The Energy Paradox
and the Diffusion of Conservation Technology

ADAM B. JAFFE AND ROBERT N. STAVINS

The energy paradox and the diffusion of conservation technology

Adam B. Jaffe[a] and Robert N. Stavins[b*]

[a] *Department of Economics, Harvard University, and National Bureau of Economic Research, Cambridge, MA, USA*
[b] *John F. Kennedy School of Government, Harvard University, and Resources for the Future, 79 John F. Kennedy Street, Cambridge, MA 02138, USA*

Abstract

We develop a framework for thinking about the 'paradox' of very gradual diffusion of apparently cost-effective energy-conservation technologies. Our analysis provides some keys to understanding why this technology-diffusion process *is* gradual, and focuses attention on the factors that cause this to be the case, including those associated with potential market failures – information problems, principal/agent slippage, and unobserved costs – and those explanations that do not represent market failures – private information costs, high discount rates, and heterogeneity among potential adopters. Additionally, our analysis indicates how alternative policy instruments – both economic incentives and direct regulations – can hasten the diffusion of energy-conserving technologies.

Key words: Energy efficiency; Conservation; Technology diffusion
JEL classification: Q48; O33

Introduction

In the long run, the development and widespread adoption of new technologies can greatly ameliorate what, in the short run, sometimes appear to be overwhelming conflicts between economic well-being and environmental quality. With existing technology, problems such as emissions of greenhouse gases and disposal of hazardous wastes pose difficult choices between potentially irreversible damage to the environment and high economic costs of control. But if history is any guide, we know that over a period of decades changes in technology can alter dramatically the nature of these tradeoffs. Therefore, the effect of public 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 Schultz, 1978).

In order to achieve widespread benefits from new technology, three steps are required: *invention* – the development of a new technical idea; *innovation* – the incorporation of a new idea into a marketable product or a usable commercial process for the first time; and *diffusion* – the typically gradual process of adoption of the new product or process by potential users. The third element – the diffusion phase – has historically been neglected both by research and public policy.[1]

Recently, however, technology diffusion has moved into the policy spotlight as a result of concern over the role played by carbon dioxide (CO_2) emissions in fostering global climate change. The largest anthropogenic source of CO_2 emissions is combustion of fossil fuels for energy generation, so reduction in energy use is potentially one of the most potent options that exists for reducing the risk of global climate change. It is widely accepted that energy use could be reduced significantly through more widespread adoption of existing technologies (Norberg-Bohm, 1990). It is almost as widely accepted that much un-adopted technology is cost-effective at current prices.[2] This has led to a decade-long discussion of the 'paradox' (Shama,

[1] For a recent example of an investigation of the innovation component, see Georg et al. (1992). A set of case studies of the three elements – in the context of 'environmental technologies' – is provided by Kemp et al. (1992).

[2] The constraint on energy improvements in the short term is not primarily technological. The primary barrier is insufficient implementation of existing cost-effective technologies' (Carlsmith et al., 1990, p. 25). 'Our stock of housing and appliances is still far less energy efficient than would be economically optimal' (U.S. Department of Energy 1991, p. 42), Prominent support for this notion came from the National Academy of Sciences (1991) in its finding that U.S. carbon dioxide (CO_2) emissions could be significantly reduced as part of an effort to address the threat of greenhouse-induced climate change – through the adoption of currently cost-effective energy efficiency technologies.

1983) of inadequate diffusion of apparently cost-effective energy-conserving technologies.

If all of the costs and benefits of energy use were internalized, then the potential existence of such a paradox might be of academic interest, but it would not have obvious policy relevance. If there are significant externalities associated with burning fossil fuels, however, then the paradox becomes much more important. Indeed, the existence of such externalities could justify public policies to reduce energy use.

The relative effectiveness and efficiency of alternative policy mechanisms to achieve this goal will depend on the nature of the energy-conserving technology diffusion process. In particular, if the diffusion process is unaffected by economic forces, then the economist's standard argument that some sort of market mechanism is the best way to internalize the social costs of CO_2 emissions would presumably carry much less weight than otherwise. If people are not using technologies that are cost-effective at today's prices, should we rely on carbon taxes or other policies that would raise the cost of energy use? We are much more likely to achieve success, the argument goes, with regulatory mandates requiring the use of particular technologies.[3]

The climate-change/energy-conservation arena presents a particularly timely example of the broader debate about the relative merits of 'command-and-control' regulation – legal standards requiring particular levels of performance or particular technologies – and 'economic incentives' – such as emission charges, tradeable permits, deposit-refund systems, and elimination of government subsidies.[4]

This paper provides a conceptual framework within which we can examine

---

[3] The technology-standard approach has been the favored approach in the past and continues to be favored by most politicians today. Widely discussed possibilities include uniform national building codes and mandatory energy efficiency standards for heating and cooling equipment and other major appliances.

[4] For descriptions and examples of these various categories of command-and-control and market-based environmental-protection mechanisms, see Hahn and Stavins (1991). There are two distinct dimensions along which incentive-based and conventional environmental policies differ. First, incentive-based policies can lead, in theory, to a cost-effective (cost-minimizing) allocation among firms of the overall burden of achieving any given level of environmental protection, in contrast with technology standards and (uniform) performance standards, which typically do not lead to cost-effective allocations. Second, incentive-based approaches can result in 'dynamic efficiency' by providing on-going incentives for firms to adopt new, improved (lower cost) pollution-control technologies; this is in contrast with command-and-control approaches, which tend to lock in existing technologies (Bohm and Russell, 1985). It is this latter, dynamic, superiority that is examined in this paper. In general and on a theoretical level, the superiority (in terms of inducing technological innovation and diffusion) of incentive-based approaches, compared with conventional command-and-control approaches is clear (Milliman and Prince, 1989; Downing and White, 1986). It should also be recognized, however, that under certain circumstances incentive-based approaches could actually reduce firms' incentives to adopt new technology (Malueg, 1989).

two inextricably linked questions: what factors determine the rate of adoption of energy-conserving technologies; and what effects can economic incentives and conventional regulations have in encouraging such adoption. By framing these questions within economic models, we hope to help clarify the 'paradox' of existing adoption patterns.[5] We proceed by developing a pair of theoretical models that: (1) are rooted in existing thought on the economics of technology diffusion; (2) are based on firm and individual optimizing behavior; (3) incorporate aspects of the process that some observers claim explain the 'paradox;' and (4) allow for the impact of regulation on the adoption decision.

Our two models reflect the two important contexts in which adoption decisions take place. First, there are situations in which a particular activity is being undertaken which *prompts* a decision about *whether or not* to incorporate an energy-conserving technology at a specified point in time. Second, there are situations in which a decision must be made not only about whether or not to adopt an energy-efficiency technology, but also about *when* to do so, if at all. In order to analyze both situations, we consider the incorporation of energy-conserving technologies in new residential structures and in existing ones. The use of such technologies in buildings is important in overall energy use,[6] and the existence of building codes provides a context in which to contrast the potential effects of economic incentives and regulations in encouraging adoption behavior.

The next section of the paper provides some background on technology diffusion and energy-conservation investment decisions. Section 3 develops a theoretical model of the decision to incorporate a given technology in a newly constructed home, while Section 4 focuses on decisions to retrofit a technology in an existing structure. We explore the policy implications of the analysis in Section 5, and we provide a brief summary and conclusion in Section 6.

2. Background: technology diffusion and energy conservation

2.1. Economic models of technological diffusion[7]

From the mechanical reaper of the nineteenth century (David, 1966), through hybrid corn seed (Griliches, 1957), chemical process innovations

---

[5] Needless to say, approaches other than economic models can be used to examine these questions. See, for example, Cebon (1992).

[6] About 25% of primary energy consumption is used for heating, cooling, hot water and lighting in residential and commercial buildings (U.S. Department of Energy, 1991).

[7] This section provides a brief overview of the technology diffusion literature. For more thorough reviews, see Stoneman (1983); Stoneman (1986); David (1986); and Thirtle and Ruttan (1986).

(Davies, 1979), steel furnaces (Oster, 1982) and optical scanners (Levin et al., 1987) in the twentieth century, research has consistently shown that diffusion of new, economically superior technologies is never instantaneous. It typically follows an s-shaped or 'sigmoid' curve, such that the adoption rate is initially slow, then faster, and then slower again as saturation is approached. Most models of technological diffusion are intended to produce dynamic paths with these general properties.

Perhaps the simplest way to generate an s-shaped diffusion curve is with an 'epidemic model' (Stoneman, 1983). This approach focuses on the spread of information regarding the existence and profitability of the innovation. People cannot use a technology of which they are unaware, and they are unlikely to use a technology that they do not understand. If knowledge of existence and profitability are increasing functions of prevalence of use of a technology, then use of that technology can be expected to spread like a disease: the probability that a non-user will adopt in any time period will be an increasing function of the fraction of the population that has already adopted. If we denote the stock of users that have adopted the technology by time t as S_t, and the universe of potential adopters as U_t, then a simple epidemic model suggests that the technology will diffuse according to:

$$\frac{dS_t}{dt} = a \cdot \left(\frac{S_t}{U_t}\right) \cdot \left(1 - \frac{S_t}{U_t}\right) \tag{1}$$

The first factor in brackets is the probability of encountering an 'infected' agent and contracting the disease (adopting); the second factor is the proportion of the population that is 'healthy' and thereby candidates for 'infection' (adoption). The multiplier, a, is the 'infectiousness' of the disease, and parameterizes the speed of the diffusion process. Integration of this equation with respect to time yields the logistic function with the characteristic shape.

In its simplest form, the epidemic model has little economic or other analytical content, but the constant, a, can depend on economic forces. In this way, the 'infectiousness' of the disease can be linked to the profitability of the diffusing innovation. The pioneering work of Griliches (1957) established the notion that the process of a gradually diffusing, superior technology could thus be understood in an economic framework, with the rate of diffusion being partly determined by the (expected) economic return to adoption. Subsequently, Mansfield (1968) demonstrated that the rate of diffusion can also depend on the size of adopting firms, the perceived riskiness of new technology, and the absolute magnitude of the required investment. In such models, it is possible that the new technology is profitable for all firms; it takes time for all to adopt only because some have not been 'exposed.' Indeed, these models generate gradual diffusion even if all

potential adopters are identical. Economic factors explain which innovations diffuse fastest, or in which regions a particular innovation diffuses fastest, but not which potential adopters actually use the technology first.

As an alternative, David (1969) proposed heterogeneity among potential adopters as an explanation for the gradual nature of the diffusion process. His model – based on inherent differences among adopters – is sometimes known as the 'probit' approach (Stoneman, 1983).[8] David posited that the population of potential adopters of an innovation differ from one another in ways that affect the desirability of technological adoption. For example, consider the innovation to be triple-pane window glazing and the important dimension that affects its desirability to be local climatic conditions. An individual deciding whether to adopt this innovation faces an investment decision. He can incur a certain cost today, which will reduce his home heating costs now and in the future, or he can wait, thus saving the cost of purchasing and installing the technology. The colder the climate in winter and the warmer the climate in summer, the more attractive will this investment be.

In this framework, one can think of there being a 'threshold' climatic index,[9] above which it is profitable to adopt the innovation and below which it is not. Over time, the cost of the triple-pane windows may fall and/ or their performance may improve, encouraging homes in more temperate climates to adopt the technology as the climatic threshold shifts to the left. This movement of the threshold sweeps out the distribution of climatic indexes; if this distribution is smooth and unimodal, the familiar sigmoid path of diffusion will result.

Such a conceptual model of diffusion is applicable to any situation in which potential adopters trade off some up-front cost – cost of equipment, cost of learning about a new technology, cost of adapting existing processes, etc. – against expected future benefits of the technology. The improvement in the attractiveness of the innovation over time can also be very general, including the spread of better information on its use, which makes it less costly to adopt. Finally, of course, it is not essential that the value of the

---

[8] The term refers to the commonly employed statistical model for limited dependent variables, which shares a conceptual foundation with David's diffusion model. See also Davies (1979); Sommers (1980); and Caswell et al. (1990); and Caswell and Zilberman (1990). Another set of models have also focused on the impacts of firm size and market structure on adoption decisions; hazard-rate models are employed by Hannan and McDowell (1984) to examine the factors affecting the adoption of automated teller machines (ATM's) and by Levin et al. (1987) to investigate adoption of optical scanners at retail grocery stores. Rose and Joskow (1990) extend the hazard model of adoption to take advantage of available information on adopters *and* non-adopters.

[9] This index would presumably be some function of heating-degree days and cooling-degree days.

innovation depend on local climate. What is crucial is that potential adopters be *heterogeneous along some dimension* that affects the value of the innovation.[10]

The 'heterogeneous adopters' and 'epidemic' models each capture important aspects of the diffusion process; the models we develop below incorporate both strands of thought, by allowing adoption decisions to be driven by adoption costs that have an unobserved heterogeneous component and another component that depends on the prevalence of the technology among the stock of potential adopters.

2.2. The workings of incentive-based and conventional regulations

From the previous discussion, we can begin to perceive how economic-incentive approaches to environmental problems would affect the diffusion of environmentally beneficial technology. Whether through the diffusion speed in the epidemic model or the adoption threshold in the 'heterogeneous adopters' model, any policy that increased the profitability of a technology would speed its diffusion. It is less obvious how, in an economic context, to model the effects of regulation intended to foster technology adoption. Indeed, most of the economic literature on the effects of regulation on technology focuses on its inhibiting effects.[11]

Non-economists have discussed the 'technology-forcing' benefits of command-and-control regulation.[12] It is certainly plausible that enacting and enforcing a law that mandates the use of triple-glazed windows (or some overall energy efficiency standard), for example, in new home construction would affect the prevalence of that practice. It is less clear what is the best way to incorporate that possibility in an internally-consistent conceptual model. Below, we suggest that the effects of such regulations can be embedded in an economic model by postulating that builders perceive that the (expected) cost of adopting a new technology is affected by building codes' treatment of that technology. Before developing that model, we return to the specifics of energy-conserving technologies, and the arguments that have been put forward to explain their observed adoption rates.

2.3. Explanations for the 'paradox

Various explanations have been put forward to explain the observed rates

---

[10] In the present context, the heterogeneity could likewise be associated with the type of home heating plant (furnace), the size of home, or individual preferences for indoor temperature.

[11] See, for example, Oster and Quigley (1977).

[12] See, for example, Ashford et al. (1985).

of adoption of new energy-conserving technologies. Although some facts are in dispute, for our purposes we will take as given that there exist proven technologies that engineering calculations show to be cost-effective at current technology and energy prices, but that are not widely used.[13] Some energy-policy authorities (particularly non-economists) have interpreted this as evidence of a failure of the invisible hand that should be corrected by government intervention; frequently advocated interventions have included minimum energy-efficiency standards for particular products and construction design standards (U.S. Department of Energy, 1991).

When most economists observe the same set of facts, their responses tend to fall broadly into two categories. One type of response is to seek to identify the specific market failure that might explain the apparent non-optimizing behavior. The other category of responses consists of reasons why observed behavior is indeed (privately) optimal, despite engineers' calculations.

2.3.1 Market failure explanations

One obvious source of potential market failure affecting adoption decisions is lack of information about available technologies. It is costly for people to learn of an innovation's existence and to learn enough about it to know if it is profitable and how to use it. Since information has public-good attributes, it is certainly possible that it is underprovided by the market. Further, if others' use of the technology is an important source of information (as in the 'epidemic' model), then adoption creates a positive externality because it generates information that is valuable to others.

Another possible source of market failure consists of principal/agent problems that can arise when energy-efficiency decisions are made by parties other those who pay the bills. In this case, difficulties in observability can make it impossible for the investing party to recover the investment from the party that pays the energy bills. This problem could take several forms. If the builder of a new house cannot credibly represent its energy efficiency to potential buyers, then the sale price may not fully reflect efficiency attributes. Similarly, a landlord may not be able to recover all of the value of energy efficiency investments where renters pay fuel bills. Conversely, there may be situations where renters would have to make the investment but the landlord pays for fuel.[14]

Finally, consumers may face artificially low energy prices that explain their disinterest in conservation (Sutherland, 1991). First, electricity and natural gas are typically priced on an average-cost basis that conceals from

---

[13] Examples that are often cited include compact fluorescent light-bulbs, improved insulation materials, and energy-efficient appliances (Norberg-Bohm, 1990).

[14] See Fisher and Rothkopf (1989).

customers the incremental cost of new energy supplies. Second, electricity is highly subsidized in some parts of the country. Third, uninternalized environmental externalities may be associated with the use of energy from particular sources (including fossil fuels, nuclear, and hydroelectric sources).

2.3.2. Non-market-failure explanations

Another set of possible 'economic responses' to observed conservation technology adoption behavior is to conclude that there exist costs of adoption that engineers are ignoring or at least underestimating. Beyond the obvious tautological validity of such a claim, there are some reasons to give credence to this assertion. One aspect of cost is that of learning about the new technology. As noted above, the pure information-creation part of this cost has public-good aspects and therefore fits into the market failure category. But there is also a purely private part of this cost that relates to information acquisition and absorption. It is by no means costless to learn how a generic technological improvement fits into one's own home or firm, nor is it costless to learn about reliable suppliers.[15] Thus, even after basic information about a technology has been generated and disseminated, the 'purchase price' of the new product is no more than a lower bound on its adoption cost; transaction costs of adoption (of various kinds) can be significant relative to the magnitude of the net benefits of adoption.[16]

Another way of explaining low adoption rates is to posit that users have relatively high implicit discount rates.[17] Hence, another way to make this behavior consistent with underlying optimizing behavior is to explain why discount rates relating to these investments should be unusually high. Sutherland (1991) notes that high discount rates may be appropriate. These are irreversible investments with much uncertainty about their payback, both because future energy prices are highly uncertain, and because actual energy life-cycle savings in any particular application can only be estimated.

Finally, even if a given technology is profitable *on average*, there will be

---

[15] Some have argued that not only costly information acquisition but also *biased* estimates by individuals of likely energy savings play a role. Consumers may not believe experts' assessments of the benefits of new technologies. On the other hand, the bias may go in the opposite direction of the energy paradox, since some studies indicate that consumers systematically overestimate energy savings associated with some types of new technologies (Stern, 1986).

[16] See Joskow and Marron (1992).

[17] Hausman (1979) estimated that consumers used average implicit discount rates of 20% for purchasing room air conditioners (with substantial variation by income class); and Dubin and McFadden (1984) found average implicit discount rates of 20% for space-heating and water-heating investments (again, with significant variation by income). In a comment on Hausman (1979), Gately (1980) estimated discount rates of 45% to 300% for refrigerators. Likewise, Ruderman et al. (1987) found personal (implicit) discount rates as low as 20% and as high as 800% for heating and cooling equipment, and residential appliances.

some individuals or firms for whom it is *not* profitable. If the relevant population is heterogenous with respect to the amount of energy they use, for example, even a technology that looks very good for the average user will not be attractive for a portion of the population. Referring again to the 'heterogeneous adopters model,' we can interpret the engineer's cost-effectiveness calculations to mean that the technology is profitable for the mean household or firm. Depending on the rate of movement of the threshold, and the shape (variance and skewness) of the underlying distribution, it could be quite some time after the threshold crosses the mean before all or even most households or firms adopt (although heterogeneity does not explain extremely low adoption rates for 'cost-effective' technologies).

The models developed below incorporate a number of these market-failure *and* non-market-failure explanations of the 'energy paradox', including information problems, principal/agent slippage, incomplete pricing, unobserved costs, heterogeneity, and potentially high discount rates.[18]

3. Use of energy-conserving technologies in new construction

We begin with the decision to incorporate a potential energy-saving technology in the construction of a new home. We imagine a builder at time T in political jurisdiction i considering the incorporation of a new technology into the design of house j. We take the decision to build the house, and its design features other than the technology under consideration as given. We assume that the builder designs the house to maximize expected profits. To do this, she will need to trade off the incremental cost of the new technology against the expected increase in selling price associated with a more energy-efficient house.

In order to allow for the considerations discussed in section 2 of the paper, we assume that houses are heterogeneous in their energy use and that the housing market may discount energy savings because builders cannot represent them credibly. On the cost side, we allow for the possible effect on incremental costs of the prevalence of the practice among builders in the area and of the builder's own experience with the technology. We allow for regulation to affect the decision by modifying the cost of the new technology.[19] We also allow for the possibility of a tax credit or other subsidy to the use of energy-conserving technologies.

---

[18] As discussed later in the text, we do not deal explicitly with uncertainty. See Howarth and Anderson (1992).

[19] One interpretation is that regulation requires the use of the technology, creating an explicit or implicit penalty for not using it. Alternatively, regulation may merely encourage use of the technology by, for example, setting an overall energy budget for the house. Under either interpretation, we treat the magnitude of this perceived effect as an unknown parameter.

The builder's decision may thus be modelled as an attempt to maximize the sum of the base selling price of the house (in the absence of the energy-saving technology) and the present discounted value of the expected energy savings if the technology is adopted (the capitalized value of the installed technology) minus the costs of adoption (where these include costs associated with up-front purchase and installation, the implicit or explicit costs effect of regulation, and learning effects due to previous use by this builder or current use by other builders in the area). We assume that the builder recognizes that uncertainty is embodied in a number of the relevant variables, that the builder forms point estimates (expected values) of these variables, and that when making decisions the builder treat these expected values as if they were known with certainty.[20] Thus, we treat the overall decision problem in a fully deterministic framework.[21] Formally, the builder's problem is:

$$\max_{\{I\}} \pi_{ijT} = B + \left[I \cdot \delta \cdot (1-w) \cdot \int_T^\infty g(k_{ijt}, \mu_{ijt}) \cdot e^{-rt} dt \right]$$

$$- I \cdot [L(C_{iT}, S_{ijT}, v_{iT}) - \gamma D_{iT} - X_{iT}] \qquad (2)$$

where upper case letters represent stocks or present values; lower case letters represent flows; and greek letters represent parameters (except for π and μ, as indicated below). The variables are:

π_{ijT} = profit associated with adopting the technology in constructing house j in geographic area (and political jurisdiction) i at time T;

I = indicator of choice to adopt the technology ($I = 1$ if the technology is used, and 0 otherwise);[22]

B = the base selling price of the house without the technology;

δ = discount ($0 \leqslant \delta < 1$) or premium ($\delta > 1$) *applied by market to value of energy savings;*[23]

---

[20] In other words, only the means of the respective probability distributions are taken into account in the optimization problem.

[21] As we indicated earlier in our discussion of possible explanations of the energy paradox, uncertainty may play a significant role in technology diffusion. It would be possible to focus on that dimension of the energy-conservation diffusion process, as do Hassett and Metcalf (1992). For broader treatments of this perspective, see, for example, Pindyck (1991), and Dixit (1992).

[22] We focus on a simple discrete technology for purposes of explication. The model can be generalized to represent multi-valued discrete or continuous technological choices, such as installation of insulation of various 'R-values' in exterior walls.

[23] This parameter is included in our formulation to allow for principal-agent problems that may arise when a builder cannot credibly represent a new home's energy efficiency to potential buyers (and hence not capture the full value of efficiency attributes in the housing price). In such as case, $0 \leqslant \delta < 1$. Alternatively, if buyers of homes place excessively high valuations on energy efficiency attributes of new homes, we would find that $\delta > 1$.

$w =$ index of average quantity of energy used by the technology relative to energy consumption if the technology were not used $(0 < w \leqslant 1)$;

$k_{ijt} =$ vector of current and expected future values of observable characteristics of the home (for example, size, type of heating plant), and region (for example, price of fuel, climate, average income and education);

$\mu_{ijt} =$ an unobserved factor affecting energy use;

$g(\cdot) =$ function that relates elements of k_{ijt} to annual fuel expenditures;

$e =$ base of natural logarithms;

$r =$ real market rate of interest;

$C_{iT} =$ engineering estimate of purchase and installation cost of adoption of the technology;

$S_{ijT} =$ the cumulative stock of houses built previously by builder j that incorporate the technology;

$v_{iT} =$ fraction of newly constructed homes in jurisdiction i that incorporate the technology;

$L(\cdot) =$ a function that generates the 'effective cost' of installation from the engineering cost and the prevalence of use of the technology;

$D_{iT} =$ dummy variable set to unity if jurisdiction i has regulation in year T requiring that the technology be installed;[24]

$\gamma =$ parameter that captures the average perceived monetary equivalent cost of ignoring regulation, presumably a function of the nature of the regulations, the magnitude of penalties, perceived probabilities of enforcement, and likely stigma;[25] and

$X_{iT} =$ subsidy or tax credit in jurisdiction i for adopting technology.

This formulation incorporates many of the features of the problem suggested above. The heterogeneity of potential adopters is reflected in the unobserved μ_{ijt}. The 'epidemic effect' related to the prevalence of the practice is represented by the $L(\cdot)$ function. Thus, in our formulation of the problem, the essence of the epidemic model is that potential adopters must learn about the new technology before they can use it, and the probability that such learning will occur depends on the fraction of the population that has adopted. Implicit in our formulation is that such learning can be viewed as one component of the overall cost of adopting a new technology. The idea that information spreads by contact with previous adopters is captured by allowing the cost of adoption to depend on the 'regional' prevalence of use. Once we have allowed cost to depend on the extent to which *other* builders are using the technology (v_{iT}), it seems natural to allow the builder's own experience with the technology (S_{ijT}) to reduce effective cost as well.

---

[24] Again, in this simple model, we deal with a '0 − 1' regulation.
[25] See Russell et al. (1986).

The potential effect of regulation is captured by converting it to equivalent cost terms in the form of γ. Finally, we also allow for the possibility that some sort of tax credit or subsidy might be used to encourage adoption.

The first-order, necessary condition for this problem compares the overall cost of adopting the new technology with the expected increase in the selling price of the house.[26] Denoting the expected discounted present value of the function $g(\cdot)$ as $G(\cdot)$, the condition for adoption is that the technology should be employed if:

$$\delta \cdot (1-w) \cdot G(\mathbf{k}_{ijT}, \mu_{ijT}) + \gamma D_{iT} > L(C_{iT}, S_{ijT}, v_{iT}) - X_{iT} \tag{3}$$

Thus, the builder will use the technology if the valuation placed by the market on the savings in expected energy costs plus the implicit or explicit value of complying with regulation (if any) exceeds the cost of installation. The 'cost of installation' includes the purchase and installation cost and the cost of learning about the technology, and may be reduced by a government subsidy.

The next steps are to specify functional forms for the $G(\cdot)$ and $L(\cdot)$ functions and to make assumptions about the distribution of the unobservable μ, all from Eq. (2), above. Some relationships in the equations are inherently multiplicative (such as price of fuel and quantity of fuel used), while others are inherently additive (such as gross installation costs and tax credits). Thus the choice of functional form is inherently somewhat arbitrary.

For simplicity, let the function $G(\cdot)$ be Cobb–Douglas. Recall that the vector k_{ijt} includes the price of fuel and attributes of the region, house, and household that affect energy use. Let k_{jt}^m denote the mth element of the $1 \times M$ vector k_{ijt}, and, in particular, let $k_{ijt}^1 = P_{ijt}$, the price of fuel to house j in region i in year t. To keep things simple, other elements of k_{ijt} (other than price) may be assumed either to be such that the agent holds static expectations about them *or* to be constant (that is, $k_{jt}^m = k_{jT}^m$ for all $t > T$, for $m = 2 \ldots M$). Finally, the unobservable μ is posited to enter multiplicatively. The function $G(\cdot)$ from Eq. (3) can now be written as:

$$G(\cdot) = \left[\int_T^\infty (P_{ijt}) e^{-rt} dt \right]^{\beta_1} \cdot \left[\prod_{m=2}^M (k_{ijT}^m)^{\beta_m} \right] \cdot \mu_{ijT} \tag{4}$$

where the specific elements comprising the vector k_{ijT} might vary depending on the particular technology in question, but would include variables such as

---

[26] This ignores the possibility implied by Eq. (2) that the builder might take into account the future reduction in costs (parameterized by α_4) that would be brought about by using the technology today.

number of rooms in the house, number of heating degree-days in the area, and income and education of the homeowner.

The cost/learning function $L(\cdot)$ can reasonably be based on proportionate reductions in the cost of installation as either the builder's own experience or the prevalence of the technology being installed increase:

$$L(\cdot) = (C_{iT})^{\alpha_1} \cdot (v_{iT})^{\alpha_2} \cdot \left(\frac{S_{ijT}}{\alpha_3}\right)^{\alpha_4} \tag{5}$$

Thus, overall cost is the product of three factors that depend respectively on: the engineering cost estimate, C_{iT}; the prevalence of installation of the technology within the area, v_{iT}; and the builder's own cumulative experience with the technology, S_{ijT}.

Eq. (5) implies that the engineering cost estimate, C_{iT}, will be the actual cost if everyone is currently installing the technology ($v_{iT} = 1$), and the builder has 'typical' experience, parameterized by α_3. When installation is less prevalent ($v_{iT} < 1$), the cost is higher, with the sensitivity parameterized by α_2 (assumed to be less than zero). For builders with more or less experience than the typical level α_3, costs are higher or lower, with the own-experience sensitivity parameterized by α_4.[27]

Next, we rearrange the condition for adoption – Eq. (3) – in the form of a benefit/cost ratio:

$$\left[\frac{\delta \cdot (1-w) \cdot G(k_{ijT}, \mu_{ijT})}{L(C_{iT}, S_{ijT}, v_{iT}) - X_{iT} - \gamma D_{iT}}\right] \geqslant 1 \tag{6}$$

Substituting Eqs. (4) and (5) into Eq. (6), and taking natural logarithms of both sides yields the following expression:

$$\log(\delta) + \log(1-w) + \beta_1 \log\left(\int_T^\infty (P_{ijt})e^{-rt}dt\right) + \sum_{m=2}^m [\beta_m \log(k_{ijT}^m)]$$

$$-\log\left((C_{iT})^{\alpha_1} \cdot (v_{iT})^{\alpha_2} \cdot \left(\frac{S_{ijT}}{\alpha_3}\right)^{\alpha_4} - \gamma D_{iT} - X_{iT}\right) + \log(\mu_{ijT}) \geqslant 0 \tag{7}$$

Eq. (7) conveniently illustrates how a variety of factors can affect the diffusion of energy efficiency technologies. First of all, principal/agent problems associated with the builder/homeowner relationship will have an

---

[27] The exponent, α_1, on the engineering cost estimate should be unity.

unambiguously negative effect on the rate of adoption. If principal/agent slack exists, the parameter δ will be greater than zero but less than unity (see Eq. (2)), and so $\log(\delta)$ in Eq. (7) will be negative. Likewise, individuals do not have perfect information about the path of future energy prices. To whatever degree they tend to underestimate (the present discounted value of) future energy prices, the likelihood of adoption of an energy-conserving technology will be reduced. Similarly, if energy prices, P_{ijt}, are 'artificially low,'[28] adoption will be slower than it would otherwise be.[29] Furthermore, it is clear from Eq. (7) that if decision makers hold relatively high discount rates, r, the anticipated energy savings and hence the tendency to adopt the new technology will be less than otherwise.

Focusing next on the term behind the summation sign in Eq. (7), we can see that climatic departures from temperate conditions (increases in heating and/or cooling degree days) will encourage adoption, ceteris paribus. Other factors affecting energy use, such as income or education, could also matter.[30]

Turning to the second line of Eq. (7), we can see that decreases in adoption costs will accelerate technology diffusion. This could be due to changes in the direct costs of equipment purchase and installation (C_{iT}), or changes in 'effective costs of adoption' associated with *learning*, inversely correlated in our model with the prevalence of installation of the technology within the region, v_{iT}; and the builder's own cumulative experience with the technology, S_{ijT}. Thus, depending on the magnitude of the parameter, α_2,

---

[28] The 'artificially low' energy prices could be due to any one of a number of factors, as we suggested earlier: departures from marginal-cost pricing of electricity by utilities; subsidies for some fuels; and/or uninternalized environmental externalities.

[29] The question of how individual expectations of future energy prices are formed is also relevant. If people have static expectations, only current prices matter; for adaptive expectations, some combination of current and past prices will be determinate; for rational expectations, all relevant information available at time t will matter.

[30] In order to judge the significance of particular effects, Eq. (7) could be estimated, at least in principle. Whether specific effects could actually be verified would depend, of course, on the identification of respective parameters. This is largely an empirical issue, but by examining the extent to which various effects are even potentially identifiable we can shed some additional light on the disputes regarding the 'paradox' of slow adoption. For example, it is clear that the effects of household and regional factors on expected energy use (β_2 to β_M in both models) are identified. Thus, it is theoretically possible to separate out the effects of these factors on adoption decisions. On the other hand, there is a rather convoluted relationship among: the discount applied by the housing market to energy savings (δ), the interest rate (r), and the sensitivity of the decision to the price of fuel (β_1) in the new construction case. If there *is* a 'paradox,' it suggests that the adoption decision is *not* as sensitive to fuel prices as would be suggested by the *simplest* benefit/cost analysis. That is, principal/agent slack could be present ($\delta < 1$), the implicit discount rate could be relatively high, or measured fuel prices could be having a relatively mild impact on expected prices ($\beta_1 < 1$). Our model suggests that it may be difficult to separate out these factors from one another.

there may be a dynamic externality in which increased adoption today fosters future adoption by increasing v_{it}. Next, direct regulations – such as building codes – can have a direct, positive effect on adoption by, in effect, decreasing the expected costs of adopting (γ),[31] and government programs in the form of subsidies or tax credits (X_{iT}) can directly reduce adoption cost and thereby spur diffusion of the technology.

4. Retrofitting energy-conserving technologies in existing structures

We next examine the adoption decision faced by an individual considering the installation of an energy-saving technology in an existing home. Thus, for example, we may consider a homeowner who is thinking about the possibility of injecting blown insulation into exterior walls.[32] We posit that such an individual will attempt to minimize expected costs, subject to various constraints, taking as given all relevant prices and government policies.[33] By formulating the problem this way, we are assuming that if the homeowner is not risk-neutral, her attitude toward risk is such that the riskiness of the investment can be captured by appropriate adjustment of the interest rate.[34] Because of the possibility that the technology may be significantly cheaper in the future (either because of technological change or 'epidemic' learning), this is not a 'yes/no' decision like that of the builder; the homeowner must decide *at what time* (if any) to perform the retrofit installation.[35]

The costs that the homeowner wishes to minimize consist of three elements – the present discounted value (PV) of annual energy costs from the present to the time of adoption of the energy-saving technology, the PV of annual energy costs after the adoption, and the PV of the one-time cost of adoption of the energy-saving technology:

[31] The magnitude of this impact is clearly an empirical matter. See, for example, Jaffe and Stavins (1993b).

[32] Whereas in the previous model we highlighted the principal/agent problem (and employed the parameter, δ, to allow for its effect), in the retrofit model we focus on homeowners and therefore do not need to consider the agency problems that may exist in the landlord–tenant relationship. The parameter, δ, refers instead exclusively to homeowners' possible lack of knowledge about the effectiveness of a given technology.

[33] It is also possible that energy conservation enters directly in some people's utility functions.

[34] Hassett and Metcalf (1991) examine the effect of uncertainty on the retrofit decision. By focussing on utility-maximization instead of cost-minimization, we could also investigate the possibility that the optimal consumption of energy services (for example, the thermostat setting) will change if the house becomes more energy-efficient.

[35] Because retrofitting an existing building is typically much more expensive than incorporating a new technology at the time of construction, our analysis of new construction reasonably ignores the possibility that the retrofit option affects the initial installation optimization problem.

$$\min_{\{T\}} PV(T) = \int_0^T g(k_{ijt}, \mu_{ijt}) \cdot e^{-rt} dt + w \cdot \int_T^\infty g(k_{ijt}, \mu_{ijt}) \cdot e^{-rt} dt$$

$$+ [L(C_{iT}, V_{iT}) - X_{iT}] \cdot e^{-rT} + \gamma \cdot \int_0^T D_{it} \cdot e^{-rt} dt \qquad (8)$$

subject to $T \geqslant 0$ (9)

where:

$T =$ the time of adoption (installation);

$V_{iT} =$ the fraction of retrofit candidates in jurisdiction i that have adopted the technology by time T;

and all other variables are as defined previously. This formulation is consistent with that used above for new construction, including the treatment of heterogeneity and the effect of regulation. We allow for the impact of regulations although such interventions are typically not utilized in this retrofitting context, because in other possible applications – such as industrial pollution control – regulations can be designed either to affect all sources (thus requiring retrofitting at existing sources) or can be designed to affect only new sources. The effect of regulations enters into the objective function as the final term in the second line of Eq. (8). Thus, we are viewing regulations as an additional cost to be minimized, where this cost is equal to the 'effective penalty' of non-compliance from the present time to the date of adoption (and thus compliance). Alternatively, the limits of the integral in the regulation term could be the time of adoption, T, and infinity, in which case the term would be subtracted instead of added. Then we would be viewing the effect of regulation as providing a benefit (an 'avoided cost') to the adopter from the time of adoption onward. Note that these two specifications of the impact of regulations are equivalent: in either case, the same first-order condition follows, as we will see below in Eq. (12).

Returning to the optimization problem, note that the installation cost is formulated slightly differently from the new-construction case. Since the homeowner will not typically have previous experience with the technology, we take the effective cost to depend only on the engineering cost and the local prevalence of the technology; because of the nature of the retrofit situation, we take this prevalence to be represented by the fraction of the stock that has been retrofitted, rather than the current retrofit rate.

First-order conditions for maximizing $PV(T)$ in Eq. (8) subject to the constraint of Eq. (9) are:

$$\frac{\partial PV(T)}{\partial T} \geqslant 0 \text{ and } \left(\frac{\partial PV(T)}{\partial T} \right) \cdot T = 0 \qquad (10)$$

The first condition indicates that retrofitting should occur at a time T such that waiting longer will not decrease the present value of costs. The second condition indicates that retrofitting should occur either at $T=0$ (when installation is first considered) or when the derivative of the present value of costs with respect to time is zero. It is useful to reformulate the conditions in into a condensed form in which adoption should occur in year T if:[36]

$$\frac{\partial PV(T)}{\partial T} \geqslant 0 \text{ and adoption has not yet occurred.} \tag{11}$$

Evaluating the inequality condition in Eq. (11) yields:

$$[(1-\delta \cdot w)g(k_{ijT},\mu_{ijT}) - r \cdot [L(C_{iT},V_{iT}) - X_{iT}] + \gamma D_{iT}] \cdot e^{-rT}$$

$$+ \left[\left(\frac{\partial L}{\partial C_{iT}} \right) \cdot \left(\frac{dC_{iT}}{dT} \right) + \left(\frac{\partial L}{\partial V_{iT}} \right) \cdot \left(\frac{dV_{iT}}{dT} \right) - \left(\frac{dX_{iT}}{dT} \right) \right] \cdot e^{-rT} \geqslant 0 \tag{12}$$

Dividing by e^{-rT} and rearranging terms, adoption is predicted to occur at time T such that:

$$(1-\delta \cdot w)g(k_{ijT},\mu_{ijT}) + \gamma D_{iT} \geqslant r \cdot [L(C_{iT},V_{iT}) - X_{iT}]$$

$$- \left(\frac{\partial L}{\partial C_{iT}} \right) \cdot \left(\frac{dC_{iT}}{dT} \right) - \left(\frac{\partial L}{\partial V_{iT}} \right) \cdot \left(\frac{dV_{iT}}{dT} \right) + \left(\frac{dX_{iT}}{dT} \right) \tag{13}$$

The left-hand side of Eq. (13) indicates that higher annual energy costs can encourage adoption of the energy-saving technology, as can the effectiveness of the technology[37] and the existence of relevant regulations. The first term on the right-hand side of the equation indicates that higher adoption costs (whether direct or indirect) and higher interest rates discourage installation, and that government subsidies can encourage adoption. Finally, the presence of the last set of terms – the time derivative of adoption cost – indicates that adoption is discouraged by expectations of decreased (effective) costs of adoption in the future. Thus, even if the current savings in energy costs are greater than (the annual annuity of) adoption costs, it can pay to wait *if* those adoption costs are expected to fall over time at a sufficiently rapid rate.

Notice that Eq. (13) is a statement about the *current* rate of energy savings; it does not involve present values of future streams (in contrast with Eq. (3) in the new construction model). This may seem counter-intuitive, but note that it is the standard condition for the purchase of a capital asset: the instantaneous rate of earnings from the asset (the left-hand side) should be

---

[36] Sufficiency depends upon the satisfaction of second-order conditions, which we discuss later.
[37] Recall that $1-\delta w$ is the expected proportion of energy saved.

greater than or equal to the carrying cost (the first line of the right-hand side) minus the instantaneous rate of capital appreciation (the last line). 'Earnings' from the asset are the energy savings; the 'cost' of the asset includes the installation cost and the cost of acquiring the necessary information, adjusted for the effects of regulation and subsidies. The 'capital appreciation rate' has terms corresponding to each of the elements of the cost of adoption. To the extent that the overall cost of adoption is expected to fall (that is, the sum of the last set of terms is negative), it is as if the asset were suffering a capital loss; instantaneous earning will have to be greater to justify the investment. To put it concretely, to the extent that one expects that compact fluorescent light bulbs are getting cheaper or easier to find or easier to install, one might wait until next year to purchase and install them even if they are currently economical.[38]

If it still seems counter-intuitive that the adoption condition depends only on current values (and not on present values of future expectations), note that if the second-order condition is satisfied, the function $PV(T)$ will have (at most) a single optimum, which will be just at the point when the instantaneous investment condition holds. It does not matter how large the savings will be in the future; overall costs are minimized by adopting at the instant when marginal costs equal marginal benefits, as represented by condition.[39]

Many of the issues addressed previously regarding functional forms for $g(\cdot)$ and $L(\cdot)$ arise, of course, in the retrofit context, as well. The addition of the terms involving the time derivatives of the cost components makes the retrofit model, on balance, 'more linear' than the new construction model, so we proceed with such a formulation. Consider the following form of the energy-cost function:

$$g(\cdot) = P_{ijT} \sum_{m=2}^{M} \beta_m k_{ijT}^m + \mu_{ijT} \tag{14}$$

First of all, note that current annual prices are employed, unlike the new-construction case, where the present value of a future stream was appropriate. Relevant features of the house and region contribute additively

---

[38] Thus the model produces a potential 'non-market-failure' explanation of the 'paradox,' beyond those suggested above. This is parallel to results derived in models with explicit uncertainty (Dixit, 1992).

[39] The intuition that expectations of future prices should matter would be correct, however, if the second-order condition is violated. In this case, the first-order condition of Eq. (13) is a necessary *but not a sufficient* condition for optimal adoption. The condition could hold at a local *maximum* of discounted costs that is not a global maximum, as it could at a *local* minimum that is not globally optimal. Hence, present discounted values would matter and thus future costs (prices) would matter.

to energy use; the fuel bill is the product of this additive function and the price of fuel. Since $g(\cdot)$ is multiplied by $(1-\delta \cdot w)$ in Eq. (13), the new technology reduces the overall fuel bill proportionately.

The learning/adoption-cost function can also be specified in linear form:

$$L(\cdot) = \alpha_3 + \alpha_1 C_{iT} + \alpha_2 V_{iT} \tag{15}$$

Note that in contrast to Eq. (5), there is no term for 'own experience.' Now, substituting Eqs. (14) and (15) and into Eq. (13), and evaluating the various derivatives yields:

$$\left[(1-\delta \cdot w) \cdot P_{iJT} \sum_{m=2}^{M} \beta_m k_{ijT}^m \right] + \gamma D_{iT} - r \cdot [\alpha_3 + \alpha_1 C_{iT} + \alpha_2 V_{iT} - X_{iT}]$$

$$+ \alpha_1 \left(\frac{dC_{iT}}{dT} \right) + \alpha_2 \left(\frac{dV_{iT}}{dT} \right) \quad \left(\frac{dX_{iT}}{dT} \right) + \mu_{ijT} \geqslant 0 \tag{16}$$

As explained above, this indicates that adoption decisions are made on the basis of current energy prices without concern for future energy price paths; nevertheless Eq. (16) indicates that interest rates still matter since it is the annuity of adoption costs that is critical. In particular, higher implicit discount rates, r, will tend to retard adoption. As in the new-construction case, adoption will be slowed by 'artificially low' energy prices (P_{ijT}); climatic departures from temperate conditions will encourage adoption; and so will other factors that increase energy use. The existence of relevant regulations can likewise encourage adoption.

The second bracketed term on the first line of Eq. (16) implies that high adoption costs will unambiguously discourage adoption, whether these adoption costs are associated with: direct costs of equipment purchase and installation (C_{iT}); changes in effective costs of adoption associated with *learning* (inversely correlated with cumulative adoption in the area, V_{iT}); or government programs in the form of subsidies or tax credits (X_{iT}).

Finally, note that although the future paths of energy prices turn out not to be relevant for adoption behavior in the retrofit case, Eq. (16) reminds us that the current time rate of change of adoption costs, *broadly defined*, does matter. In particular, if purchase and/or installation costs are falling, it can pay to wait, despite the fact that *current* net benefits of adoption are positive. Likewise, if adoption is taking place very fast and information about the technology is thus increasing rapidly, it can pay to wait (since $\alpha_2 < 0$). Finally, if government subsidies or tax credits are increasing sufficiently rapidly over time, one may choose to wait (for the higher subsidy at a later date) despite the fact that the current benefit-cost picture is otherwise positive.

5. Policy implications

Our analysis indicates that market imperfections and other factors can slow diffusion and thus help explain the observed 'energy paradox.' Some of the factors we identify suggest a role for government intervention, but others should *not* be taken as meriting policy responses. In particular, the 'non-market-failure causes' may help to explain the gradual diffusion of energy conservation technologies, but they *do not* argue for government intervention. Falling into this category are high discount rates,[40] the private costs of information acquisition, heterogeneity of potential adopters, and the 'dynamic wait-and-see' conditions that emerge in the retrofit case.

The other major set of factors we have examined – the market-failures – not only help explain the 'energy paradox' but also provide a set of potential justifications for government intervention. We summarize these policy implications in Table 1. Some of these implications arise from simple inspection of our final behavioral equations; others require investigation of respective partial derivatives; and some – because of the dynamic nature of the model – are best examined through dynamic simulations. The simulation approach also enables us to view the results in graphical terms.

For illustrative purposes, we employ a simulation model of aggregate technological diffusion in the new home construction case, based upon the related behavioral inequality, Eq. (7). By assuming that the unobserved energy intensity, μ, has a logistic distribution and is independent of the other house-specific variables, the fraction of homes in year T that will incorporate the technology is simply the probability that condition (7) holds, which is equal to the logistic cumulative probability function evaluated at the left-hand side of Eq. (7), or:

$$v_T = \frac{1}{1 + e^{-A_T}} \tag{17}$$

where v_T is the fraction of newly constructed homes in year T that use the technology; and A_T is the left-hand side of Eq. (7).[41]

A base-case (no new policy) diffusion path is found in Fig. 1. We use the time period 1978–1988 for the simulations because this encompasses a

---

[40] As noted below, to whatever degree high personal discount rates reflect the public good aspect of incomplete information (uncertainty), high discount rates *do* provide a potential justification for government intervention.

[41] Given the assumption of independence of μ *and the other variables, those variables in Eq.* (7) *that vary across i* and/or *j* are evaluated at their means. To keep things simple for the policy analysis, we drop the term with S_{ijT} from the learning function; i.e., we set α_4 in Eq. (7) equal to zero. Otherwise it would be necessary to simulate multiple builder decisions simultaneously. Also, for the simulation model, we replace v_{iT} by the previous period's value, $v_{i,T-1}$; and we adopt simple static expectations on prices, so that P_{ijt} is replaced by P_{ijT}.

Table 1
Market failure and policy prescriptions – the diffusion of energy conservation technologies

Problem	Policy prescription	Consequences of policy in models	
		New construction	Retrofit
Incomplete Information (Public Good Aspect)	Establish standards for energy audits and disclosure for new buildings	$\delta\uparrow$	–
	Public information campaigns	$\delta\uparrow$, $\alpha_1\downarrow$, $r\downarrow$	$\alpha_3\downarrow$, $r\downarrow$
	Product labelling requirements/guidelines	$\alpha_1\downarrow$, $\delta\uparrow$	$\alpha_3\downarrow$, $\delta\uparrow$
Principal/Agent Issues (Builder/Buyer)	Federal home energy rating system	$\delta\uparrow$	–
	Standards for audits and disclosure	$\delta\uparrow$	–
Departures from Marginal Cost Pricing by Electrical Utilities	Change from average to marginal cost electricity pricing	$P_{ijt}\uparrow$	$P_{ijT}\uparrow$
Federal and State Energy Subsidies	Eliminate/reduce fuel subsidies	$P_{ijt}\uparrow$	$P_{ijT}\uparrow$
Uninternalized Environmental Externalities	Internalize externalities	$P_{ijt}\uparrow$	$P_{ijT}\uparrow$
	Regulation	$D_{iT}\uparrow$	$D_{iT}\uparrow$
Insufficient Research & Development	Government support for technological R&D	$C_{iT}\downarrow$, $w\downarrow$	$C_{iT}\downarrow$, $w\downarrow$
Positive Adoption Externalities	Adoption subsidies	$X_{iT}\uparrow$	$X_{iT}\uparrow$
	Tax credits	$X_{iT}\uparrow$	$X_{iT}\uparrow$

significant turning point in real energy prices. The resulting non-monotonic diffusion curve found in Fig. 1 is not atypical of the experience with energy-efficiency technologies in new homes over this time period. In fact, our base-case parameter and variable values reflect actual data for triple-pane windows (Tables 2 and 3),[42] and the simulated diffusion curve is similar to the observed diffusion path of that technology in the United States.[43]

---

[42] These base-case parameter values reflect all of the assumptions previously specified regarding the underlying behavioral relationships. For example, we use values for α_1 and α_2 that yield the appropriately shaped cost/learning function. Referring to Eq. (5), we find that $\partial L(\cdot)/\partial v_{t-1} < 0$, $\partial^2 L(\cdot)/\partial v_{t-1}^2 > 0$, $\partial L(\cdot)/\partial \alpha_2 < 0$, and $\partial^2 L(\cdot)/\partial \alpha_2^2 > 0$. Thus, as v_{t-1} approaches 1.0 (its maximum value) and as α_2 approaches 0 (from below), the effective cost of adoption falls and approaches the simple engineering cost.

[43] Not surprisingly, the non-monotonicity of the diffusion path is partly a consequence of the related path of (expected) real energy prices. See Jaffe and Stavins (1993a).
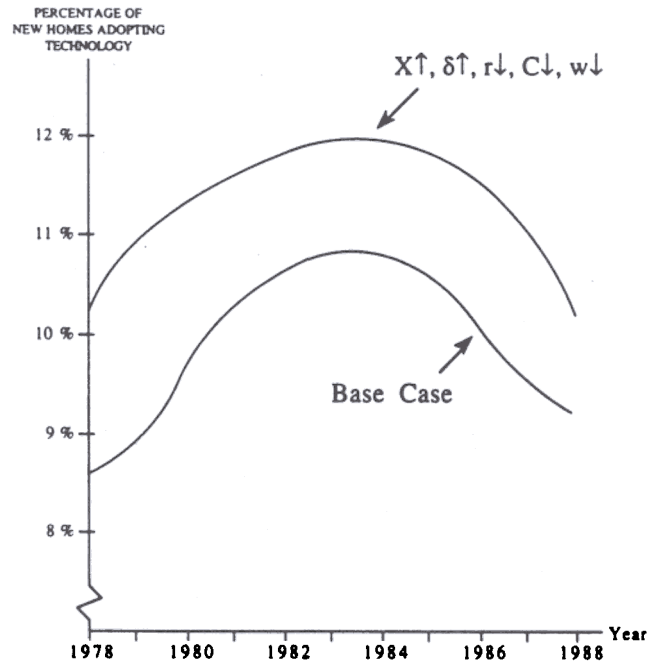
Fig.   Base-case simulation and the effect of alternative constant policy changes.

With the help of the simulation model, simple differential calculus, or simpler inspection of the behavioral relationships, we can now proceed to investigate the implications of potential public policies. First of all, the public good aspect of incomplete information can suggest a number of policy responses, depending upon the nature of the incomplete information. For situations in which there is uncertainty surrounding the potential benefits of energy conservation technologies in new construction, our analysis suggests that government could conceivably establish standards for energy audits and disclosure requirements for new buildings, thereby increasing δ. Graphically, the effect of this is to shift the diffusion path in Fig. 1 upward. Likewise, public information campaigns about the potential benefits and costs of adopting new technologies could be effective both in the new construction case ($\delta\uparrow$, $\alpha_1\downarrow$, $r\downarrow$) and the retrofit case ($\alpha_3\downarrow$, $r\downarrow$).[44] Focusing on the attributes of the technologies themselves, product labelling requirements or guidelines could be effective for new construction ($\alpha_1\downarrow$, $\delta\uparrow$) and retrofitting ($\alpha_3\downarrow$, $\delta\uparrow$).

---

[44] As with increases in δ, so too with decreases in the (constant) interest rate, r, the effect is to shift the diffusion path upward, while retaining its basic (non-monotonic) shape. What is striking, however, is the dramatic effect of decreases in interest rates. Whereas increasing δ from 0.50 to 0.75 shifts the peak of the diffusion path (in the year 1983) from a 5.8% adoption rate to 8.5%, decreasing real interest rates from 5% (the base case) to 1% shifts the peak of the adoption curve from 11.2% to over 40%. On the other hand, note that the relationship between interest rates and adoption is not linear; an increase in the interest rate from 5% to 10% has a much smaller effect on adoption, shifting the peak downward from 11.2% to 5.8%.

Table 2
Base-case parameter and variable values

Parameter or variable	Description	Base-case value
α_1	Engineering cost coefficient	1.00
α_2	Learning-effect coefficient	0.05
β_1	Expected-price coefficient	1.00
$\beta_2 \ldots \beta_M$	Observable characteristic coefficients	0.00
δ	Market's discount of value of energy savings	1.00
γ	Cost of regulatory non-compliance	0.00
r	Real market rate of interest	0.05
v_0	Initial rate of technological adoption	0.10
C_t	Engineering purchase and installation cost	$240.00
D_t	Regulatory requirement dummy variable	0.00
$k_2 \ldots k_M$	Observable characteristics of home and region	1.00
w_t	Relative energy use of technology	0.87
X_t	Subsidy or tax credit for adopting technology	0.00
P_t	Expected energy price in year t	

*Time series of base-case energy prices are found in Table 3.

Table 3
Base-case energy prices

Year	Effective energy price*
1978	9.73
1979	10.18
1980	11.25
1981	12.02
1982	12.51
1983	13.03
1984	12.56
1985	12.32
1986	11.93
1987	11.43
1988	10.95

*Average effective energy price for 48 states, in 1988 dollars per million BTU's; a weighted average of prices of alternative fuels of newly built homes.

Principal/agent problems can be particularly severe in the new construction case. If a builder cannot credibly represent a home's energy efficiency to potential buyers, the sales price will not fully reflect efficiency attributes. This concern has led in the past to legislation in the Congress to require the U.S. Department of Energy to develop a *voluntary* home energy rating system to provide consumers with better information on the efficiency of prospective homes $(\delta\uparrow)$. Standards for audits and disclosure would have the same basic result.

We noted earlier that there are a set of reasons why the price of energy may be artificially low. Not surprisingly, the appropriate policy response will depend upon the reason for the problematic pricing. Changes from average-cost to marginal-cost pricing of electricity at utilities are one approach. The result in our models would be to increase energy prices $(P_{ijt}\uparrow)$. Similarly, consideration should be given to eliminating or at least reducing the subsidies that exist for particular fuels $(P_{ijt}\uparrow)$. In this same context, the existence of uninternalized environmental externalities associated with particular sources of energy clearly calls for those externalities to be internalized, such as through pollution taxes, tradeable permit systems, or other economic instruments $(P_{ijt}\uparrow)$, or through conventional command-and-control regulations $(D_{iT}\uparrow)$.

It is frequently asserted that free-rider problems will lead to less than the socially optimal amount of research and development by private firms. To the extent that this is true in the energy-efficiency technology area, government support for technological research and development may be called for. In our analysis, this could translate into decreases in the purchase and installation costs of new technologies $(C_{iT}\downarrow)$ and increases in the effectiveness (engineering efficiency) of those technologies $(w\downarrow)$. Finally, we noted at the outset that adoption behavior can itself result in positive externalities if others' use of a technology is an important source of valuable information. In this case, there is an argument in favor of government employing 'adoption subsidies' or tax credits $(X_{iT}\uparrow)$.[45]

As indicated, some energy-efficiency technologies used in new home construction – such as triple-pane windows – have exhibited non-monotonic diffusion paths, apparently as a result of the turning point in real energy prices experienced in the early 1980's. From the perspective of public policy, it is natural to ask what policies could have been used to foster a monotonicly increasing diffusion path, in the face of falling real energy prices. First of all, if adoption costs had been falling sufficiently fast over time, the

---

[45] In the new home construction case, simulations of decreases in the purchase and installation costs of new technologies, C_{iT}, increases in those technologies' engineering efficiency, $1-w$, and increases in adoption subsidies or tax credits, X_{iT}, exhibit the same effect – upward shifts of the non-monotonic diffusion path (see Fig. 1).
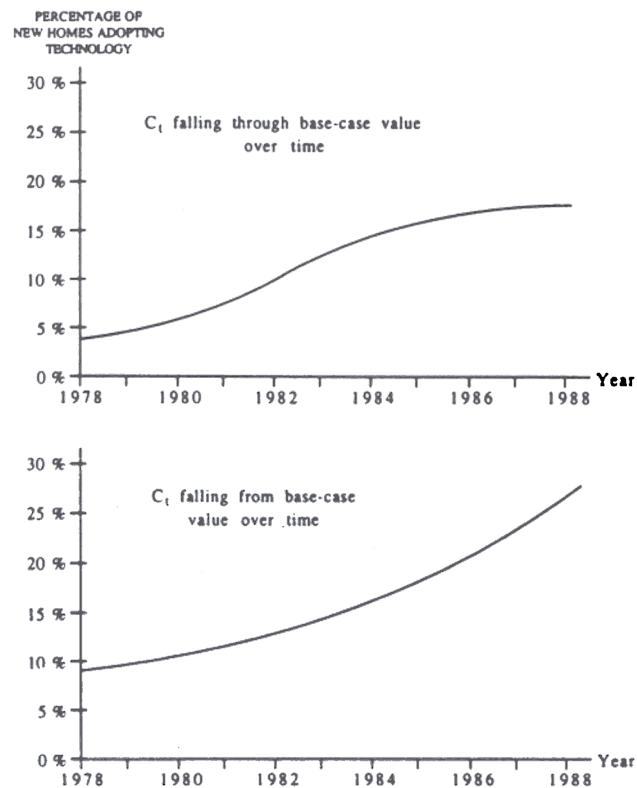
Fig. 2. The effect of decreasing adoption costs on technological diffusion.

depressing incentive effects of falling energy prices would have been reversed. Indeed, various counterfactual time paths of falling adoption costs (C_{iT}) produce diffusion paths in which the 'negative effect' of falling energy prices after 1983 is overcome. Depending upon the rate at which adoption costs fall, the diffusion path of the technology can take on a constantly rising pattern or a classical sigmoid shape (Fig. 2).[46]

As noted above, government support of technological research and development efforts could have the effect of driving down C_{iT}. How else might government policy be employed to counteract the post-1983 price effects and maintain adoption rates or even push them to continually higher levels? First, government support of research and development – an approach that is favorably viewed by the present Administration for a host of environmental and resource problems – can not only have the effect of decreasing adoption costs but can also increase the efficiency of available technologies $(w\downarrow)$. As depicted in Fig. 3, as w falls over time from an initial value of 0.99 (indicating virtually no efficiency advantage) to 0.50 (indicating that the technology cuts energy demand by 50 percent), annual adoption

---

[46] Also, there is a less extreme counterfactual path of adoption costs that will case adoption rates to remain more or less constant at their peak 1983 rate.
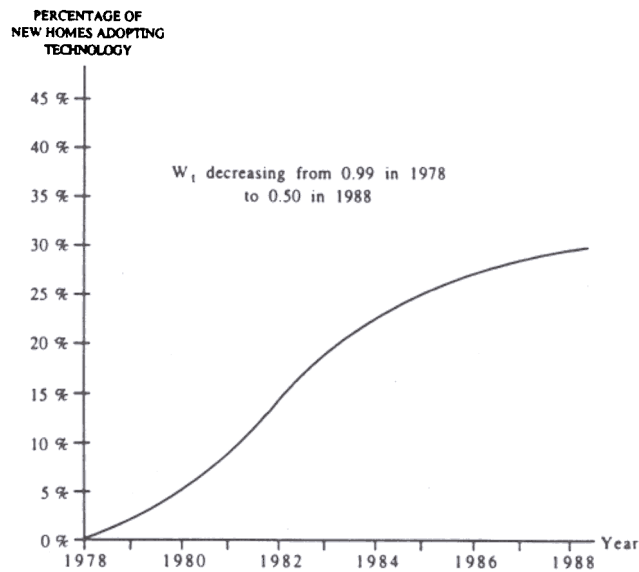
Fig. 3. The effect of increasing engineering-efficiency on technological diffusion.
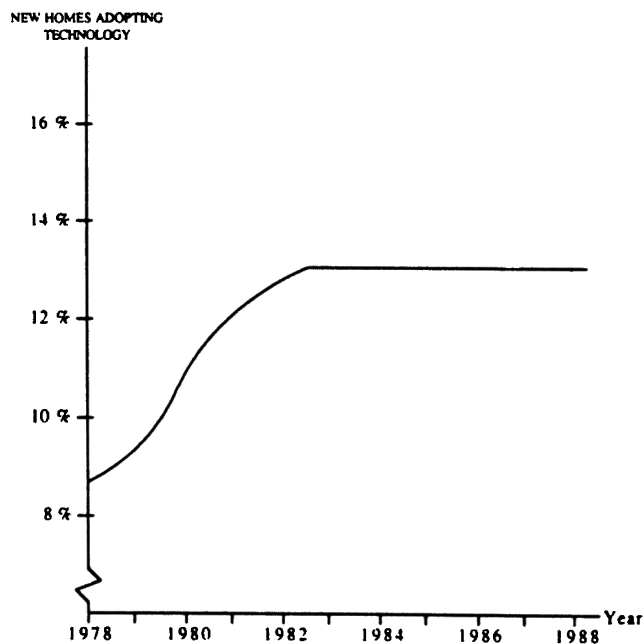

Fig. 4. The effect of a continually increasing subsidy on technological diffusion.

increases monotonicly in an essentially sigmoid path from zero to 30 percent of newly constructed homes.

Other dynamic government policies could – in theory – be employed to compensate for falling energy prices. The simulated diffusion path in Fig. 4 illustrates that a *continuously increasing* subsidy (X_{iT}) of sufficient magnitude could be used to maintain adoption rates at their peak level (again, in the
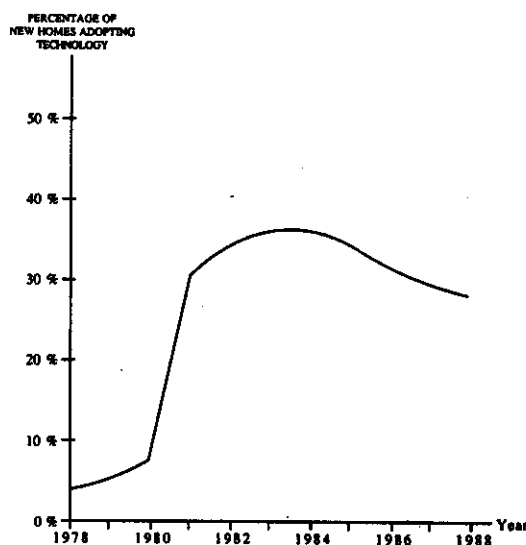
Fig. 5. The effect of a one-time increase in regulatory stringency on technological diffusion.

face of falling energy prices). Subsidies of various magnitudes can be employed to have essentially whatever effect is desired. At one extreme, a constant subsidy set equal to the basic engineering cost of the technology results in a 100 percent rate of adoption after only eight years (the delay being due to the effect of learning on effective costs of adoption).

The obvious alternative to a subsidy on the technology (or a tax on energy prices) is a conventional regulatory approach, such as use of building codes in the new-construction context. As indicated above and in Table 1, regulations can – in theory – have the desired effect. Our dynamic simulations illustrate, however, that a one-time change in regulatory stringency should not be expected to lead automatically to an increasing or even a constant level of annual adoption. Fig. 5 represents a situation in which a command-and-control regulation is initiated in the year 1981. As expected, adoption increases dramatically in that year and then continues to increase at a much slower rate to the peak year of 1983. Subsequent to that time, however, the effects of falling energy prices dominate, and we find the rate of diffusion falling gradually despite the constant level of regulation. Conventional regulations, like market-based instruments, can be effective, but neither are likely to be a panacea in the face of strong, contrary forces in the economy.

Either conventional command-and-control regulatory policies or incentive-based economic instruments can be used to achieve various levels and rates of change of technological diffusion desired by, policy makers, whether

because of (economically legitimate) market-failure reasons or otherwise. Which policy instruments will be best will depend in well-defined ways upon the relative importance of the various causes of the gradual diffusion of those technologies, in the first place.

6. Summary and conclusions

In this paper, we have developed a framework for thinking about the 'paradox' of very gradual diffusion of apparently cost-effective energy-conservation technologies. Our analysis provides some keys to understanding why this technology-diffusion process *is* gradual, and focuses attention on the factors that cause this to be the case, including those associated with potential market failures – information problems, principal/agent slippage, and unobserved costs – and those explanations that do not represent market failures – private information costs, high discount rates, and heterogeneity among potential adopters. Furthermore, our analysis indicates how alternative policy instruments – both economic incentives and direct regulations – can hasten the diffusion of energy-conserving technologies.

Because there are two important contexts in which energy conservation adoption decisions can take place, our analysis builds upon two conceptual models: a model in which an activity is being undertaken which *prompts* a decision about *whether or not* to adopt an energy-conserving technology at a specified point in time (our new construction case); and a model in which a decision must be made not only about whether or not to adopt an energy-efficiency technology, but also about *when* to do so (our retrofit case). Our analysis focused on the incorporation of energy-conserving technologies in new residential structures and retrofitting in existing homes.

First of all, in the case of new residential construction, our analysis demonstrates how principal/agent problems thought to arise in that context can directly inhibit the diffusion of energy efficiency technologies. We also found that 'artificially low' energy prices – due to electrical utility pricing practices, government fuel subsidies, or environmental externalities – can provide another market-failure explanation of the paradox. As has frequently been discussed in the empirical literature, relatively high individual discount rates can significantly retard adoption and diffusion. Similarly, our analysis illustrated how decreases in the costs of adoption will accelerate technology diffusion, whether due to changes in the direct costs of equipment purchase and installation, or changes in the 'effective costs of adoption' associated with learning about the technology and its application. We also saw how regulations – such as building codes – can have a direct, positive effect on adoption, as can other government programs, including subsidies and tax credits. Of somewhat less concern in terms of public policy perhaps, we also

noted how departures from temperate climatic conditions, and increases in income and education can accelerate diffusion.

Second, we examined the case of retrofitting energy-efficiency technologies in existing residential structures. We found, somewhat counter-intuitively, that under certain circumstances adoption decisions are influenced by current energy prices, without concern for future energy price paths. Nevertheless, high discount rates can impede adoption by driving up the adoption-cost annuity. As in the new-construction case, we found that adoption will be slowed by 'artificially low' energy prices; and that climatic departures from temperate conditions will encourage adoption. Not surprisingly, low adoption costs will unambiguously encourage adoption, as may government programs in the form of subsidies or tax credits.

Although the future paths of energy prices turn out not to be relevant for adoption behavior in the retrofit case, the current time rate of change of adoption costs, *broadly defined*, does matter. In particular, if purchase and/or installation costs are falling, it can pay to wait, despite the fact that *current* net benefits of adoption are positive. Likewise, if adoption is taking place very fast and information about the technology is thus increasing rapidly, it can pay to wait. Finally, if government subsidies or tax credits are increasing sufficiently rapidly over time, one may choose to wait (for the higher subsidy at a later date) despite the fact that the current benefit-cost picture is otherwise positive.

In conclusion, if the 'energy paradox' of gradual diffusion of apparently cost-effective energy-efficiency technologies does exist – as many observers have claimed – it is necessary to understand the sources of the gradual diffusion before identifying appropriate policy responses. One set of causes of the paradox, which we have labelled the 'non-market-failure' causes, do not provide legitimate justifications for government intervention. On the other hand, a fairly large number of potential market-failure explanations of the paradox can provide solid arguments for government action. Which specific policy instruments will be appropriate, however, will depend in well-defined ways upon the relative importance of the various underlying explanations of the energy paradox.

References

Ashford, N.A., C. Ayers and R.F. Stone, 1985, Using regulation to change the market for innovation, Harvard Law Review 9, 419–466.

Bohm, P. and C.S. Russell, 1985, Comparative analysis of alternative policy Instruments, in: A.V. Kneese and J.L. Sweeney, eds., Handbook of natural resource and energy economics, Vol. I (North-Holland, Amsterdam) 395–460.

Carlsmith, R., W. Chandler, J. McMahon and D. Santino, 1990, Energy efficiency: how far can we Go? (Oak Ridge National Laboratory [TM-11441], Oak Ridge, TN).

Caswell, M., E. Lichtenberg and D. Zilberman, 1990, The effects of pricing policies on water conservation and drainage, American Journal of Agricultural Economics 72, 883-890.

Caswell, M. and D. Zilberman, 1990, The diffusion of resource-quality-augmenting technologies: output supply and input demand effects, Discussion Paper (Department of Agricultural and Resource Economics, University of California, Berkeley, CA).

Cebon, P.B., 1992, Twixt cup and lip: organizational behavior, technical prediction, and conservation practice, Energy Policy 20, 802-814.

David, P.A., 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.A., 1969, A contribution to the theory of diffusion, Stanford Center for Research in Economic Growth Memorandum 71 (Stanford University, Stanford, CA).

David, P.A., 1986, Technology diffusion, public policy, and industrial competitiveness, in: R. Landau and N. Rosenberg, eds., The positive sum strategy: harnessing technology for economic growth (National Academy Press, Washington, DC) 373-391.

Davies, S.W., 1979, Inter-firm diffusion of process innovations, European Economic Review 12, 299-317.

Dixit, A., 1992, Investment and hysteresis, Journal of Economic Perspectives 6, 107-132.

Downing, P.B. and L.J. White, 1986, Innovation in pollution control, Journal of Environmental Economics and Management 13, 18-27.

Fisher, A.C. and M.H. Rothkopf, 1989, Market failure and energy policy, Energy Policy 17, 397-406.

Georg, S., I. Ropke and U. Jorgensen, 1992, Clean technology – innovation and environmental regulation, Environmental and Resource Economics 2, 533-550.

Griliches, Z., 1957, Hybrid corn: an exploration in the economics of technological change, Econometrica 25, 501-522.

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.

Hannan, T.H. and J.M. McDowell, 1984, The determinants of technology adoption: the case of the banking firm, Rand Journal of Economics 15, 328-335.

Hassett, K.A. and G.E. Metcalf, 1992, Energy tax credits and residential conservation investment, Working Paper 4020 (National Bureau of Economic Research, Cambridge, MA).

Hausman, J.A., 1979, Individual discount rates and the purchase and utilization of energy-using durables, The Bell Journal of Economics 10, 33-54.

Howarth, R.B. and B. Anderson, 1992, Market barriers to energy efficiency, Working Paper LBL-32541 (Lawrence Berkeley Laboratory, Energy and Environment Division, Berkeley, CA).

Jaffe, A.B. and R.N. Stavins, 1993a, The diffusion of energy conserving windows: the effect of economic incentives and building codes, paper presented at the annual meeting of the American Economic Association, Anaheim, CA.

Jaffe, A.B. and R.N. Stavins, 1993b, Prices, regulation, and energy conservation, paper prepared for presentation at the Conference on Market Approaches to Environmental Regulation, Stanford University, Stanford, CA.

Joskow, P.L. and D.B. Marron, 1992, What does a negawatt really cost? Evidence from utility conservation programs, The Energy Journal 13, 41-74.

Kemp, R., X. Olsthoorn, F. Oosterhuis and H. Verbruggen, 1992, Supply and demand factors of cleaner technologies: some empirical evidence, Environmental and Resource Economics 2, 615-634.

Kneese, A. and C. Schultze, 1978, Pollution, prices, and public policy (Brookings Institution, Washington, DC).

Levin, S.G., S.L. Levin and J.B. 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.

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.

Mansfield, E., 1968, Industrial research and technological innovation (W.W. Norton, New York).

Hassett, K.A. and G.E. Metcalf, 1991, Residential energy tax credits and home improvement behavior, paper presented at the Universities Research Conference on Economics of the Environment (National Bureau of Economic Research, Cambridge, MA).

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.

Norberg-Bohm, V., 1990, Potential for carbon dioxide emissions reductions in buildings, Global Environmental Policy Project Discussion Paper (Energy and Environmental Policy Center, John F. Kennedy School of Government, Harvard University, Cambridge, MA).

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

Oster, S.M. and J.M. Quigley, 1977, Regulatory barriers to the diffusion of innovation: some evidence from building codes, The Bell Journal of Economics 8, 361–377.

Pindyck, R.S., 1991, Irreversibility, uncertainty, and investment, Journal of Economic Literature 29, 1110–1152.

Rose, N.L. and P.L. Joskow, 1990, The diffusion of new technologies: evidence from the electric utility industry, Rand Journal of Economics 21, 354–373.

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, 101–124.

Russell, C.S., W. Harrington and W.J. Vaughan, 1986, Enforcing pollution control laws (Resources for the Future, Washington, DC).

Shama, A. 1983, Energy conservation in US buildings, solving the high potential/low adoption paradox from a behavioral perspective. Energy Policy, June.

Sommers, P., 1980, The adoption of nuclear power generation. The Bell Journal of Economics 11, 283–291.

Stern, P.C., 1986, Blind spots in policy analysis: what economics doesn't say about energy use. Journal of Policy Analysis and Management 5, 200–227.

Sutherland, R., 1991, Market barriers to energy-efficiency investments. The Energy Journal 12(3), 15–34.

Stoneman, P., 1983, The economic analysis of technological change (Oxford University Press, Oxford).

Stoneman, P., 1986, Technological diffusion: the viewpoint of economic theory. Ricerche Economiche 40, 585–606.

Thirtle, C. and V. Ruttan, 1987, The role of demand and supply in the generation and diffusion of technical change (Harwood Academic Publishers, London)

U.S. Department of Energy, 1991, National energy strategy: powerful ideas for America, 1st ed. (Washington, DC) February.

U.S. National Academy of Sciences, 1991, Policy implications of greenhouse warming – report of the Mitigation Panel. (National Academy Press, Washington, DC).