", Economic Journal 84:940–958.

Binswanger, H.P., and V.W. Ruttan (1978), Induced Innovation: Technology, Institutions, and Development (John Hopkins University Press, Baltimore, MD).

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

Bound, J., C. Cummins, Z. Griliches, B. Hall and A. Jaffe (1984), "Who does R&D and who patents?", in: Z. Griliches, ed., R&D, Patents and Productivity (University of Chicago Press, Chicago, IL).

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

Boyd, G., and J. McClelland (1999), "The impact of environmental constraints on productivity improvement and energy efficiency an integrated paper and steel plants", The Journal of Economics and Environmental Management 38:121–146.

Boyd, G., and J. Pang (2000), "Estimating the linkage between energy efficiency and productivity", Energy Policy 28:289–296.

Bresnahan, T., and M. Trajtenberg (1995) "General purpose technologies: engines of growth?", Journal of Econometrics, Annals of Econometrics 65:83–108.

Caballero, R.J., and A.B. Jaffe (1993), "How high are the giants' shoulders: an empirical assessment of knowledge spillovers and creative destruction in a model of economic growth", in: O.J. Blanchard and S. Fischer, eds., NBER Macroeconomics Annual (MIT Press, Cambridge, MA) 15–74.

Cadot, O., and B. Sinclair-Desgagne (1996), "Innovation under the threat of stricter environmental standards", in: C. Carraro et al., eds., Environmental Policy and Market Structure (Kluwer Academic Publishers, Dordrecht) 131–141.

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

Carraro, C., and D. Siniscalaco (1994), "Environmental policy reconsidered: The role of technology innovation", European Economic Review 38: 545–555.

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

Cohen, W.M., and R.C. Levin (1989), "Empirical studies of innovation and market structure", in: R. Schmalensee and W. Willig, eds., Handbook of Industrial Organization (North-Holland, Amsterdam) Chapter 18.

Cohen, W.M., R.R. Nelson and J.P. Walsh (2000), "Protecting their intellectual assets: Appropriability conditions and why U.S. manufacturing firms patent (or not)", Working Paper No. 7552 (National Bureau of Economic Research, Cambridge, MA).

Conrad, K. (2000), "Energy tax and competition in energy efficiency: The case of consumer durables", Environmental and Resource Economics 15:159–177.

Cowan, R. (1990), "Nuclear power reactors: A study in technological lock-in", Journal of Economic History 50:541–567.

Cowan, R., and D. Kline (1996), The Implications of Potential 'Lock-In' in Markets for Renewable Energy (National Renewable Energy Laboratory, Golden, CO).

Cowan, R., and P. Gunby (1996), "Sprayed to death: Path dependence, lock-in and pest control strategies", Economic Journal 106:521–542.

Cowan, R., and S. Hulten (1996), "Escaping lock-in: The case of the electric vehicle", Technological Forecasting and Social Change 53:61–79.

Dasgupta, P., and K. Mäler (2000), "Net national product, wealth, and social well-being", Environment and Development Economics 5:69–93.

Dasgupta, P., and J. Stiglitz (1980a), "Industry structure and the nature of innovative activity", Economic Journal 90:266–293.

Dasgupta, P., and J. Stiglitz (1980b), "Uncertainty, industry structure and the speed of R&D", Bell Journal of Economics 11:1–28.

David, P. (1966), "The mechanization of reaping in the ante-bellum Midwest", in: H. Rosovsky, ed., Industrialization in Two Systems (Harvard University Press, Cambridge, MA) 3–39.

David, P. (1969), "A contribution to the theory of diffusion", Mimeo, in: David, P., Behind the Diffusion Curve (Westview Press, Boulder, CO) Chapters 1–3, forthcoming.

David, P., B. Hall and A. Toole (2000), "Is public R&D a complement or substitute for private R&D? A review of the econometric evidence", Research Policy 29:497–529.

David, P.A. (1985), "Clio and the economics of QWERTY", American Economic Review 75:332–337.

David, P.A. (1997), "Path dependence and the quest for historical economics: One more chorus in the ballad of QWERTY", Discussion Papers in Economic and Social History No. 20 (University of Oxford).

Day, G.S., and D.B. Montgomery (1983), "Diagnosing the experience curve", Journal of Marketing 47:22–58.

DeCanio, S.J. (1998), "The efficiency paradox: Bureaucratic and organizational barriers to profitable energy-saving investments", Energy Policy 26:441–454.

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

Denison, E. (1979), Accounting for Slower Economic Growth (Brookings Institution, Washington, DC).
Downing, P.B., and L.J. White (1986), "Innovation in pollution control", Journal of Environmental Economics and Management 13:18–29.
Dutton, J.M., and A. Thomas (1984), "Treating progress functions as a managerial opportunity", Academy of Management Review 9:235–247.
Energy Modeling Forum (1996), Markets for Energy Efficiency, EMF Report 13, Vol. 1 (Stanford University).
Evenson, R.E. (1991), "Patent data by industry: Evidence for invention potential exhaustion?", in: Technology and Productivity: The Challenge for Economic Policy (Organization for Economic Cooperation and Development, Paris) 233–248.
Evenson, R. (1995), "Technology change and technology strategy", in: J. Behrman and T.N. Srinivasan, eds., Handbook of Development Economics, Vol. 3A (North-Holland, Amsterdam).
Fabricant, S. (1954), Economic Progress and Economic Change (National Bureau of Economic Research, New York).
Fare, R., S. Grosskopf and C. Lovell (1994), Production Frontiers (Cambridge University Press, New York).
Farrell, J., and G. Saloner (1985), "Standardization, compatibility, and innovation", RAND Journal of Economics 16:70–83.
Fischer, C., I.W.H. Parry and W.A. Pizer (forthcoming), "Instrument choice for environmental protection when technological innovation is endogenous", Journal of Environmental Economics and Management.
Foray, D. (1997), "The dynamic implications of increasing returns: Technological change and path dependent inefficiency", International Journal of Industrial Organization 15:733–752.
Freeman, A.M., and R.H. Haveman (1972), "Clean rhetoric and dirty water", Public Interest 28:51–65.
Fudenberg, D., R. Gilbert, J. Stiglitz and J. Tirole (1983), "Preemption, leapfrogging and competition in patent races", European Economic Review 22:3–31.
Fudenberg, D., and J. Tirole (1983), "Learning by doing and market performance", Bell Journal of Economics 14:522–530.
Geroski, P.A. (1995), "Markets for technology: Knowledge, innovation and appropriability", in: P. Stoneman, ed., Handbook of the Economics of Innovation and Technological Change (Blackwell, Oxford) 90–131.
Geroski, P.A. (2000), "Models of technology diffusion", Research Policy 29:603–626.
Goldberg, P.K. (1998), "The effects of the corporate average fuel efficiency standards in the U.S.", Journal of Industrial Economics 46:1–3.
Gollop, F.M., and M.J. Roberts (1983), "Environmental regulations and productivity growth: The case of fossil-fueled electric power generation", Journal of Political Economy 91:654–674.
Goodman, A.C. (1983), "Willingness to pay for car efficiency: A hedonic price approach", Journal of Transport Economics 17:247–266.
Goolsbee, A. (1998), "Does government R&D policy mainly benefit scientists and engineers?", American Economic Review 88:298–302.
Goulder, L.H., and K. Mathai (2000), "Optimal CO_2 abatement in the presence of induced technological change", Journal of Environmental Economics and Management 39:1–38.
Goulder, L.H., and S.L. Schneider (1999), "Induced technological change and the attractiveness of CO_2 emissions abatement policies", Resource and Energy Economics 21:211–253.
Gray, W.B. and R.J. Shadbegian (1995), "Pollution abatement costs, regulation, and plant-level productivity", Working Paper No. 4994 (National Bureau of Economic Research).
Gray, W.B., and R.J. Shadbegian (1998), "Environmental regulation, investment timing, and technology choice", Journal of Industrial Economics 46:235–256.
Greene, D.L. (1990), "CAFE or price?: An analysis of the effects of federal fuel economy regulations and gasoline price on new car MPG, 1978–89", The Energy Journal 11(3):37–57.
Greening, L.A., A.H. Sanstad and J.E. McMahon (1997) "Effects of appliance standards on product price and attributes: An hedonic pricing model", Journal of Regulatory Economics 11:181–194.
Greenstone, M. (2002), "The impacts of environmental regulations on industrial activity: Evidence from the 1970 and 1977 Clean Air Act amendments and the census of manufactures", Journal of Political Economy 110(6):1175–1219.

Griliches, Z. (1957), "Hybrid corn: An exploration in the economics of technical change", Econometrica 48:501–522.

Griliches, Z. (1979), "Issues in assessing the contribution of research and development to productivity growth", Bell Journal of Economics 10:92–116.

Griliches, Z. (1984), R&D, Patents and Productivity (University of Chicago Press, Chicago, IL).

Griliches, Z. (1990), "Patent statistics as economic indicators: A survey", Journal of Economic Literature 28:1661–1707.

Griliches, Z. (1992), "The search for R&D spillovers", Scandinavian Journal of Economics 94:S29–S47.

Griliches, Z. (1994), "Productivity, R&D and the data constraint", American Economic Review 84:1–23.

Griliches, Z. (1998), R&D and Productivity, The Econometric Evidence (University of Chicago Press, Chicago, IL).

Grossman, G., and E. Helpman (1994), "Endogenous innovation in the theory of growth", Journal of Economic Perspectives 8:23–44.

Grossman, G., and E. Helpman (1995), Technology and trade, in: G.M. Grossman and K. Rogoff, eds., Handbook of International Economics, Vol. 3 (North-Holland, Amsterdam).

Grubb, M. (1997), "Technologies, energy systems, and the timing of CO_2 emissions abatement: An overview of economic issues", Energy Policy 25(2):159–172.

Grübler, A., and S. Messner (1999), "Technological change and the timing of mitigation measures", Energy Economics 20:495–512.

Grübler, A., N. Nakicenovic and D.G. Victor (1999), "Dynamics of energy technologies and global change", Energy Policy 27:247–280.

Guellec, D., and B. van Pottelsberghe (2000), "The impact of public R&D expenditure on business R&D", DSTI Working Paper (Organization for Economic Cooperation and Development, Paris).

Ha-Duong, M., M. Grubb and J.-C. Hourcade (1997), "Influence of socioeconomic inertia and uncertainty on optimal CO_2 abatement", Nature 390:270–273.

Hahn, R.W., and R.N. Stavins (1991), "Incentive-based environmental regulation: A new era from an old idea?" Ecology Law Quarterly 18:1–42.

Hall, B., and J. Van Reenen (2000), "How effective are fiscal incentives for R&D? A review of the evidence", Research Policy 29:449–469.

Hall, B., A. Jaffe and M. Trajtenberg (2000), "Market value and patent citations: A first look", Working Paper No. 7741 (National Bureau of Economic Research).

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

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

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

Helpman, E. (ed.) (1998), General Purpose Technologies and Economic Growth (MIT Press, Cambridge, MA).

Hicks, J. (1932), The Theory of Wages (Macmillan & Co, London).

Hockenstein, J.B., R.N. Stavins and B.W. Whitehead (1997), "Creating the next generation of market-based environmental tools", Environment 39(4):12–20, 30–33.

Holmström, B.R., and J. Tirole (1987), "The theory of the firm", in: R. Schmalensee and R. Willig, eds., Handbook of Industrial Organization, Vol. 1 (North-Holland, Amsterdam) 61–133.

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

Interlaboratory Working Group (1997), "Scenarios of carbon reductions: potential impacts of energy technologies by 2010 and beyond (Office of Energy Efficiency and Renewable Technologies, U.S. Department of Energy, Washington, DC).

Islas, J. (1997), "Getting round the lock-in in electricity generating systems: The example of the gas turbine", Research Policy 26:49–66.

Jaffe, A.B. (1986), “Technological opportunity and spillovers of R&D: Evidence from firms’ patents, profits and market value”, American Economic Review 76:984–1001.
Jaffe, A.B. (1988), “Demand and supply influences in R&D intensity and productivity growth”, Review of Economics and Statistics 70:431–437.
Jaffe, A.B. (1998a), “The importance of ‘spillovers’ in the policy mission of the advanced technology program”, Journal of Technology Transfer, Summer 1998:11–19.
Jaffe, A.B. (1998b), “Measurement issues”, in: L.M. Branscomb and J.H. Keller, eds., Investing in Innovation (MIT Press, Cambridge, MA).
Jaffe, A.B. (2000), “The U.S. patent system in transition: policy innovation and the innovation process”, Research Policy 29:531–558.
Jaffe, A.B., and K. Palmer (1997), “Environmental regulation and innovation: A panel data study”, Review of Economics and Statistics 79:610–619.
Jaffe, A.B., and R.N. Stavins (1994), “The energy paradox and the diffusion of conservation technology”, Resource and Energy Economics 16:91–122.
Jaffe, A.B. and R.N. Stavins (1995), “Dynamic incentives of environmental regulations: The effects of alternative policy instruments on technology diffusion”, Journal of Environmental Economics & Management 29:S43–S63.
Jaffe, A.B., R.G. Newell and R.N. Stavins (1999), “Energy-efficient technologies and climate change policies: Issues and evidence”, in: M. Toman, ed., Climate Change Economics and Policy (Resources for the Future, Washington, DC) 171–181.
Jaffe, A.B., S. Peterson, P. Portney and R.N. Stavins (1995), “Environmental regulation and the competitiveness of U.S. manufacturing: What does the evidence tell us?”, Journal of Economic Literature 33:132–163.
Jones, C., and J. Williams (1998), “Measuring the social return to R&D”, Quarterly Journal of Economics 113:1119–1135.
Jorgenson, D. (1984), “The role of energy in productivity growth”, in: J.W. Kendrick, ed., International Comparisons of Productivity and the Causes of the Slowdown (Ballinger, Cambridge, MA) 279–323.
Jorgenson, D. (1990), “Productivity and economic growth”, in: E. Berndt and J. Triplett, eds., Fifty Years of Economic Measurement (University of Chicago Press, Chicago, IL) 19–118.
Jorgenson, D., and Z. Griliches (1967), “The explanation of productivity change”, Review of Economic Studies 34:249–283.
Jorgenson, D.W., and K.J. Stiroh (2000), “Raising the speed limit: U.S. economic growth in the information age”, Brookings Papers on Economic Activity 1:125–211.
Joskow, P.L., and G.A. Rozanski (1979), “The effects of learning by doing on nuclear plant operating reliability”, Review of Economics and Statistics 61:161–168.
Jung, C.H., K. Krutilla and R. Boyd (1996), “Incentives for advanced pollution abatement technology at the industry level: An evaluation of policy alternatives”, Journal of Environmental Economics and Management 30:95–111.
Kamien, M.I., and N.L. Schwartz (1968), “Optimal induced technical change”, Econometrica 36:1–17.
Karshenas, M., and P. Stoneman (1995), “Technological diffusion”, in: P. Stoneman, ed., Handbook of the Economics of Innovation and Technological Change (Blackwell Publishers, Oxford).
Katsoulacos, Y., and A. Xepapadeas (1996), “Environmental innovation, spillovers and optimal policy rules”, in: C. Carraro et al., eds., Environmental Policy and Market Structure (Kluwer Academic Publishers, Dordrecht) 143–150.
Katz, M.L., and C. Shapiro (1986), “Technology adoption in the presence of network externalities”, Journal of Political Economy 94:822–841.
Katz, M.L., and C. Shapiro (1994), “Systems competition and network effects”, Journal of Economic Perspectives 8:93–115.
Kemp, R. (1997), Environmental Policy and Technical Change (Edward Elgar, Cheltenham, UK).
Kemp, R. (1998), “The diffusion of biological waste-water treatment plants in the Dutch food and beverage industry”, Environmental and Resource Economics 12:113–136.

Kemp, R., and L. Soete (1990), "Inside the 'Green Box': On the economics of technological change and the environment", in: Freeman, C. and L. Soete, eds., New Explorations in the Economics of Technological Change (Pinter, London).
Kendrick, J.W. (1956), Productivity Trends: Capital and Labor (National Bureau of Economic Research, New York).
Keohane, N.O. (1999), "Policy instruments and the diffusion of pollution abatement technology", Mimeo (Harvard University).
Keohane, N.O. (2001), "Essays in the economics of environmental policy", Ph.D. Dissertation (Harvard University), unpublished.
Kerr, S., and R.G. Newell (forthcoming), "Policy-induced technology adoption: Evidence from the U.S. lead phasedown", Journal of Industrial Economics.
Klette, T., J. Møen and Z. Griliches (2000), "Do subsidies to commercial R&D reduce market failures? Microeconometric evaluation studies", Research Policy 29:471–495.
Kneese, A., and C. Schultze (1975), Pollution, Prices, and Public Policy (Brookings Institution, Washington, DC).
Kolstad, C.D., and M.H.L. Turnovsky (1998), "Cost functions and nonlinear prices: Estimating a technology with quality-differentiated inputs", Review of Economics & Statistics 80:444–453.
Laffont, J., and J. Tirole (1996a), "Pollution permits and compliance strategies", Journal of Public Economics 62:85–125.
Laffont, J., and J. Tirole (1996b), "Pollution permits and environmental innovation", Journal of Public Economics 62:127–140.
Lancaster, K. (1971), Consumer Demand: A New Approach (Columbia University Press, New York).
Landjouw, J.O., and A. Mody (1996), "Innovation and the international diffusion of environmentally responsive technology", Research Policy 25:549–571.
Lanjouw, J., and M. Schankerman (1999), "The quality of ideas: Measuring innovation with multiple indicators," Working Paper No. 7345 (National Bureau of Economic Research).
Leibenstein, H. (1966), "Allocative efficiency as 'X-inefficiency' ", American Economic Review 56:392–415.
Lester, R.K., and M.J. McCabe (1993), "The effect of industrial structure on learning by doing in nuclear power plant operation", RAND Journal of Economics 24:418–438.
Levin, R.C., and P.C. Reiss (1988), "Cost-reducing and demand-creating R&D with spillovers", RAND Journal of Economics 19:538–556.
Levin, S., S. Levin and J. Meisel (1987), "A dynamic analysis of the adoption of a new technology: The case of optical scanners", Review of Economics and Statistics 69:12–17.
Liebowitz, S.J., and S.E. Margolis (1994), "Network externality: An uncommon tragedy", Journal of Economic Perspectives 8:133–150.
Lucas, R.E. (1988), "On the mechanics of economic development", Journal of Monetary Economics 22:3–42.
Macauley, M.K., and T.J. Brennan (2001), "Enforcing environmental regulation: Implications of remote sensing technology", in: P. Fishbeck and S. Farrow, eds., Improving Regulation: Cases in Environmental, Health, and Safety (Resources for the Future, Washington, DC).
Magat, W.A. (1978), "Pollution control and technological advance: A dynamic model of the firm", Journal of Environmental Economics and Management 5:1–25.
Magat, W.A. (1979), "The effects of environmental regulation on innovation", Law and Contemporary Problems 43:3–25.
Majd, S., and R.S. Pindyck (1989), "The learning curve and optimal production under uncertainty", Rand Journal of Economics 20:331–343.
Maloney, M.T., and G.L. Brady (1988), "Capital turnover and marketable pollution rights", Journal of Law and Economics 31:203–226.
Malueg, D.A. (1989), "Emission credit trading and the incentive to adopt new pollution abatement technology", Journal of Environmental Economics and Management 16:52–57.
Mankiw, N.G., and M.D. Whinston (1986), "Free entry and social inefficiency", RAND Journal of Economics 17:48–58.

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

Mansfield, E. (1989), "Industrial robots in Japan and the USA", Research Policy 18:183–192.

Marin, A. (1991), "Firm incentives to promote technological change in pollution control: Comment", Journal of Environmental Economics and Management 21:297–300.

Marshall, A. (1922), Principles of Economics, Book 5 (Macmillan & Co, London) Chapter 6.

Martin, S., and J. Scott (2000), "The nature of innovation market failure and the design of public support for private innovation", Research Policy 29:437–448.

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

Metcalf, G.E., and K.A. Hassett (1999), "Measuring the energy savings from home improvement investments: Evidence from monthly billing data", The Review of Economics and Statistics 81:516–528.

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

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

Montero, J.P. (2002), "Market structure and environmental innovation", Journal of Applied Economics 5(2):293–325.

Mowery, D., and N. Rosenberg (1989), Technology and the Pursuit of Economic Growth (Oxford University Press, Oxford).

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

Nakicenovic, N. (1996), "Technological change and learning", in: N. Nakicenovic, W.D. Nordhaus, R. Richels and F.L. Toth, eds., Climate Change: Integrating Science, Economics, and Policy (International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria).

National Science Board (1998), Science and Engineering Indicators – 1998 (National Science Foundation, Washington), available online at http://www.nsf.gov/sbe/srs/seind98/frames.htm.

Neij, L. (1997), "Use of experience curves to analyze the prospects for diffusion and adoption of renewable energy technology", Energy Policy 23:1099–1107.

Nelson, R., and S. Winter (1982), An Evolutionary Theory of Economic Change (The Belknap Press of Harvard University Press, Cambridge, MA).

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

Newell, R.G., A.B. Jaffe and R.N. Stavins (1999), "The induced innovation hypothesis and energy-saving technological change", The Quarterly Journal of Economics 114:941–975.

Newell, R.G. (1997), Environmental Policy and Technological Change, Ph.D. Dissertation (Harvard University).

Nijkamp, P., C.A. Rodenburg and E.T. Verhoef (2001), "The adoption and diffusion of environmentally friendly technologies among firms", International Journal of Environmental Technology and Management 1(1/2): 87–103.

Nordhaus, W.D. (2000), "Modeling induced innovation in climate-change policy", Mimeo (Yale University).

Ohta, M., and Z. Griliches (1976), "Automobile prices revisited: Extensions of the hedonic hypothesis", in: N.E. Terleckyj, ed., Household Production and Consumption (National Bureau of Economic Research, New York).

Ohta, M., and Z. Griliches (1986), "Automobile prices and quality: Did the gasoline price increases change consumer tastes in the U.S.?", Journal of Business & Economic Statistics 4:187–198.

Organization for Economic Cooperation and Development (2000), Basic Science and Technology Statistics: 1999 Edition (Organization for Economic Cooperation and Development, Paris).

Orr, L. (1976), "Incentive for innovation as the basis for effluent charge strategy", American Economic Review 66:441–447.

Oster, S. (1982), “The diffusion of innovation among steel firms: The basic oxygen furnace”, The Bell Journal of Economics 13:45–56.

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

Palmer, K., W.E. Oates and P.R. Portney (1995), “Tightening environmental standards: The benefit-cost or the no-cost paradigm?” Journal of Economic Perspectives 9:119–132.

Parry, I.W., W.A. Pizer and C. Fischer (forthcoming), “How large are the welfare gains from technological innovation induced by environmental policies?”, Journal of Regulatory Economics.

Parry, I.W.H. (1995), “Optimal pollution taxes and endogenous technological progress”, Resource and Energy Economics 17:69–85.

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

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

Pizer, W.A., W. Harrington, R.J. Kopp, R.D. Morgenstern and J. Shih (2001), “Technology adoption and aggregate energy efficiency”, Resources for the Future Discussion Paper 01-21 (Resources for the Future, Washington, DC).

Popp, D. (2001), “The effect of new technology on energy consumption”, Resource and Energy Economics 23(4):215–239.

Popp, D. (2002), “Induced innovation and energy prices”, American Economic Review, 92(1):339–349.

Porter, M.E., and C. van der Linde (1995), “Toward a new conception of the environment-competitiveness relationship”, Journal of Economic Perspectives 9:97–118.

Purvis, A., and J. Outlaw (1995), “What we know about technological innovation to achieve environmental compliance: Policy issues for an industrializing animal agriculture sector”, American Journal of Agricultural Economics 77:1237–1243.

Reinganum, J. (1982), “A dynamic game of R&D: patent protection and competitive behavior”, Econometrica 50:671–688.

Reinganum, J. (1989), “The timing of innovation: Research, development and diffusion”, in: R. Schmalensee and R. Willig, eds., Handbook of Industrial Organization, Vol. 1 (North-Holland, Amsterdam) 850–908.

Reinhardt, F.L. (2000), Down to Earth: Applying Business Principles to Environmental Management (Harvard Business School Press, Boston, MA).

Reppelin-Hill, V. (1999), “Trade and environment: An empirical analysis of the technology effect in the steel industry”, Journal of Environmental Economics and Management 38:283–301.

Requate, T. (1998), “Incentives to innovate under emission taxes and tradeable permits”, European Journal of Political Economy 14:139–165.

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).

Romer, P.M. (1990), “Endogenous technical change”, Journal of Political Economy 98:S71–S102.

Romer, P.M. (1994), “The origins of endogenous growth”, Journal of Economic Perspectives 8:3–22.

Rose, N., and P. Joskow (1990), “The diffusion of new technologies: Evidence from the electric utility industry”, RAND Journal of Economics 21:354–373.

Rosenberg, N. (1982), Inside the Black Box (Cambridge University Press, Cambridge, UK).

Rosenberg, N. (1990), “Why do firms do basic research (with their own money)?”, Research Policy 19:165–174.

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

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

Ruttan, V.W. (1997), “Induced innovation, evolutionary theory and path dependence: Sources of technical change”, Economic Journal 107:1520–1529.

Ruttan, V.W. (2000), "Technology, resources and environment", in: V.W. Ruttan, ed., Technology, Growth and Environment: An Induced Innovation Perspective (University of Minnesota, St. Paul, MN).
Sanstad, A., C. Blumstein and S. Stoft (1995), "How high are option values in energy-efficiency investments", Energy Policy 23:739–743.
Scherer, F. (1986), Innovation and Growth, Schumpeterian Perspectives (The MIT Press, Cambridge, MA).
Scherer, F.M., and D. Harhoff (2000), "Technology policy for a world of skew-distributed outcomes", Research Policy 29:559–566.
Scherer, F., D. Harhoff and J. Kukies (2000), "Uncertainty and the size distribution of rewards from technological innovation", Journal of Evolutionary Economics 10:175–200.
Schmalensee, R. (1994), "The costs of environmental protection", in: M.B. Kotowski, ed., Balancing Economic Growth and Environmental Goals (American Council for Capital Formation, Center for Policy Research, Washington, DC) 55–75.
Schmookler, J. (1966), Invention and Economic Growth (Harvard University Press, Cambridge, MA).
Schumpeter, J. (1942), Capitalism, Socialism and Democracy (Harper, New York).
Shama, A. (1983), "Energy conservation in U.S. buildings, solving the high potential/low adoption paradox from a behavioral perspective", Energy Policy 11:148–168.
Sharp, J.A., and D.H.R. Price (1990), "Experience curve models in the electricity supply industry", International Journal of Forecasting 6:531–540.
Shrestha, R.M., and B.K. Karmacharya (1998), "Testing of barriers to the adoption of energy-efficient lamps in Nepal", The Journal of Energy and Development 23(1):71–82.
Simon, H.A. (1947), Administrative Behavior: A Study of Decision-Making Processes in Administrative Organization (Macmillan Co., New York).
Solow, R.M. (1957), "Technical change and the aggregate production function", Review of Economics and Statistics 39:312–320.
Solow, R.M. (1999), "Neoclassical growth theory", in: J.B. Taylor and M. Woodford, eds., Handbook of Macroeconomics, Vol. 1A (North-Holland, Amsterdam).
Solow, R.M. (2000), Growth Theory: An Exposition (Oxford University Press, New York).
Spence, A.M. (1981), "The learning curve and competition", Bell Journal of Economics 12:49–70.
Spence, A.M. (1984), "Cost reduction, competition and industry performance", Econometrica 52(1):101–121.
Stavins, R.N. (1998), "What have we learned from the grand policy experiment: Lessons from SO_2 allowance trading", Journal of Economic Perspectives 12(3):69–88.
Stewart, R.B. (1981), "Regulation, innovation, and administrative law: A conceptual framework", California Law Review 69:1256–1270.
Stoneman, P. (1983), The Economic Analysis of Technological Change (Oxford University Press, Oxford, UK).
Stoneman, P. (1987), The Economic Analysis of Technology Policy (Oxford University Press, Oxford, UK).
Sunding, D., and D. Zilberman (2000), "The agricultural innovation process: Research and technology adoption in a changing agricultural industry", in: B. Gardner and G.C. Rausser, eds., Handbook of Agricultural and Resource Economics (North-Holland, Amsterdam), forthcoming.
Sutton, J. (1998), Technology and Market Structure (The MIT Press, Cambridge, MA).
Thirtle, C.G., and V.W. Ruttan (1987), "The role of demand and supply in the generation and diffusion of technical change", Fundamentals of Pure and Applied Economics, Vol. 21 (Harwood Academic Publishers, New York).
Tirole, J. (1988), The Theory of Industrial Organization (The MIT Press, Cambridge, MA).
Trajtenberg, M. (1990), Economic Analysis of Product Innovation: The Case of CT Scanners (Harvard University Press, Cambridge, MA).
Trajtenberg, M. (2000), "R&D Policy in Israel: An Overview and Reassessment", Working Paper No. 7930 (National Bureau of Economic Research).
Ulph, A., and D. Ulph (1996), "Trade, strategic innovation and strategic environmental policy – a general analysis", in: C. Carraro et al., eds., Environmental Policy and Market Structure (Kluwer Academic Publishers, Dordrecht) 181–208.

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

U.S. Bureau of Labor Statistics (2000), Multifactor Productivity Trends, 1998 (U.S. Bureau of Labor Statistics, Washington, DC), available at http://www.bls.gov/news.release/prod3.toc.htm.

Weitzman, M.L. (1974), "Prices vs. quantities", Review of Economic Studies 41:477–491.

Weyant, J.P. (1993), "Costs of reducing global carbon emissions", Journal of Economic Perspectives 7:27–46.

Wigley, T.M.L., R. Richels and J.A. Edmonds (1996), "Economic and environmental choices in the stabilization of atmospheric CO_2 concentrations", Nature 379(18):240–243.

Wilcox, J. (1984), "Automobile fuel efficiency: measurement and explanation", Economic Inquiry 22:375–385.

Winter, S.G., Y.M. Kaniovski and G. Dosi (2000), "Modeling industrial dynamics with innovative entrants", Structural Change and Economic Dynamics 11:255–293.

Yaisawarng, S., and J.D. Klein (1994), "The effects of sulfur dioxide controls on productivity change in the U.S. electric power industry", Review of Economics & Statistics 76:447–460.

Yelle, L.E. (1979), "The learning curve: Historical review and comprehensive survey", Decision Sciences 10:302–328.

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

Zimmerman, M.B. (1982), "Learning effects and the commercialization of new energy technologies: The case of nuclear power", Bell Journal of Economics 13:297–310.