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EXECUTIVE SUMMARY

The effect of public policies on technological change may, in the long run, be among the most important determinants of success in environmental protection. In this paper, we develop a new framework for analyzing the diffusion of environmentally desirable technology. This framework can be used to compare quantitatively the effectiveness of direct regulation and economic-incentive approaches to environmental protection in fostering adoption of energy-conserving technologies, a particularly important issue in the context of greenhouse-gas emissions and the threat of global climate change.

We develop a dynamic model of the adoption decision faced by an individual who must determine whether and at what time to invest in an existing energy-saving technology. First-order, necessary conditions emerge which are aggregated into a model which can be econometrically estimated with aggregate data, by taking account of unobserved heterogeneity among households. Econometric estimation results can be used in factual and counterfactual simulations to investigate the implications of alternative policy mechanisms. In this working paper, we simply develop an initial formulation of the underlying theoretical model of technological adoption, and we demonstrate how it can yield an econometrically estimatable model of the diffusion process. Our purpose here is to solicit feedback regarding the general framework and specific theoretical specification which we propose. Subsequently, we intend to carry out econometric estimation of a refined model's parameters

with data on the use of various energy-conserving building practices, and thereby to examine a set of hypothesis regarding the relative effectiveness of economic incentives and direct regulation for environmental protection in terms of their impacts on the diffusion of technology.

EVALUATING THE RELATIVE EFFECTIVENESS OF ECONOMIC INCENTIVES AND DIRECT REGULATION FOR ENVIRONMENTAL PROTECTION: IMPACTS ON THE DIFFUSION OF TECHNOLOGY

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1. 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 dramatically alter the nature of these tradeoffs. Therefore, the effect of public policies on the process of technological change may, in the long run, be among the most important determinants of success or failure in environmental protection.

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 been neglected both by research and public policy (Mowery and Rosenberg 1989). In the environmental area, there has been much interest in the development of environmentally-benign technology, but it has typically been assumed that getting people to use such new technologies need not be a major concern. This is now changing, as widespread disappointment at the rate of adoption of energy-efficient and other environmentally-benign technologies leads to d interest in the determinants of the rate of technological diffusion.

1.1 Direct Regulation and Economic Incentives for Environmental Protection

In this paper, we develop a new framework for analyzing the diffusion of environmentally desirable technology. This framework permits quantitative evaluation of the relative effectiveness of alternative policy approaches to fostering the diffusion of technologies. In particular, we develop a model that can distinguish empirically the relative effectiveness of direct regulation[1] and economic incentives[2] in causing the adoption of energy-conserving technologies. This is of particular importance in the context of global climate change, concern for which has led to renewed interest in energy efficiency.

The use of economic incentives to achieve regulatory goals has long been advocated by economists,[3] and recently these ideas have begun to receive greatly increased attention from policy makers.[4] The 1990 amendments to the Clean Air Act[5] plus a variety of additional policy proposals now under consideration[6] suggest that we may witness a significant expansion in the use of market-oriented approaches to achieve environmental objectives. The theoretical arguments in favor of incentive-based approaches are strong: (1) such approaches facilitate achievement of environmental goals and standards at the lowest aggregate cost to society (i.e., in a cost-effective manner); and (2) such approaches provide dynamic incentives for firms to adopt better pollution-control technologies.[7]

These theoretical arguments and some general frustration with the amount of progress being made with conventional, command-and-control approaches are among the major reasons for the heightened interest in incentive-based environmental policies.[8] There is, however, relatively little systematic empirical evidence documenting the effectiveness of economic incentives in changing behavior in ways desired by regulators. This is primarily because the relatively limited use of incentive-based approaches has not generated much data with which these policies can be evaluated.[9]

World events affecting energy markets have, however, generated just such an experiment. The dramatic rise in oil prices and the coincident shortages in the 1970's led to a variety of regulatory efforts designed to reduce consumption of energy. At the same time, the rise in the cost of energy itself generated strong economic incentives for conservation. The subsequent significant drop in the price of oil reduced these incentives considerably. From the point of view of conservation as a policy goal, this

reduction in incentives may have been unfortunate, but it has greatly improved our ability to assess the relative effectiveness of the regulatory actions that were taken (many of which are still in effect) and the changes in prices that occurred. This natural experiment can enable us to quantify the relative effectiveness of conventional command-and- control regulations and market incentives by examining statistically the use of energy-saving building practices in new construction across different states and across time. Two major factors, among others, affect the choice of such technologies as insulation (of varying density and thickness) and the use of double or triple glazed windows: the cost of the conservation measure relative to the value of the energy saved, and direct regulatory constraints, i.e. building codes. Many state and local governments incorporated energy-conservation features in their building codes at various times beginning in the mid-1970's, thus attempting a command-and-control approach to conservation, at the same time that energy prices created incentives in the same direction. These variations in both building codes and prices across states and over time can be used to sort out their respective effects.

1.2 Overview

In this working paper, we develop an initial formulation of the underlying model of technological adoption, and we demonstrate how it can yield an econometrically estimatable model of the diffusion process. Our purpose here is to solicit feedback regarding the general framework and specific model which we propose. Subsequently, we intend to carry out econometric estimation of a refined model's parameters. The next section of the paper examines the "paradox" of the slow adoption of new energy-conserving technologies, in the context of the economics of technological diffusion. We note that policy decisions relating to global climate change present a particularly pressing arena in which an improved understanding of technological diffusion can lead to formulation of better public policy. In section 3, a formal model of the diffusion process is developed that is capable of incorporating both economic and policy influences. Within this analytical framework, we demonstrate that the relative effectiveness of direct regulation and economic incentives is an empirical issue that can be resolved with sufficient data. In section 4, we describe how results from econometric estimation can be used to examine the implications of alternative policy approaches. Finally, we summarize the paper and examine the next steps.

2. CONCEPTUAL FRAMEWORK: ENVIRONMENTAL POLICY AND TECHNOLOGY DIFFUSION

2.1 Current Policy Issues

In many spheres, environmental quality could be enhanced by more widespread adoption of existing

technologies. Encouraging such diffusion has hence been an explicit or implicit goal of a number of environmental policies, although there has been much debate about the most appropriate means of achieving such a goal. In particular, economists and others have long argued that economic-incentive mechanisms would create the appropriate inducements for firms to adopt new pollution-control technologies, when and where it was cost-effective to do so.[10] But Federal, state, and local laws and regulations have relied, for the most part, on command-and-control mechanisms to direct the adoption of new technologies, either directly, using technology standards that specify equipment and/or processes, or indirectly via performance standards (with performance levels frequently chosen on the basis of what particular technologies can achieve).[11]

This debate has been sharpened by the recently signed Clean Air Act amendments[12] and by increased attention given by the Federal government to the threat of global climate change due to the greenhouse effect.[13] In the latter case, renewed interest in energy efficiency has been generated by increased concern over the role of carbon dioxide (CO_2) in global climate change. As consideration is given to the relative merits of incentive- based and conventional regulatory approaches to reducing CO_2. emissions, largely a consequence of fossil-fuel combustion, it is necessary to come to grips with the "paradox" (Shama 1983) of relatively low adoption rates of existing energy-conserving technologies, despite their apparent economic advantages (Hausman 1979; Norberg-Bohm 1990). If appropriate policies are to be developed to increase the rate of adoption of such technologies, it is essential first to understand what has determined their rate of adoption in the past.

Because the diffusion of apparently profitable technologies such as fluorescent lighting, insulation, and multi-glazed windows has not been instantaneous, some commentators have suggested that energy-conserving policies aimed at the greenhouse problem would be very inexpensive (Williams 1990).[14] This conclusion is far from obvious, however, when one addresses the question in the context of the more general problem of technological diffusion. From the mechanical reaper of the nineteenth century (David 1966), through hybrid corn seed (Griliches 1957), chemical process innovations (Davies 1979), and optical scanners (Levin, Levin, and Meisel 1987) in the twentieth century, research has consistently shown that diffusion of new, economically superior technologies is never instantaneous. It should be no more puzzling today that not all commercial buildings have florescent lighting than it was puzzling in the 1950's that not all farms used hybrid corn seed. An acceleration of technology diffusion may be socially desirable, but it is by no means costless. Speeding up the diffusion process involves overcoming real obstacles. Designing effective and efficient programs to overcome these impediments will require understanding of the diffusion process itself.

2.2 The Process of Technological Diffusion[15]

The pioneering work of Griliches (1957) established the notion that the process of the gradual diffusion of a superior technology could be understood in an economic framework, and the determinants of

the rate of diffusion could be measured empirically. Griliches showed that the rate of diffusion of new hybrid corn varieties was most rapid in states where the (expected) economic return to hybrid corn was greatest. Subsequently, Mansfield (1968) demonstrated that the rate of diffusion also depended on the size of adopting firms, the perceived riskiness of new technology, and the absolute magnitude of the required investment. [16]

FIGURE 1:

THRESHOLD VALUES AND THE DISTRIBUTION OF HETEROGENEITY

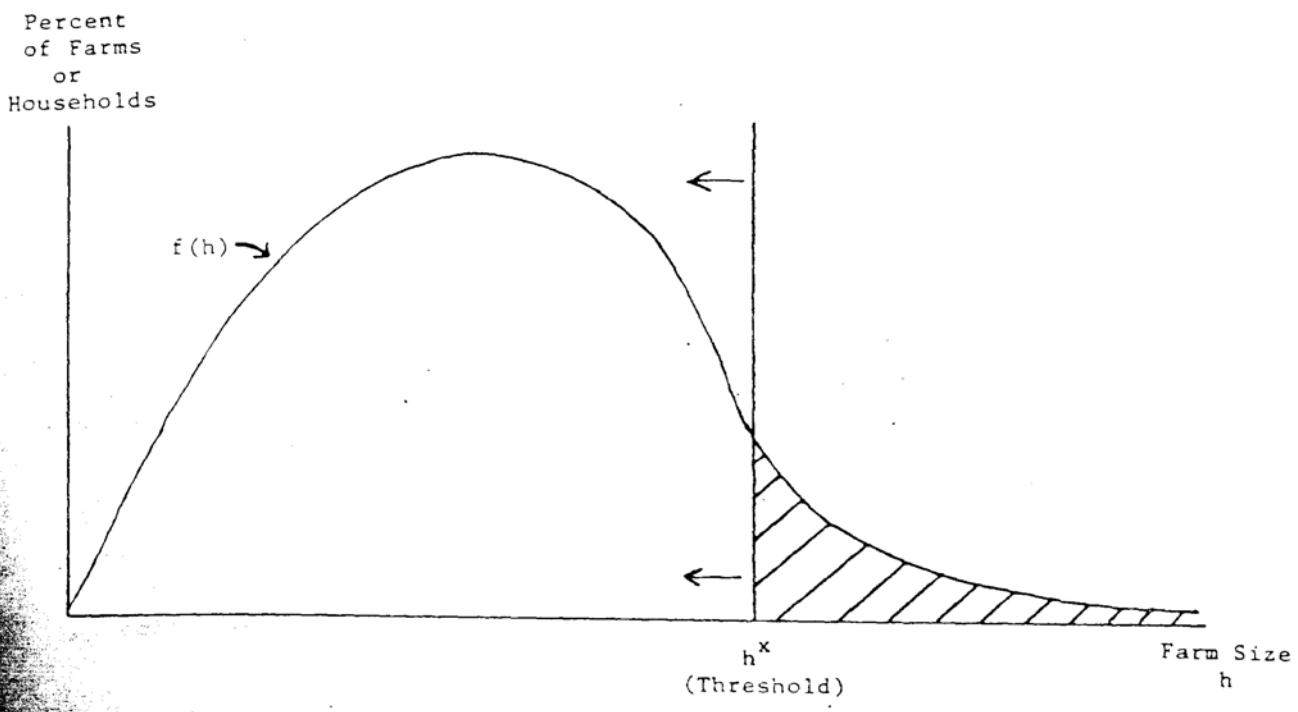
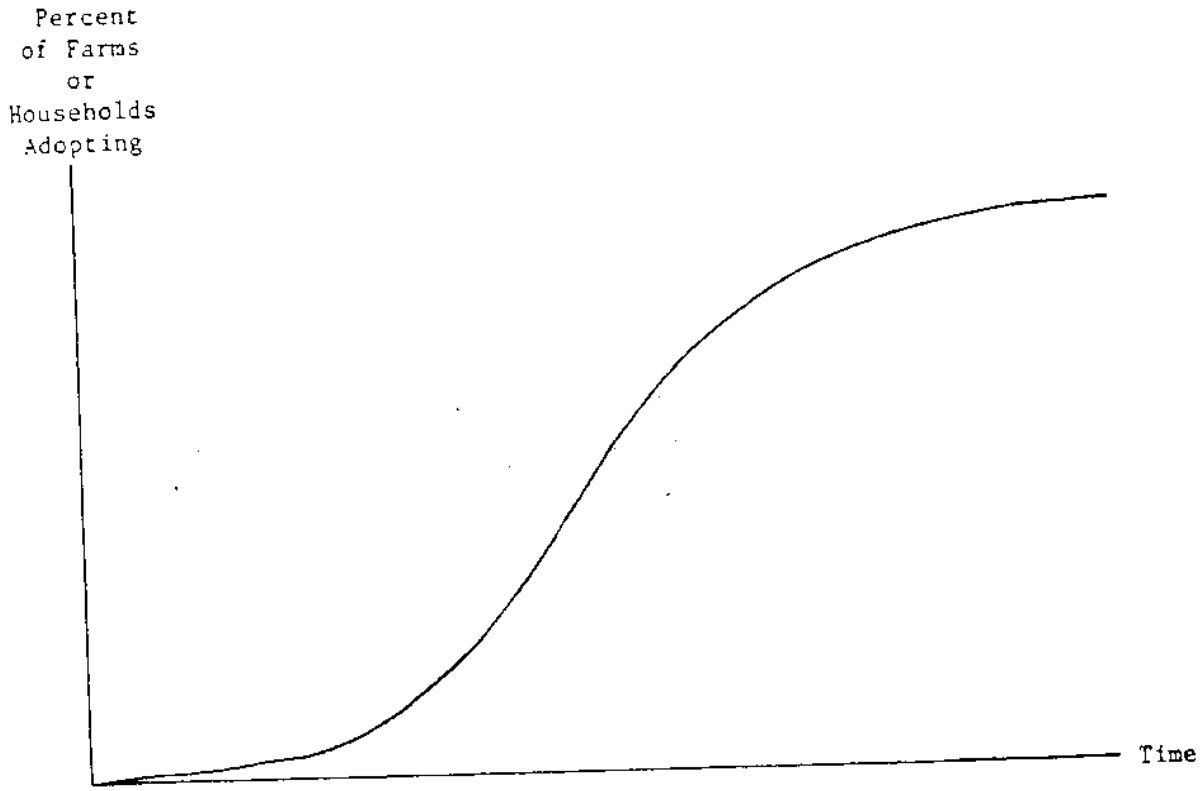


FIGURE 2:

THE S-SHAPED PATH OF TECHNOLOGY DIFFUSION



David (1969) noted that the work of Griliches and Mansfield, while useful in explaining variations (across innovations or across states) in *rates* of diffusion, failed to explain why, for any given innovation, some firms adopt early and others adopt late.

Differences among potential adopters are presumably the very essence of the diffusion phenomenon, and so David argued that they should be the focus of diffusion theory. To this end, David suggested what has come to be called the "probit" approach (Stoneman 1983).[17] He posited that the population of potential adopters of an innovation differ from one another in ways that affect the desirability of technological adoption. For concreteness, one may think of the innovation as being a mechanical reaper[18] and the important dimension that affects its desirability as being the size of individual farms (David 1966). A farmer deciding whether to adopt this innovation faces an investment decision. He can incur a certain cost today, which will reduce his harvesting costs now and in the future, or he can wait, thus saving the cost of adoption. Because of the significant capital outlay required, the larger the farm, the more attractive is this investment.[19]

In this framework, one can think of there being a "threshold" farm size, at any moment in time, above which it is profitable to adopt the innovation and below which it is not. This situation is depicted graphically in Figure 1. Over time, the cost of the reaper falls and its performance improves, enabling smaller farms to adopt the technology as the size-threshold shifts to the left. This movement of the threshold "sweeps out" the distribution of farm sizes and yields the classic S-shaped diffusion process for the innovation (Figure 2).

Such a conceptual model of diffusion is by no means limited to innovations involving the purchase of large capital equipment. All that is required is that potential adopters trade off some up-front cost -- cost of equipment, cost of learning about a new technology, cost of adapting existing processes to it, etc. – against expected future benefits of the technology. Similarly, the improvement in the attractiveness of the innovation over time could take the form 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 innovation depend on firm size. What is crucial is that potential adopters be *heterogeneous along some dimension* that affects the value of the innovation.

In order to use this conceptual framework directly to investigate the factors affecting technological diffusion, observations of individual adoption decisions are required. Frequently, however, the only data available to analysts are in aggregate form (often in accordance with political or other geographic jurisdictions). The methodology we develop -- and which we describe more fully in the following section

-addresses this problem by beginning with a (parameterized) optimization model of individual adoption behavior, and combining that with a (parameterized) model of unobserved heterogeneity among firms, in order to construct a comprehensive analytical model of technological diffusion, the parameters of which can be estimated econometrically with available aggregate data.

3. ANALYTICAL MODEL

Our approach provides a general framework for analyzing policies designed to accelerate the diffusion of desirable technologies. Conceptually, there are two major types of policies available. One the one hand, if the government can change the economic calculus in favor of the new technology, it will speed the movement of the threshold to the left, and thereby increase the rate of diffusion. On the other hand, the government can attempt, by fiat, to force firms to the left of the threshold to adopt the technology despite its unprofitability. At this level of abstraction, either policy could be effective, and neither would be without cost.

In order to identify the preferred policy, imagine the following hypothetical experiment. A new technology comes along, or economic circumstances suddenly change to make a previously available but uneconomic technology now economically attractive. We partition the universe of potential adopters into two groups. In one group, we pass a law saying that they all must use the superior technology. In the other group, we place a tax on firms that don't use it (or we impose a tax on an input for which the technology is input-saving). Such an experiment would quantify empirically the relative effectiveness of regulations and incentives for fostering rapid diffusion of desirable technologies.

As we indicated previously, such an experiment has, in a sense, already been performed. The large increase in energy prices in the 1970's made various energy-conserving technologies attractive. But their profitability varied significantly over time, as prices rose and fell, and over space, depending on climate and the availability of alternative fuels. At the same time, governments attempted to influence directly the adoption of some energy-conserving technologies through the use of laws and regulations. Thus, we have a natural experiment which, at least for this group of technologies, may allow us to examine empirically the relative effectiveness of economic incentives and direct regulation in fostering technological diffusion.

3.1 A Model of Adoption of Energy-Conserving Technology

Our modeling approach to this problem is direct. We view an agent as maximizing long run utility, taking as given both prices and policies that impinge on that utility. Econometric estimation of the properly specified model can yield parameter estimates that quantify the effects of both regulatory actions and prices.[21] Using these parameters, one can then simulate the behavior of the system under alternative assumptions about prices or policy.

We begin with a simple model of the adoption decision faced by an individual who must determine whether and at what time to invest in an existing energy-saving technology. Thus, for example, we may consider a homeowner who is thinking about the possibility of injecting blown insulation into exterior

walls. We posit that such an individual will attempt to minimize costs, subject to various constraints, taking as given all relevant prices and government policies.[22] Thus, a risk-neutral homeowner may be expected to attempt to minimize the present discounted value of the stream of expected costs associated with providing an adequate degree of warmth in his home. These costs may be thought of as consisting 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 from the time of adoption until the end of the relevant planning horizon,[23] and the *PV* of the one-time cost of adoption of the energy-saving technology:

$$\min_{\{T\}} \; PV(T) = \int_0^T g(h_{ijt}, k_{it}) \cdot e^{-rt} dt + \int_T^{\infty} g(h_{ijt}, k_{it}) \cdot w \cdot e^{-rt} dt + C_{iT} \cdot e^{-rT} \tag{1}$$

$$\text{subject to} \quad T \geq 0 \tag{2}$$

where i indexes a local jurisdiction (the minimum level of disaggregation of available information), j indexes individual homes, and *t* indexes time; upper case letters represent stocks or present values; and lower case letters represent flows. The variables are:

h_{ijt} = index of efficiency of individual home heating plant and preferences regarding heating (heterogeneous across homes/homeowners);

k_{it} = average annual energy cost for heating, in absence of the energy-saving technology;

w = index of the average effect of the new technology (blown wall insulation) on annual energy consumption (k_{it}) -- hence, $0 < w \leq 1$;

g(•) = function which relates average annual energy cost for region i at time t and efficiency of household heating plant in a specific home with that home's annual energy cost (for heating);

C_{iT} = cost of adoption of new technology;

e = base of natural logarithms;

r = the real interest rate; and

T = the time of adoption (installation)[24]

Note that only the index of heating-plant efficiency is specific to the individual home; all of the other

variables are measured at the level of aggregation denoted by the regional subscript i. This is a consequence of the limited data which are typically available, *and is* indicative of the information which is actually available to homeowners. The variable, k_{it}, average annual energy expenses for heating services (in the absence of the energy-saving technology) is, itself, a function of a number of variables, including regional fuel costs, typical fuel mix in the region, and climatic factors. The index which differentiates individual homes/homeowners, $h_{ijt,}$ is a function of home characteristics (for example, type of construction, size, age, furnace type) and of personal household characteristics (for example, family size, age, income, education).

First-order, necessary conditions for maximizing *PV(T)* in equation (1) subject to the constraint of equation (2) are: [25]

$$\left[\frac{\partial PV(T)}{\partial T}\right] \cdot T = 0 \tag{3}$$

and

$$\frac{\partial PV(T)}{\partial T} \geq 0 \tag{4}$$

Evaluation of the partial derivative in equation (4) yields:

$$\left[g(h_{ijt}, k_{it}) - g(h_{ijt}, k_{it}) \cdot w - r \cdot C_{iT} + \frac{\partial C_{iT}}{\partial T}\right] \cdot e^{-rT} \geq 0 \tag{5}$$

Dividing by e^{-rT}, multiplying by -1, and rearranging terms, adoption is predicted to occur at time *t* such that:

$$\left[g(h_{ijt}, k_{it})\right] \cdot (1 - w) \geq \left[r \cdot C_{it} - \frac{\partial C_{it}}{\partial t}\right] \tag{6}$$

In order to re-express this relationship in terms of present values, we divide by r. Thus, we predict that adoption will occur when the following condition first holds:

$$\left[G(h_{ijt}, k_{it})\right] \cdot (1 - w) > \left[C_{it} - \frac{1}{r} \cdot \frac{\partial C_{it}}{\partial t}\right] \tag{7}$$

where *G()* is the present-value equivalent of the function g(•).[26]

Thus, the homeowner will adopt the energy-conserving technology (blown insulation, in our example) if and when the expected savings in energy costs (the discounted present value of the future stream of avoided energy costs) is greater than the cost of adoption (the sum of capital and labor for installation) of the new technology minus the product of the expected rate of change of adoption cost and the reciprocal of the interest rate.

The logic behind this relationship is straightforward. The left-hand side of equation (7) indicates that higher annual energy costs encourage adoption of the energy-saving technology. Thus, more effective new technologies (in terms of reducing energy use -- i.e., smaller w) encourage adoption. The first term on the right-hand side of the equation indicates that higher adoption costs (whether direct or indirect) discourage installation. Finally, the presence of the second term on the right-hand side, $1/r \cdot (\partial C_{it} / \partial t)$, indicates that adoption is discouraged by expectations of decreased costs of adoption in the future.

3.2 The Aggregation of the Adoption Condition and the Diffusion of Technology

Equation (7) implies that if all households within any region i at any time t were identical, then either all homes would have the advanced technology or no homes would. Such instantaneous diffusion of technology, of course, is typically *not* observed. Partly, this may reflect deviations from the steady state,[27] but it also reflects heterogeneity among households in terms of their heating plants and heating preferences. Intuitively, those households that are greater consumers of energy for heating (possibly because of larger size and/or a different age or type of structure) will stand to benefit more from the adoption of the energy-saving technology than would a less energy-intensive household, even if both face identical prices and regulatory constraints.

In order to analyze precisely how the underlying (and unobserved) heterogeneity can lead to a gradual diffusion process, we first define:

$$X_{ijt} = \left[G(h_{ijt}, k_{it}) \right] \cdot (1 - w) - C_{it} + \frac{1}{r} \cdot \frac{\partial C_{it}}{\partial t} \qquad (8)$$

Thus, the condition expressed in equation (7) is simply that:

Adoption occurs if $X_{ijt} > 0$ and new technology is not in place (9)

Since there is an incentive to adopt the energy-conserving technology if $X_{ijt} > 0$, there is by implication a threshold value of h_{ijt} denoted h^x_{jt} above which the incentive for adoption manifests itself. This threshold is a function of all of the variables in equation (7), above. The heterogeneity of h_{ijt} may be characterized in terms of a probability density function, $f_i(h_{ijt})$.[28]

We must allow for the fact that some homes may have adopted the energy-conserving technology because they are required to do so by law or regulation, not because it is economically advantageous. Taking this into account, the expression for the diffusion of the energy-saving technology may be expressed in terms of the probability density function, $f_i(s)$:

$$TECH_{it} = p_1 \cdot \int_{h_{it}^*}^{\infty} [f_i(s)]\, ds + p_2 \cdot R_{it} \cdot \int_{0}^{h_{it}^*} [f_i(s)]\, ds + p_3 \cdot R_{it} \cdot \int_{h_{it}^*}^{\infty} [f_i(s)]\, ds$$

where $TECH_{it}$ = percentage of households in region i at time t that have adopted the energy-saving technology;

p_1 = a parameter that indexes the probability that someone for whom the technology investment is profitable and who is not subject to relevant laws or regulations will adopt the technology;

p_2 = a parameter that indexes the probability that someone for whom the technology investment is unprofitable will adopt anyway because of existing laws or regulations;

p_3 = a parameter that indexes the additional probability of adoption due to laws and regulations for households where the investment is in fact profitable;[29] and

R_{it} = a dummy variable (treated exogenously) that equals unity if a relevant regulation exists, and zero otherwise.

Referring again to Figure 1, the first term in equation (10) corresponds to the fraction of households to the right of the adoption threshold; these can all be expected to use the new technology, but, for completeness we allow for the possibility that they do not do so with probability one.[30] In addition, some fraction (p_2) of the households to the left of the threshold will adopt the technology if required to do so by law, and the fraction (p_3) of households adopting that are to the right of the threshold *and* subject to

regulation may be greater than the fractions adopting when only one condition holds.

The fraction of homes within region *i* which "should" have adopted the technology by time t may be expressed in terms of the cumulative distribution function, $F_i(h^x_{it})$:

$$TECH_{it} = \rho_1 \cdot \left[1 - F(h^x_{it})\right] + \rho_2 \cdot R_{it} \cdot F(h^x_{it}) + \rho_3 \cdot R_{it} \cdot \left[1 - F(h^x_{it})\right]$$

By rearranging terms, we have:

$$TECH_{it} = \left[\rho_1 + (\rho_3 \cdot R_{it})\right] + \left[(\rho_2 - \rho_3) \cdot R_{it} - \rho_1\right] \cdot F(h^x_{it})$$

Note that in the absence of binding regulations -- when the regulatory dummy, R_{it}, equals zero -- equation (12) simplifies to $TECH_{it} = p_1 \bullet [1 - F(h^x_{it})]$. As we describe below, the parameters of equation (12) can be estimated econometrically with panel data. In so doing, a number of important policy questions regarding the influences of economic incentives and direct regulation on technological diffusion can be addressed by specifying them as empirically refutable hypotheses.[31] Furthermore, the estimated equation can be used to carry out a variety of simulations of the likely consequences of potential, alternative policy mechanisms.

4. FRAMEWORK FOR POLICY ANALYSIS

4.1 Econometric Analysis

Econometric estimation of equation (12) can yield quantitative estimates of the relative importance of the factors driving the adoption of energy conserving technologies. The estimation process involves several steps. First, it is necessary to identify a technology for which data are available in which both the economic attractiveness of the technology and the extent to which it is affected by regulations vary significantly across jurisdictions. An obvious set of candidates are building practices, such as window glazing and insulation. Their economic attractiveness varies significantly with climate and also varies as fuel prices rise and fall. Such practices are also affected by building codes, which vary across states and over time.[32]

Next, it is necessary to specify the function, $G(h_{ijt}, k_{it})$. This involves identification of observable

factors, such as climate, fuel use, and energy prices, that affect the profitability of adopting the new technology, and also the identification of the nature of the relevant unobserved individual characteristics. For example, an extremely simple form for this function to take for a space-heat-conserving investment might be: [33]

$$G(h_{ijt}, k_{it}) = P_{it} \cdot D_{it} \cdot h_{ijt} \tag{13}$$

where P_{it} = weighted average price of heating fuel in region i at time t;

D_{it} = average number of heating-degree-days; and

h_{ijt} = index, as above, representing the efficiency of the individual heating plant and preferences regarding how warm to keep the house.

Once the form of the function *G(•)* has been specified, then the threshold level, h^x_{it} can be written as a function of the exogenous variables, because h^x_{it} is defined implicitly by equations (8) and (9), above. For the simple form of the function, $G(h_{ijt}, k_{it})$, given by equation (13), we have:

$$h^x_{it} = \left[\frac{C_{it} - \frac{1}{r} \cdot \frac{\partial C_{it}}{\partial t}}{P_{it} \cdot D_{it} \cdot (1 - w)} \right] \tag{14}$$

Thus, the adoption threshold decreases (adoption is more favored) with increases in heating fuel prices, the time rate of change of adoption costs, and the number of heating-degree-days; and the threshold increases (adoption is less favored) with increases in the cost of adoption, and interest rates.

The next step, as indicated above, is to construct a set of data containing information on the use of the chosen technology, the economic determinants of its attractiveness, and the regulations that affect it. For the building-practices example, a panel of states over time may be assembled, including data on the use of the practice, fuel prices, fuel mixes, climate, and building codes.

The National Research Center of the National Association of Home Builders compiles information on a geographically aggregated[34] basis and over time on the use of various building practices, including a number that directly relate to energy conservation. The Department of Energy compiles information on regional energy prices. Regional information on heating and cooling degree days is also relevant, since, for given prices, these affect the value of conservation investments. Finally, the National Council of State Building Codes and Standards compiles information on building codes nationwide, although the level of detail available may require the collection and integration of substantial amounts of supplementary information from direct contact with state agencies. [35]

Thus, a panel data set of states over time may be constructed. Though there is probably some

correlation across states in the use of regulation and the effective incentives, there is not likely to be a perfect correspondence; and there is certainly significant independent variation in the time dimension as well. A related problem is the possible endogeneity of regulations. One might expect that regulators who "know" that regulation is relatively effective (ineffective) in their state, will be more (less) likely to adopt it. This would bias estimates of the effectiveness of regulation.[36] A solution to this problem could lie in finding instruments for the use of regulation, such as political attributes that are unrelated to energy.[37]

With a data set developed, it is next necessary to specify a parametric distribution for the unobservable h_{ijt}. For many applications, including that mentioned above, it is convenient to assume that h_{ijt} is distributed lognormally, with mean μ and variance o^2, themselves parameters to be estimated from the data. If $Fi(h^x_{it})$ in equation (12) is taken to be the lognormal cumulative distribution function, then we have:

$$TECH_{it} = \left[\rho_1 + (\rho_3 \cdot R_{it})\right] + \left[(\rho_2 - \rho_3) \cdot R_{it} - \rho_1\right] \cdot Z\left[\frac{[\log(h^x_{it}) - \mu]}{\sigma}\right] \tag{15}$$

where Z[•] is the cumulative, standard normal distribution function, and h^x_{it} is defined as in equation (14).

Thus, the model embodied in equations (14) and (15) may be estimated by non-linear least squares. This simultaneously yields statistical estimates of the parameters of equation (15), the function GO, and the distribution of h_{ijt} The econometric estimation results are point estimates of parameters and estimates of variances of these estimated parameters. These permit statistical tests of the significance of the various parameters that embody the effects of interest.[38] Thus, for example, the parameter p_2 in equation (15) captures the relative effectiveness of regulations in affecting adoption behavior for households for which the technology investment is unprofitable. If p_2 is statistically significantly greater than zero, then the data reject the hypothesis that regulations have had no effect in such circumstances. If p_2 is significantly greater than p_1 then there is a sense in which regulations have been more effective than economic incentives in affecting behavior.

4.2 Policy Simulations

Tests of parameter significance are useful in understanding the process, but they do not answer all questions of interest. For policy purposes, we care about quantitative significance as much as we do about statistical significance.[39] We wish to know, for example, how much difference building codes actually made. Likewise, we would like to know how large a tax on energy would have been necessary to get the same effect as the building codes. We would also like to know whether we could get significantly greater

rates of diffusion through the use of taxes or expanded codes, and how long it would take.

To answer questions like these, one can use the parameter estimates derived in the econometric estimation in dynamic "counter-factual" simulations. The world presented us with a particular experiment, i.e. a particular combination of prices and regulations; from the behavior that resulted from that experiment, we can derive estimates of the parameters of the model. Once we have those parameters, we can then go back and simulate what adoption would have been if the data had been different; that is, if prices were higher or lower, or regulations more or less widespread. In this way, we can obtain estimates of the likely effectiveness of alternative policy mechanisms.[40]

Table I shows the kinds of policy scenarios that can be simulated. The first group of simulations are historic counter-factual simulations, in which we ask how adoption would have differed historically if conditions had been different. For example, we can ask whether adoption of multi-glazed windows to date would have

TABLE 1: EXAMPLES OF COUNTER-FACTUAL AND POLICY SIMULATIONS

I. FACTUAL AND COUNTERFACTUAL HISTORICAL SIMULATIONS

A. Base case: what actually occurred.
B. No states adopted energy-conservation measures into building codes.
C. All states adopted the most stringent code used by any, and did so early in the period.
D. World energy prices did not fall after 1985, but rather continued upward at some trend rate.
E. The U.S. imposed a stiff tariff on imported oil, and the price of natural gas rose to maintain the historic differential between the two.

II. PROSPECTIVE POLICY SIMULATIONS

A. Base case: current policy and current prices remain in effect.
B. Stringent energy-conservation measures are universally incorporated in building codes.
C. Carbon taxes of various levels are implemented.
D. The cost of adoption of energy-conserving technologies is subsidized.

been any less if they had not been incorporated into building codes. It is quite possible that regulations requiring them were statistically effective, but quantitatively unimportant, in the sense that the world would not have been very different without them. Similarly, we can ask what the world would have been like if oil prices had continued to rise, or how much use of these technologies would have been brought about by building codes alone.

We can also simulate the model prospectively, asking what is likely to occur in the future under alternative policies.[41] If we tax carbon at various rates, or subsidize the adoption of new technologies, or

adopt broader or more stringent codes, the model will predict differing levels of diffusion, relative to a "base case" related to current policy. This is, of course, precisely the kind of information that we would like to have as we begin to formulate policy for global climate change in the face of the energy-conservation "paradox."

5. SUMMARY AND IMPLICATIONS

In this paper, we have outlined a framework for thinking about the diffusion of environmentally beneficial technologies. On a conceptual level, our model facilitates understanding of why the technology-diffusion process is gradual, and focuses attention on the different ways in which economic and regulatory mechanisms affect this process. More quantitatively, the model provides for empirical measurement of the relative effectiveness of economic incentives and direct regulations in hastening technology diffusion. The example discussed here is the adoption of energy-conserving building practices. The results of such an empirical analysis may have direct relevance for the formulation of public policy relating to environmental concerns such as greenhouse-gas emissions and the risk of global climate change.

The analysis is also relevant to the broader issue of alternative policies for encouraging diffusion of desirable technologies. Many existing or potential technologies will generate decision problems for firms of the form we have modeled here. For example, technologies that permit greater recycling of hazardous wastes pose up-front costs that firms will trade off against future materials and disposal-cost savings. Policies to encourage the diffusion of such technologies could take the form of subsidies to adoption, taxation, or other measures that make purchases of raw materials or disposal more expensive, [42] or conventional direct regulation. The model developed in this paper provides a framework for comparing these different options.

Other applications will call for separate empirical analyses. The building sector is by no means typical of the broader economy. On the one hand, builders may perceive economic incentives less directly than manufacturing firms, because they may doubt whether investments in energy efficiency will be returned in consumers' valuations of buildings. On the other hand, because of the fragmented nature of the construction industry, enforcement of regulations may be much more difficult than it would be for large manufacturing companies. Subsequent to this first empirical application, it may be desirable to identify other "experiments" that history has provided that would allow quantification of these effects for other technologies and industries.

The framework developed in this paper is of significance along several dimensions. It can facilitate rigorous empirical comparisons of the efficacy of incentive-based versus conventional command-and-control environmental policies. Such empirical research would be unique in comparing those policy mechanisms in terms of their relative impacts on technological diffusion. In particular, a methodology has been outlined for analyzing major, alternative policy strategies related to greenhouse gas emissions and the threat of global climate change. More broadly, we have proposed a new methodology for implementing empirically a microeconomic model of technological diffusion with aggregated time series/cross-sectional

data.

ENDNOTES

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[1]Reference is to "Command-and-Control" policy mechanisms -- technology standards and performance standards, which have dominated environmental policy in the U.S. and other industrialized nations.

[2]Economic-incentive or market-based environmental policy mechanisms include: emission or ambient charges; tradeable permits; deposit-refund systems; market-barrier reductions; and government-subsidy elimination. Each is described in Stavins (1989).

[3]See, for example: Dales (1968).

[4]See, for example: Stavins (1988).

[5]These amendments constituted a major overhaul of the Clean Air Act, including the Bush Administration's proposal of an incentive-based approach (tradeable permits) for the control of acid rain.

[6]See: U.S. Environmental Protection Agency (1990).

[7]See, for example: Bohm and Russell (1985).

[8]For an investigation of these and other factors which explain the recent increase in interest in incentive- based environmental policies, see: Hahn and Stavins (1991).

[9]Hahn's extensive research' on the U.S. Environmental Protection Agency's (EPA) experiences with tradeable;permit programs (as in EPA's so-called "bubble policy") is -- to some degree -- the notable exception; is also evidence of the constraints imposed on analysis by severe data limitations. See, for example: In any event, the limited empirical analysis that has compared incentive-based to conventional environmental policy mechanisms has focused exclusively on aggregate costs of control (i.e. cost-effectiveness ; there have been no empirical analyses of the dynamic incentives for technological change that are incentive-based approaches.

[10]It is important to distinguish between two dimensions along which incentive-based and conventional environmental policies differ. First, incentive-based policies lead 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 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). In general and on a theoretical level, the superiority (in terms of inducing technological innovation and diffusion) of incentivebased approaches, compared with conventional command-and-control approaches is clear (Milliman and Prince 989). It should be recognized, however, that under certain circumstances incentive-based approaches could actually reduce firms' incentives to adopt new technology (Malueg 1989).

[11] For an examination of the factors that have tended to favor the promulgation and enactment of command- and-control environmental policies, see: Hahn and Stavins (1991).

[12] See footnote 5, above.

[13] The Administration has suggested that consideration be given to the use of international tradeable permit ms for the management of global climate change (Bush 1990).

[14] A less optimistic assessment is provided by: Marine and Richels 1990.

[15]This section provides a brief overview of the technology diffusion literature, particularly as it relates to empirical measurement of the factors affecting diffusion. For more thorough reviews, see: Stoneman (1983); Stoneman (1986); David (1986); and Thirtle and Ruttan (1986).

[16]Romeo (1975) applied Mansfield's approach to analysis of numerically controlled machine tools; and Nasbeth and Ray (1974) examined the diffusion of a wide variety of industrial innovations. Oster's (1982) analysis of the diffusion

of the basic oxygen furnace in the U.S. steel industry used a normal-probability model - - like Mansfield and Romeo -- but replaced their ordinary-least-squares (OLS) estimation with a Tobit approach.

[17]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); Caswell and Zilberman (1985); Lichtenberg (1989); Caswell, Lichtenberg, and Zilberman (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, Levin, and Meisel (1987) to investigate adoption of optical scanners at retail grocery stores. Rose and Joskow (1990) have extended the hazard model of adoption to take advantage of available information on adopters *and* non-adopters in a double censored framework.

[18]The reaper was a horse-drawn mechanism for harvesting wheat and other small grains; it revolutionized midwestern agriculture in the mid to late nineteenth century.

[19]This simple description obviously ignores possibilities of farmers renting "reaper services" from others. a David's analysis, however, does consider such possibilities.

[20]For example, the fraction of relevant firms in an area which have adopted a particular technology at a specific point in time.

[21]The model developed below is related to that employed in: Stavins and Jaffe (1990); and Stavins (1990).

[22] Note that we focus here on a "retrofit" situation, as opposed to new construction, where decisions regarding the adoption of energy-conserving technology also arise. By doing so, we are able to develop a simpler model than would otherwise be possible since we can ignore the principal-agent problem that may exist between a builder or architect and the "principal" --the ultimate user of the building. It is possible that the agent may choose a design that is not optimal from the point of view of the principal. At least on the surface, it seems that if there is any divergence of objectives, the agent would likely be relatively more responsive to regulation and less responsive to prices that the principal. This implies that the approach developed here, if not modified, would be biased against finding prices effective, and would only strengthen the results if it were found that price effects were significant. If the analysis is to focus on a situation where the principal-agent problem does arise, the optimization model must be modified to allow for the principal-agent relationship associated with decisions regarding new construction, for example, as contrasted with retrofitting. We consider this later in the paper.

[23]he planning horizon in the objective function employed here is an infinite one; this can be changed to any finite horizon, without affecting the general nature of the derived necessary conditions.

[24]A continuous-time, rather than a discrete-time model is employed for purposes of notational simplicity. Note, however, that the problem could be reformulated and solved in a discrete-time context; the final econometric specification which emerges from the optimization model is identical.

[25]These are two of the Kuhn-Tucker conditions for inequality constrained optimization (Kuhn and Tucker 1951).

[26]Since a present value is a simple linear transformation of an annuity (multiplying by a constant), the function Go is a constant (related to the interest rate and the planning horizon) times g(•).

[27]That is, it may be that due to some constraints, homeowners are not adopting the advanced technology as soon as it is economically rational to do so, but are instead only gradually adjusting. This possibility may be modeled through the introduction of a partial adjustment or other such sub-model. See: Stavins and Jaffe (1990).

[28]Once a particular (parameterized) probability distribution has been specified, it is a simple matter to write down the explicit definition of h^x_{jt}. We do this later in the paper.

[29] The effectiveness of regulations may increase over time after the date of initial implementation. This effect can be incorporated into the model by making p,, p_2, and p_3 functions of time since passage rather than constants.

[30]If, as suggested above in footnote 27, a partial adjustment or other such sub-model is introduced to allow for observed adjustment that is more gradual than that implied by economic rationality, then that sub-model would, in effect, take the place of the simple approach presented here in the form of the parameter, p,. Which approach to take is an empirical question to be resolved by the data.

[31]A somewhat different approach is taken by Greene (1990), who models auto company decisions under the Federal fuel efficiency standards by postulating that firms suffer a quadratic loss function if the standards are violated. A related analysis is that of Leone and Parkinson (1990). Note first that the fuel efficiency standards are already a hybrid policy, in which a tax is imposed for performance below the standard (Roberts and Spence 1976). More generally, we believe that the modeling approach suggested here provides a more direct comparison of the effects of direct regulation and economic incentives.

[32]Note that reference here is to new construction. We believe that this offers the best possibility for collecting the necessary data. It does involve additional complexities, however. On this, see footnote 20, above.

[33]We present this particular specification of the function *G(•)* for illustrative purposes only. It is likely that the relationship is not this simple, and that a parametric specification would be more appropriate.

[34]My smallest aggregates available are for three-digit zip codes, but county-level or even state-level data may be sufficient for our purposes.

[35]Local building codes obviously differ within states, but it is reasonable to assume that, on average, the effective code faced by a builder is stricter in a state that has a strict state code than in one that does not.

[36]Although this would again imply that our estimates of the relative effectiveness of prices would be downward-biased.

[37]Oster and Quigley (1982) econometrically analyzed the factors affecting building codes, including attributes of local firms, labor unions, building officials, and housing demand.

[38] This brief overview has bypassed a number of statistical issues that have to be addressed in carrying out this estimation, but methods exist to resolve each of them.

[39]For a survey of studies of technology-diffusion policy, see: David (1986).

[40] This method of using dynamic counterfactual simulations to estimate the consequences of alternative policy mechanisms is parallel to the approach taken by Stavins (1990) to examine the consequences of land-use decisions of internalizing environmental externalities.

[41]The prospective simulations are more speculative because in their use we implicitly assume that the model's parameters remain constant over time. Since past behavior is the only evidence we really have, however, it is reasonable to base our predictions about the future on our experiences of what has actually transpired in the past.

[42]Policies, such as waste-end taxes, which make (legal) disposal more costly,. create incentives for illegal dumping. For this reason, deposit-refund systems are appropriate for certain kinds of hazardous wastes (Stavins 1989).

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