Energy-Efficiency Investments and Public Policy

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Concern about carbon dioxide as a greenhouse gas has focused renewed attention on energy conservation because fossil fuel combustion is a major source of CO_2 emissions. Since it is generally acknowledged that energy use could be significantly reduced through broader adoption of existing technologies, policy makers need to know how effective various policy instruments might be in accelerating the diffusion of these technologies. We examine the factors that determine the rate of diffusion, focusing on (i) potential market failures: information problems, principal-agent slippage, and unobserved costs, and (ii) explanations that do not represent market failures: private information costs, high discount rates, and heterogeneity among potential adopters. Through a series of simulations we explore how alternative policy instruments—both economic incentives and more conventional, direct regulations—could hasten the diffusion of energy-conserving technologies.

INTRODUCTION

The role new technologies can play in solving a wide range of environmental and natural resource problems is receiving increasing attention from policy makers.[1] Concern about carbon dioxide (CO_2) as a greenhouse gas has focused particular attention on the role of energy-conserving technologies.

1. A prominent spokesman for this perspective has been U.S. Vice President Al Gore. See Gore (1992). Activity within the Congress has also been significant. For example, Senate Bill S-978, introduced by Senator Max Baucus—the Chairman of the Senate Environment and Public Works Committee—would create a National Environmental Technology Panel under the White House Office of Science and Technology Policy to unify the efforts of the ten Federal agencies that spent $4 billion on environmental technology development in 1992. It would also establish an EPA Bureau of Environmentally Sustainable Technologies to channel Federal funds to support "green technology" development. Five other pending bills contain similar goals.

Since the largest anthropogenic source of CO_2 emissions is combustion of fossil fuels for energy generation, reductions in energy use could constitute a powerful option for reducing the risk of global climate change. It is widely acknowledged that energy use could be significantly reduced through broader adoption of existing technologies, and it is almost as widely accepted that much unadopted technology is cost-effective at current prices.[2]

In this paper, we examine two inextricably linked questions: what factors determine the rate of adoption of energy-conserving technologies; and what types of public policy can accelerate their diffusion. Our analysis reflects two contexts in which energy-conservation adoption decisions occur. One setting *prompts* a decision about *whether or not* to incorporate an energy-conserving technology at a specified time. In the second context, a decision must be made not only *whether* to adopt such a technology but also *when* to do so.

INVESTING IN ENERGY-EFFICIENCY TECHNOLOGIES

There appear to exist a number of proven technologies that engineering calculations show to be cost-effective at current prices but that are not widely used. Frequently cited examples include compact fluorescent light bulbs, improved insulation materials, and energy-efficient appliances (Norberg-Bohm 1990). From an economic perspective, there are two fundamental categories of potential explanations of this seemingly anomalous behavior: (1) market failures may cause what appears to be non-optimizing behavior; and (2) there may be reasons why the observed behavior is indeed privately optimal, despite engineers' calculations.

Market-Failure Explanations

Several sources of potential market failure may affect energy-conserving technology adoption rates. One of these is lack of information. It is costly for people to learn of an innovation's existence, and to learn enough to know if it is profitable and how to use it. Because information has public-good attributes, it may be under provided by the market. Further, if others' use of a technology is an important source of information, adoption creates positive externalities because it generates information that is valuable to others.

Principal-agent problems are another possible source of market failure. These failures can arise when energy-efficiency decisions are made by parties other than those who pay the bills. If the builder of a new house cannot credibly represent its energy-conserving features to potential buyers, the sale

2. See, for example, Carlsmith, Chandler, McMahon, and Santino (1990) and Shama (1983).

price may not fully reflect efficiency attributes. Similarly, a landlord may not be able to recover the total value of energy-efficiency investments where renters pay fuel bills. Conversely, in some situations, renters may have to make investments but landlords pay for fuel (Fisher and Rothkopf 1989).

Finally, consumers may face "artificially low" energy prices that explain their disinterest in conservation. First, electricity and natural gas are typically priced on an average-cost basis that may not reflect 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.

Non-Market-Failure Explanations

The second category of "economic explanations" of low adoption rates consists generally of the view that engineers are ignoring or at least underestimating certain costs of adoption. Beyond the tautological validity of such a claim, there are reasons to give it credence. Learning about the new technology is one aspect of cost. Although the pure information-creation part of this cost has public-good aspects and therefore fits into the market failure category, there is also a purely private part of the 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 or to learn about reliable suppliers.[3] 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.

An alternative explanation of low adoption rates is that users have relatively high implicit discount rates.[4] As will be discussed further below, the empirical observation that consumers make decisions *as if* they had very high discount rates could mean either that principal/agent problems or other market failures exist, or that they truly have high discount rates. Sutherland (1991) and Hassett and Metcalf (1992) argue that truly high discount rates may, in fact, be

3. Some have argued that not only costly information acquisition but also *biased* estimates 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, since some studies indicate that consumers systematically overestimate energy savings associated with some types of new technologies (Stern 1986).

4. Hausman (1979) estimated that consumers used average implicit discount rates of 20 percent for purchasing room air conditioners with substantial variation by income class; and Dubin and McFadden (1984) found average implicit discount rates of 20 percent 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 percent for refrigerators. Likewise, Ruderman, Levine, and McMahon (1987) found personal implicit discount rates as low as 20 percent and as high as 800 percent for heating and cooling equipment and for residential appliances.

appropriate, because these investments are irreversible and there is much uncertainty about their payback, given that future energy prices are highly uncertain, and energy life-cycle savings in any particular application can only be estimated.[5] To the extent that consumers' true discount rates are high for these reasons, this would not represent a market failure.

Finally, even if a given technology is profitable on *average*, it will not be profitable for some individuals or firms. If the relevant population is heterogeneous with respect to the amount of energy they use, for example, even a technology that looks very good for the average user will be unattractive for a portion of the population. Hence, we can also interpret the engineer's cost-effectiveness calculations to mean that the technology is profitable for the mean household or firm.

As a necessary precondition for our policy analysis, we go on to explore both these market and nonmarket failures in light of the two classes of energy-efficiency investments noted above. The first group, requiring a decision about *whether* to incorporate a technology at a given time, may include construction of new industrial, commercial, or residential structures or expansions or other modifications of existing establishments. By way of example, we will discuss the question of whether to incorporate a potential energy-saving technology in the construction of a new home. The second group, requiring "*whether*-and-*when* determinations," includes retrofit decisions in various types of structures; here, our discussion will focus on the adoption decision faced by an individual considering the installation of an energy-saving technology in an existing home.

STATIC ADOPTION DECISIONS

Here we consider a builder who has the option of incorporating a new technology into the design of a house at a specified time, taking as given other design features of the house. We allow for the factors noted in the preceding section, as follows: (1) Houses may be heterogeneous in their energy use. (2) The housing market may discount energy savings because builders cannot represent them credibly. (3) The prevalence of the practice among builders in the area as well as the builder's own experience with the technology may affect incremental adoption costs. (4) Regulation may affect the decision by modifying

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5. Stoft (1993) attempts to use the CAPM model of Sutherland to estimate how high consumer discount rates should be, and finds that this mechanism does not explain implicit discount rates as high as have typically been found by researchers. This analysis does not, however, incorporate the mechanism modelled by Hassett and Metcalf.

the cost of the new technology.[6] (5) Tax credits or other subsidies may be associated with the use or adoption of energy-conserving technologies.

The builder's decision may be modeled 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 (that is, the capitalized value of the installed technology), minus the costs of adoption.[7] These may include costs associated with up-front purchase and installation, the implicit or explicit cost effects of regulation, and learning effects due to previous use by this builder or current use by other builders in the area.

Not surprisingly, such an optimization problem yields a necessary condition for technology adoption that compares the overall cost of adoption with the expected increase in the selling price of the house.[8] In particular, the technology should be employed at time of construction, T, if:

$$\delta \cdot (1 - w) \cdot G(k_{ijT}, \mu_{ijT}) + \gamma D_{iT} > L(C_{iT}, S_{ijT}, v_{iT}) - X_{iT} \qquad (1)$$

where δ =   discount ($0 \leq \delta < 1$) or premium ($\delta > 1$) applied by market to value of energy savings;

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

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

μ_{ijT} =   unobserved factor affecting energy use;

$G(\cdot)$ =   function that relates elements of k_{ijT} to expected discounted present value of fuel expenditures;

6. Our 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.

7. This approach is fully deterministic, but as our previous discussion of potential explanations of the gradual diffusion of energy-efficiency technologies suggests, uncertainty may play a significant role. It is possible to focus instead on that dimension of the diffusion process. See, for example: Hassett and Metcalf (1992); and Howarth and Anderson (1992).

8. The optimization problem and its basic solution is provided in Appendix A. For a detailed description of the model and its solution, see Jaffe and Stavins (1994).

γ = 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;[9]

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

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

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

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

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

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

This inequality indicates that 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 regulations (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. It may be reduced by a government subsidy.

By specifying reasonable functional forms for the $G(\cdot)$ and $L(\cdot)$ functions, rearranging the adoption condition in the form of a benefit/cost ratio, and taking logarithms of both sides of the resulting expression, we have:[10]

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9. See Russell, Harrington, and Vaughan (1986).
10. For a discussion of functional forms and complete derivation, see Jaffe and Stavins (1994).

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

(2)

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

where P_{it} =   price of fuel;

β_m =   set of parameters associated with the k_{ijT}^m observable characteristics;

e =   base of natural logarithms; and

r =   real market rate of interest.

Equation (2) 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 unambiguously negative impact. If principal-agent slack exists, the parameter δ will be greater than zero but less than unity, and so $\log(\delta)$ in equation (2) will be negative. Ideally, it would be desirable to model explicitly the information problems that create principal/agent slack in the new-home market. This would be necessary, for example, in order to quantify the effect on energy efficiency of policy interventions such as mandatory energy-efficiency audits. This effort would only be worthwhile, however, if the parameters of the richer model could be estimated empirically. Because information itself is unobserved, we do not believe that this is possible. For this reason, we use the simpler formulation where the parameter δ is a placeholder for the more complex phenomenon.

Equation (2) also shows that adoption will be more likely the higher future energy prices are expected to be, and will be lower the higher is the discount rate r that individuals apply to expected energy savings. To clarify further the relationship among principal/agent slack (captured by δ), the discount rate r, and expected future prices, we assume for simplicity that consumers expect that the future price of energy will be some constant value P_i', and we then rearrange equation (2), solving out the present discounted value price term:

$$\log(\delta) + \beta_1 \log(P_I') - \beta_1 \log(r) \geq \log \left[(C_{iT})^{\alpha_1} \cdot (v_{iT})^{\alpha_2} \cdot (\frac{S_{ijT}}{\alpha_3})^{\alpha_4} - \gamma D_{iT} - X_{iT} \right]$$

$$- \log(1 - w) - \sum_{m=2}^{M} \left[\beta_m \log(k_{ijT}^m) \right] - \log(\mu_{ijT}) \tag{3}$$

Equation (3) shows that the effects of δ, P_I', and r are indistinguishable from each other. If we could measure r and P_I', then we could use equation (3) (together with assumptions about the distribution of μ_{ijT}) to estimate δ. In practice, we cannot measure either of these. So instead what is typically done is to ignore the principal/agent issue (i.e. set δ to unity), assume that P_I' is equal to the current price, and then *estimate* the discount rate from some version of equation (3). What is typically found is that r is relatively high. But what equation (3) shows is that this result can mean any of three different things. It could mean that δ is less than unity; it could mean that P_I' is less than assumed by the researcher; or it could mean that consumers truly utilize a high discount rate to evaluate these investments. There is simply no way, based only on observed purchase decisions, to disentangle these three phenomena.

Returning to equation (2), the term behind the summation sign shows 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. The second line of equation (2) demonstrates that decreases in adoption costs will accelerate technology diffusion. Such decreases could be due to: changes in the direct costs of equipment purchase and installation (C_{iT}); 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}). Depending on the magnitude of the parameter (α_2), there may be a dynamic externality in which increased adoption today fosters future adoption by increasing v_{it}.

Finally, direct regulations—such as building codes—can directly and positively affect adoption by decreasing expected costs (γ),[11] and government programs in the form of subsidies or tax credits (X_{iT}) can directly reduce costs and thereby spur diffusion.

11. The magnitude of this impact is clearly an empirical matter. See, for example: Jaffe and Stavins (1993a, 1993b). In another strand of this research, we investigate the empirical implications of this model by specifying appropriate functional forms, and estimating parameters econometrically with data on the diffusion of thermal insulation in new residential construction in the United States over the period 1979-1988 (Jaffe and Stavins 1993b).

DYNAMIC ADOPTION DECISIONS

In this second case, we consider a homeowner who is thinking about injecting blown insulation into exterior walls. To minimize expected costs,[12] he or she must decide *at what time* (if any) to perform the retrofit installation.[13] Because the technology may be significantly less costly in the future, this is not simply a yes-no decision like the one faced by the builder.

The costs that the homeowner wishes to minimize consist of three elements—the present discounted value of annual energy costs from the present to the time that the energy-saving technology is adopted; the present value of annual energy costs after the adoption; and the present value of the one-time cost of adoption. This dynamic optimization problem[14] yields a necessary condition that adoption is predicted to occur at time T such that:

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

$$- \left[\frac{\partial L}{\partial C_{iT}} \right] \cdot \left[\frac{dC_{iT}}{dT} \right] - \left[\frac{\partial L}{\partial V_{iT}} \right] \cdot \left[\frac{dV_{iT}}{dT} \right] + \left[\frac{dX_{iT}}{dT} \right]$$

(4)

where $g(\cdot)$ is a function that relates elements of k_{ijT} to annual fuel expenditures; V_{iT} is the fraction of retrofit candidates in jurisdiction i that have adopted the technology by time T; and all other variables are as defined previously.

The left-hand side of equation (4) indicates that higher annual energy costs can encourage adoption, as can the effectiveness of the technology[15] 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

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12. It is also possible that energy conservation enters directly in some people's utility functions. Further, note that if the homeowner is not risk-neutral, the riskiness of the investment can be captured by appropriate adjustment of the interest rate. In this regard, Hassett and Metcalf (1992) examine the effect of uncertainty on the retrofit decision. By focusing 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) would change if the house became more energy-efficient.

13. 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 ignored the possibility that the retrofit option affects the initial installation optimization problem.

14. The model is presented and solved in Appendix B. A more complete version is found in Jaffe and Stavins (1994).

15. Note that $1 - \delta w$ is the expected proportion of energy saved.

expectations of decreased effective costs of adoption in the future. Thus, even if the current savings in energy costs are greater than the yearly annuity of adoption costs, it can pay to wait *if* those adoption costs are expected to fall over time at a sufficiently rapid rate.

By adopting appropriate functional forms for $g(\cdot)$ and $L(\cdot)$ in the retrofit context, we have:

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

$$+ \alpha_1 \left[\frac{dC_{iT}}{dT} \right] + \alpha_2 \left[\frac{dV_{iT}}{dT} \right] - \left[\frac{dX_{iT}}{dT} \right] + \mu_{ijT} \geq 0 \tag{5}$$

Equation (5) is a statement about the *current* rate of energy savings; it does not involve present values of future streams, in contrast with equation (2) in the new construction case. On the other hand, it does include the time rate of change of adoption costs, which brings into play current expectations of future adoption costs. Put more 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.[16]

Adoption decisions in the retrofit case are thus made on the basis of current energy prices without concern for the future paths of energy prices. However, equation (5) does indicate that interest rates still matter, since it is the annuity of adoption costs that is critical. 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_{iT}). Climatic departures from temperate conditions will encourage adoption, as will other factors that increase energy use. The existence of relevant regulations can encourage adoption as well.

The second bracketed term on the first line of equation (5) implies that high adoption costs will unambiguously discourage adoption, whether they 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}).

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16. Thus the model produces a potential nonmarket-failure explanation of gradual diffusion, beyond those suggested above.

Despite the irrelevance of future energy price paths, equation (5) reminds us that the current time rate of change of adoption costs does matter. In particular, it can pay to wait if purchase or installation costs, or both, are falling, even though *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 fast enough over time, one may choose to wait for the higher subsidy at a later date even though the current benefit-cost picture is otherwise positive.

THE ROLE OF PUBLIC POLICY

Either conventional command-and-control regulatory policies or incentive-based economic instruments can be used to influence the rate of technological diffusion. 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. If the diffusion process is relatively 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, for example, 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 would be more likely to achieve success, the argument goes, with regulatory mandates requiring the use of particular technologies.

Some of the factors we have identified as influencing the rate of diffusion suggest a role for government intervention, but others should *not* be taken as meriting policy responses. In particular, the nonmarket failures may help to explain the gradual diffusion, but they *do not* argue for government intervention.[17] Falling into this category are high discount rates,[18] the individual costs of absorbing and adapting to a new technology, 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

17. More rapid diffusion is not necessarily better; in other words, the socially optimal rate of diffusion is not instantaneous. To the degree that a "gradual" diffusion rate is partially explained by market failures, however, that diffusion rate can be said to be sub-optimal. In such case, appropriate government actions can be employed to correct for the market-failure and thus to accelerate the diffusion process.

18. To the extent that high *implicit* discount rates reflect market failures such as principal/agent problems, they might provide evidence in favor of a need for policy intervention. To the extent, however, that consumers are not choosing efficient technologies because they truly have high discount rates for these kinds of investments, this would not merit a policy response.

only help explain gradual diffusion but also provide a set of potential justifications for government intervention.

The evaluation of policies intended to influence energy-efficiency technology adoption decisions requires simulations that emulate the dynamic nature of the respective decision processes. For illustrative purposes, we develop a simulation model of aggregate technological diffusion in the new-home construction case, based on equation (2). To simplify our analysis, we assume that μ (an unobserved factor influencing energy use) has a logistic distribution and is independent of other house-specific variables. Therefore, the fraction of homes in year T that will incorporate the technology is the probability that condition (2) holds, which is equal to the logistic cumulative probability function evaluated at the left-hand side of equation (2), or:

$$v_T = \frac{1}{1 + e^{-A_T}} \qquad (6)$$

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 equation (2).[19]

Using this simulation model, we graph in Figure 1 a base-case (no new policy) diffusion path for the time period 1978-1988. We chose to simulate this particular time interval because it encompasses a significant turning point in real energy prices. The resulting nonmonotonic diffusion curve is typical of some energy-efficiency technologies in new homes during this period.[20] With the help of the simulation model, simple differential calculus, or simpler inspection of the behavioral relationships, we can now explore the likely consequences of alternative public policies.

19. Given the assumption of independence of μ and the other variables, those variables in equation (2) 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 equation (2) 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_t is replaced by P_{iT}.

20. In fact, our base-case parameter and variable values reflect actual data for triple-pane windows, and the simulated diffusion curve is similar to the observed diffusion path of that technology in the United States. The shape of the diffusion path is partly a consequence of the related path of expected, real energy prices, and is related to the decreasing use of triple-pane windows during the second half of the timer period (Jaffe and Stavins 1993a).

Figure 1. Base-Case Simulation and the Effects of Alternative Constant Policy Changes
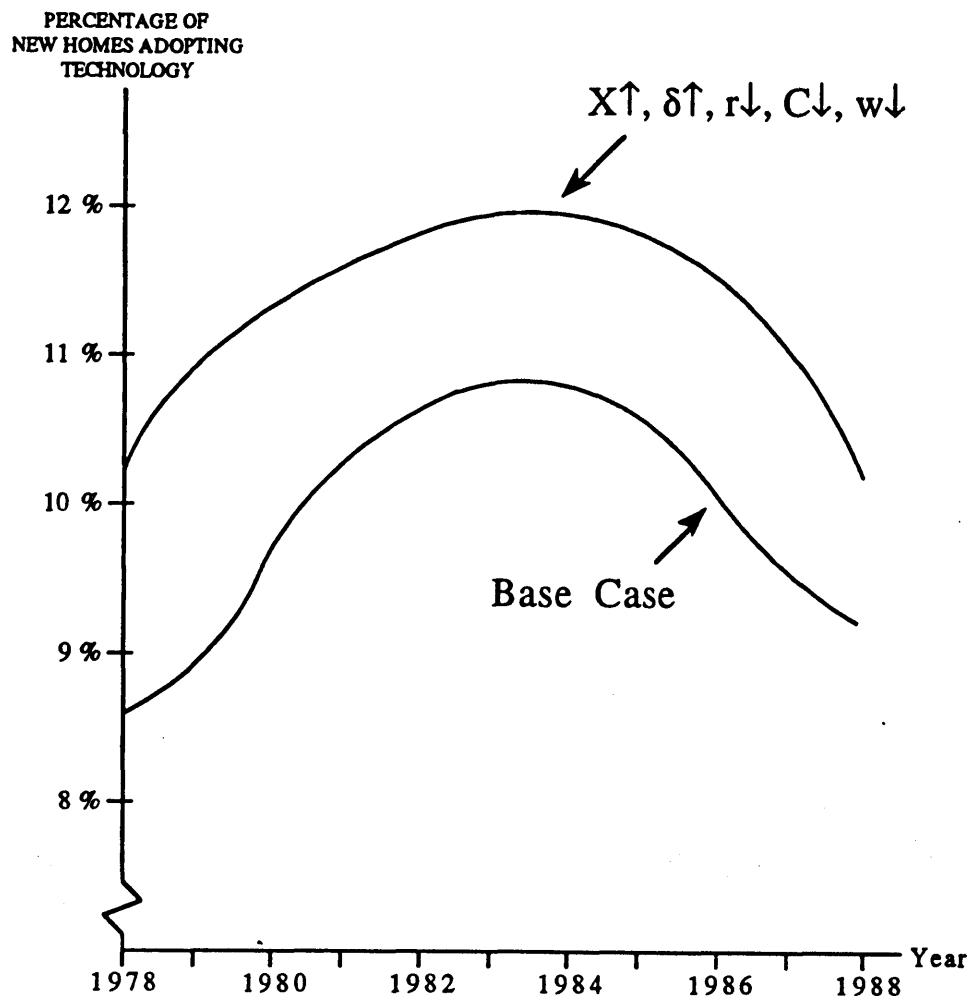
First, the public-good aspect of incomplete information can suggest a number of policy responses, depending upon the nature of the incomplete information. Where uncertainty surrounds the potential benefits of energy-conservation technologies in new construction, our analysis suggests that government could establish standards for energy audits and disclosure requirements for new buildings, thereby increasing δ. Graphically, this shifts the diffusion path in Figure 1 upward. Likewise, public information campaigns about the potential benefits and costs of adopting new technologies could be effective in the new construction case ($\delta\uparrow$, $\alpha_1\downarrow$, $r\downarrow$) and the retrofit case ($\alpha_3\downarrow$, $r\downarrow$).[21] Focusing on the attributes of the technologies themselves, product

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21. 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 (nonmonotonic) shape.

labeling requirements, or guidelines could be effective for new construction ($\alpha_1\downarrow$, $\delta\uparrow$) and retrofitting ($\alpha_3\downarrow$, $\delta\uparrow$).

Concern about principal-agent problems has led in the past to legislative proposals requiring the U.S. Department of Energy to develop a *voluntary* home energy rating system that would provide consumers with better information on the efficiency of prospective homes ($\delta\uparrow$). Standards for audits and disclosure would have the same basic result.
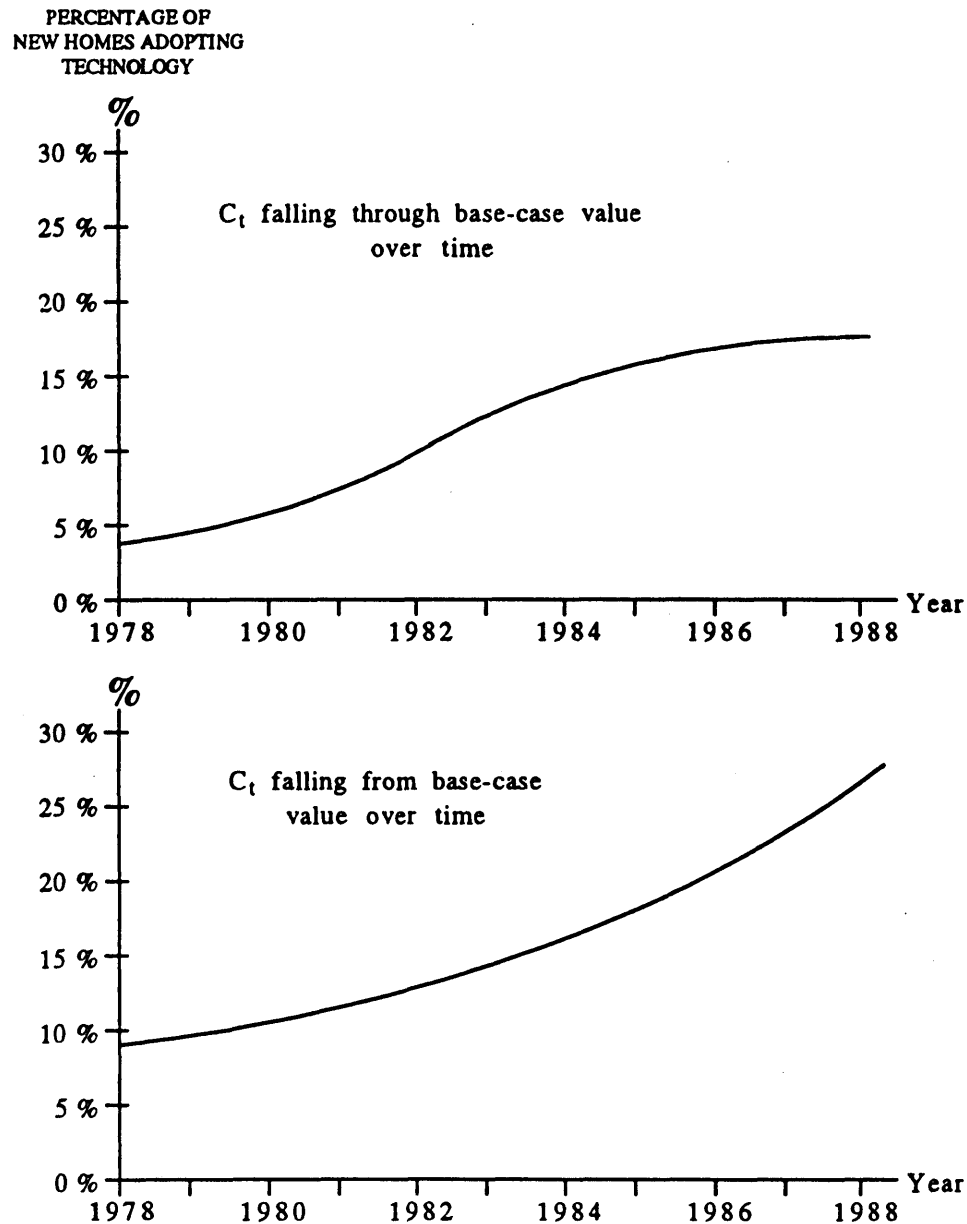
The appropriate policy response to artificially low energy prices will depend, of course, upon the reason for the problematic pricing. One approach would be to increase energy prices ($P_{it}\uparrow$) in those markets where they are currently subsidized. In this same context, the existence of uninternalized environmental externalities associated with particular sources of energy clearly calls for those externalities to be internalized, through pollution taxes, tradeable permit systems, or other economic instruments ($P_{it}\uparrow$), 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/or increases in the effectiveness (engineering efficiency) of those technologies ($w\downarrow$). Further, since adoption behavior can itself result in positive externalities if others' use of a technology is an important source of valuable information, there is an argument in favor of government employing "adoption subsidies" or tax credits ($X_{iT}\uparrow$).[22]

As indicated, some energy-efficiency technologies used in new home construction—such as triple-pane windows—have exhibited nonmonotonic diffusion paths. 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 rapidly over time, the depressing incentive effects of falling energy prices would have been reversed. Indeed, various hypothetical 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 (Figure 2).

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22. 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 (I-w), and increases in adoption subsidies or tax credits (X_{iT}) exhibit the same effect: upward shifts of the nonmonotonic diffusion path (see Figure 1).

Figure 2. The Effect of Decreasing Adoption Costs on Technological Diffusion

PERCENTAGE OF
NEW HOMES ADOPTING
TECHNOLOGY

$\%$

C_t falling through base-case value
over time

30 %
25 %
20 %
15 %
10 %
5 %
0 %

1978   1980   1982   1984   1986   1988   Year

$\%$

C_t falling from base-case
value over time

30 %
25 %
20 %
15 %
10 %
5 %
0 %

1978   1980   1982   1984   1986   1988   Year

Besides supporting technological research and development efforts to bring down adoption costs, 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 have the

Figure 3. The Effect of Increasing Engineering-Efficiency on Technological Diffusion

PERCENTAGE OF
NEW HOMES ADOPTING
TECHNOLOGY

W_t decreasing from 0.99 in 1978 to 0.50 in 1988
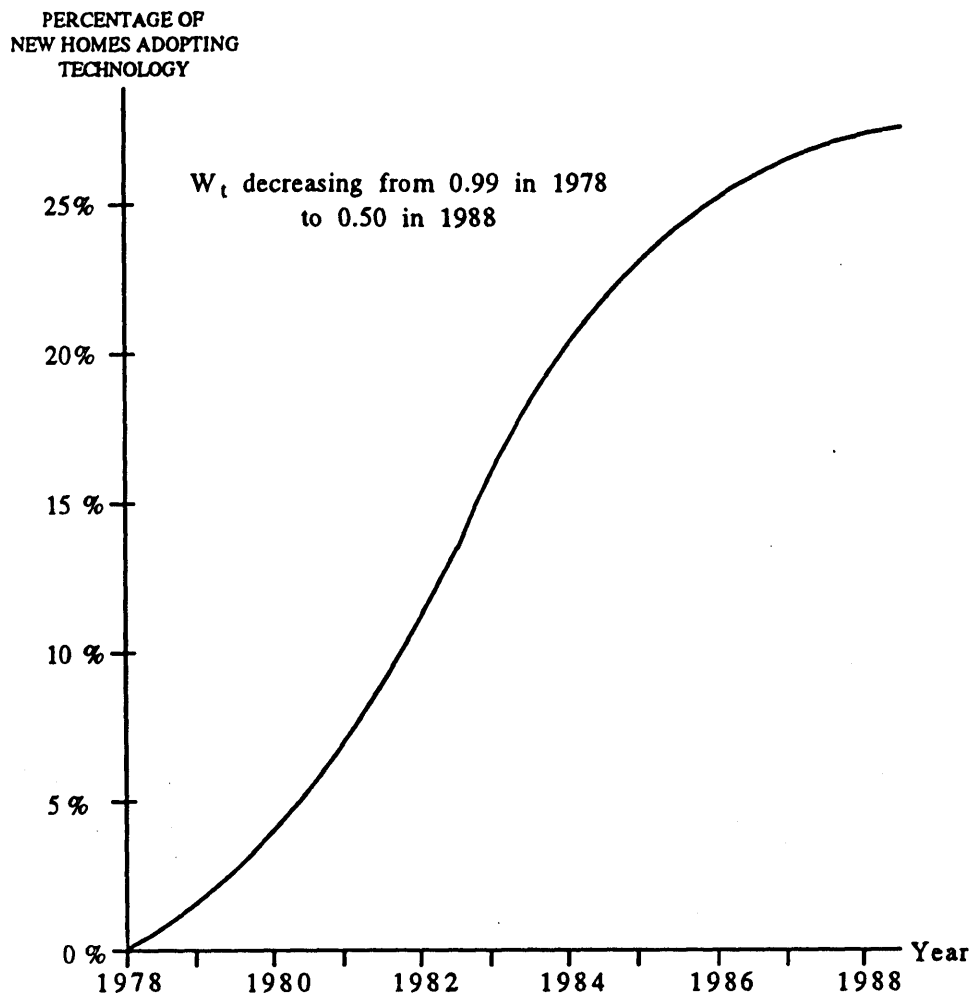
effect not only of decreasing option costs but also on increasing the efficiency of available technologies (w↓). Figure 3 shows that as w falls over time from an initial value of 0.99 (indicating virtually no efficiency advantage) to 0.50 (indicating that the technology cuts energy demand by 50 percent), annual adoption increases monotonicly in an essentially sigmoid path from zero to 30 percent of newly constructed homes.

Other dynamic government policies could be employed to compensate for falling energy prices. For example, a *continuously increasing* subsidy (X_{iT}) of sufficient magnitude could be used to maintain adoption rates at their peak level (again, in the face of falling energy prices). Indeed, 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 resulting from the effect of learning on effective costs of adoption).

Figure 4. The Effect of a One-Time Increase in Regulatory Stringency on the Annual Rate of Technological Diffusion

PERCENTAGE OF
NEW HOMES ADOPTING
TECHNOLOGY
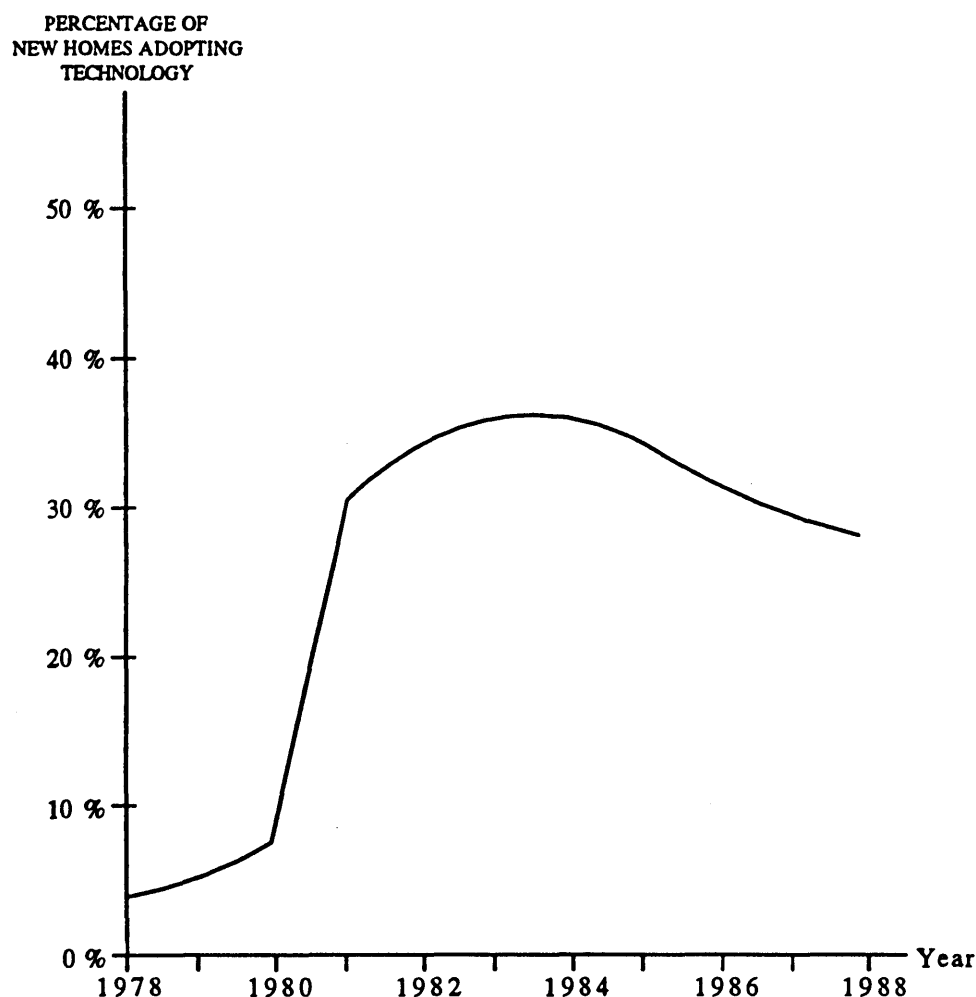
The obvious alternative to a subsidy on the technology (or a tax on energy prices) is a conventional regulatory approach, such as the use of building codes in the new-construction context. Although regulations can—in theory—have the desired effect, our analysis indicates that a one-time change in regulatory stringency should not be expected to lead automatically to an increasing or even a constant level of annual adoption. Figure 4 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.

CONCLUSIONS

Understanding the causes of the gradual diffusion of energy-conserving technologies is key to identifying appropriate policy responses. One set of causes, which we have labelled the "nonmarket-failure" causes—private information costs, high discount rates, and heterogeneity among potential adopters—do not provide legitimate justifications for government intervention. On the other hand, a fairly large number of potential market-failure explanations —information problems, principal-agent slippage, and unobserved costs—can provide solid arguments for government action. While our analysis indicates how alternative policy instruments—both economic incentives and direct regulations—can hasten the diffusion of energy-conserving technologies, the selection of appropriate policy instruments will depend upon the relative importance of the various underlying explanations of the gradual diffusion of energy-efficiency technologies.

APPENDIX A

In the new construction case, we focus on a simple discrete technology for purposes of explication, although 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. In our example, the builder's problem is:

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

$$- I \cdot \left[L(C_{iT}, S_{ijT}, v_{iT}) - \gamma D_{iT} - X_{iT} \right] \tag{A1}$$

where uppercase letters represent stocks or present values; lowercase 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);

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

$\delta =$ discount $(0 \le \delta < 1)$ or premium $(\delta > 1)$ applied by market to value of energy savings;

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

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

$\mu_{ijt} =$ 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 cost of adoption of the technology;

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

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

$L(\cdot) =$ 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;

$\gamma =$ 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; and

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

This optimization problem yields a necessary condition for technology adoption that compares the overall cost of adoption with the expected increase in the selling price of the house. We derive the necessary condition for adoption by denoting the expected discounted present value of the function $g(\cdot)$ as $G(\cdot)$. Thus, the technology should be employed if:

$$\delta \cdot (1 - w) \cdot G(k_{ijT}, \mu_{ijT}) + \gamma D_{iT} > L(C_{iT}, S_{ijT}, V_{iT}) - X_{iT} \qquad (A2)$$

APPENDIX B

In the retrofit case, 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 that the energy-saving technology is adopted; the PV of annual energy costs after the adoption; and the PV of the one-time cost of adoption:

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

$$+ [L(C_{iT}, V_{iT}) - X_{iT}] \cdot e^{-rT} + \gamma \cdot \int_0^T D_{it} \cdot e^{-rt} dt \qquad (B1)$$

subject to $T \geq 0$

where T is the time of adoption (installation); V_{iT} is the fraction of retrofit candidates in jurisdiction i that have adopted the technology by time T; and all other variables are as defined previously. Although interventions such as regulations are typically not utilized in this retrofit context, we allow for their impact here because in other possible applications—such as industrial pollution

control—they can be designed either to affect all sources (thus requiring retrofitting at existing sources) or only new sources.[1]

The formulation of installation cost differs slightly in the retrofit case from the new construction case. Since the homeowner will not usually 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. Given 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 equation (B1) subject to the constraint of equation (B2) can be expressed in a condensed form in which adoption should occur in year *T* if:[2]

$$\frac{\partial PV(T)}{\partial T} \geq 0 \quad \text{and adoption has not yet occured.} \quad \text{(B3)}$$

By evaluating the inequality condition in equation (B3), dividing by e^{-rT}, and rearranging terms, we have the following equation, in which adoption is predicted to occur at time *T* such that:

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

$$- \left[\frac{\partial L}{\partial C_{iT}} \right] \cdot \left[\frac{dC_{iT}}{dT} \right] - \left[\frac{\partial L}{\partial V_{iT}} \right] \cdot \left[\frac{dV_{iT}}{dT} \right] + \left[\frac{dX_{iT}}{dT} \right] \quad \text{(B4)}$$

1. The effect of regulation enters into the objective function as the final term in the second line of equation (B1). Thus, we are viewing regulations as an additional cost to be minimized, where this cost is equal to the "effective penalty" of noncompliance from the present time to the date of adoption (and 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. These two specifications of the impact of regulations are equivalent.

2. Sufficiency depends upon the satisfaction of second-order conditions, discussed in Jaffe and Stavins (1994).

ACKNOWLEDGMENTS

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