The Induced Innovation Hypothesis and Energy-Saving Technological Change

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Abstract

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Key Words: induced innovation, energy efficiency, technological change, economic incentives, regulation, standards, climate change

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ABSTRACT. We develop a methodology for testing Hick's induced innovation hypothesis by estimating a product-characteristics model of energy-using consumer durables, augmenting the hypothesis to allow for the influence of government regulations. For the products we explored, the evidence suggests: (i) the *rate* of overall innovation was independent of energy prices and regulations, (ii) the *direction* of innovation was responsive to energy price changes for some products but not for others, (iii) energy price changes induced changes in the subset of technically feasible models that were offered for sale, (iv) this responsiveness increased substantially during the period after energy-efficiency product labeling was required, and (v) nonetheless, a sizeable portion of efficiency improvements were autonomous.

I. INTRODUCTION

There is currently much interest in the potential for public policies to reduce energy consumption because of concerns about global climate change linked with the combustion of fossil fuels. Basic economic theory suggests that if the price of energy relative to other goods rises, the energy intensity of the economy will fall as a result of a series of behavioral changes: people would turn down their thermostats and drive slower; they would replace their furnaces and cars with more efficient models available on the market; and over the long run, the pace and direction of technological change would be affected, so that the menu of capital goods available for purchase would contain more energy-efficient choices.

This last conjecture—that increasing energy prices will lead to technological change that facilitates the commercialization of capital goods that are less energy-intensive in use—is a modern manifestation of the "induced innovation" hypothesis of Sir John Hicks: "a change in the relative

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prices of the factors of production is itself a spur to invention, and to invention of a particular kind—directed to economizing the use of a factor which has become relatively expensive [1932, pp. 124–125]."

There is a considerable theoretical and empirical literature on the induced innovation hypothesis, often formulated as the principle that increases in real wages will induce labor-saving innovation. That literature typically analyzes the inducement effect in the framework of an aggregate production function.[1] Technological change, however, is inherently a microeconomic, product-level phenomenon. If the inducement mechanism operates with respect to energy, it does so largely by leading firms to develop and introduce new models of cars, appliances, and industrial equipment that deliver greater services per unit of energy consumed. From this perspective, it seems natural to formulate the inducement hypothesis in terms of a product-characteristics framework, summarizing the technological possibilities for the production of a good as a menu of feasible vectors. Each vector represents the characteristics of technically feasible models, including the resource cost of producing such models. Innovation is the introduction into the relevant menu of a vector that was previously not available.

In this we follow Schumpeter [1939], who used "invention" for the act of creating a new technological possibility, and "innovation" for the commercial introduction of a new technical idea. Both are to be distinguished from the third stage of Schumpeter's trichotomy, diffusion, which is the gradual adoption by firms or individuals of commercially available products.[2] Thus, the induced innovation hypothesis implies that when energy prices rise, the characteristic "energy efficiency" of items on the capital goods menu should improve faster than it otherwise would.

In this paper, we formalize the inducement hypothesis in this framework and we test it empirically. We also generalize the Hicksian notion of inducement to investigate whether government regulations have affected energy-efficiency innovation. We find evidence that both energy prices and government regulations have affected the energy efficiency of the models of room air conditioners, central air conditioners, and gas water heaters available on the market over the last four decades, although there have also been substantial improvements in energy efficiency that do not appear to be induced by price changes or regulations.

1. See, for example, Binswanger and Ruttan [1978]. See Thirtle and Ruttan [1987] for a summary of this literature.

2. For an empirical an analysis of the diffusion of energy-efficient technologies, see Jaffe and Stavins [1995].

In section II of the paper, we describe technological change in terms of product characteristics and lay out our econometric approach for estimating induced innovation using "characteristics transformation surfaces". In section III, we describe our data and present empirical estimates of such transformation surfaces for three products over the past several decades, including the extent to which technological change in these products has been induced by prices and regulations. In section IV, we develop the distinction between improvements in efficiency due to changes in technological possibilities and improvements due to the "substitution" of models along a given set of technological possibilities. We econometrically assess the importance of these factors in generating changes in the composition of models actually offered along the frontier. In section V, we offer some concluding observations.

II. THE CHARACTERISTICS TRANSFORMATION SURFACE

II.A. Innovation in the Product Characteristics Framework

Theoretical analysis within the product characteristics framework has been discussed by numerous authors.[3] Innovation in this framework can be thought of as the introduction of a product model with a bundle of characteristics that was not previously available, *or* the production of a previously available bundle of characteristics at a cost that is lower than was previously feasible. To incorporate both of these possibilities, we characterize a product model by a vector of dimensionality $n+1$ where n is the number of product attributes or characteristics that consumers care about, and the additional vector element is an index of the quantity of real inputs used to produce that model. In effect, we treat the real cost of producing a model as an additional characteristic of that model. At any point in time, the frontier of the technologically feasible production set can then be described in terms of a functional relationship between the bundle of characteristics and the input quantity necessary to produce that bundle.

To be concrete, consider an air conditioner with two characteristics: energy flow per unit of time f and cooling capacity c. Let k represent the real cost of producing a model i with a

3. See, for example, Rosen [1974], Triplett [1985, 1987], Trajtenberg [1990], and Berry, Levinsohn, and Pakes [1995].

particular bundle of characteristics. We approximate the transformation surface as a simple log-linear function with k as the dependent variable.[4] Thus, at a particular point in time we have

$$\ln k_i = \alpha + \beta_1 \ln f_i + \beta_2 \ln c_i . \qquad (1)$$

The β parameters are interpretable as elasticities of product cost with respect to each characteristic. Figure I illustrates a projection of the transformation surface onto the k-f plane for a fixed level of capacity, at two points in time. For the specific example at hand, because energy use is a bad, the curve is downward sloping and we would expect β_1 to be negative.[5]

Referring to Figure I, suppose the curves ψ_0 and ψ_1 represent econometrically estimated functions based on the set of models offered for sale at times t_0 and a later time t_1, where individual models are represented by the two sets of points in the figure. Suppose further that the price of energy increased between time t_0 and t_1. As drawn, three things have occurred. The frontier has moved towards the origin, making it possible to produce models that are simultaneously cheaper and more energy efficient than was previously possible. Second, the slope of the frontier has decreased, meaning that the elasticity of product cost with respect to energy flow is lower, or, equivalently, that the tradeoff at a point in time between production cost and energy efficiency has shifted so that energy efficiency is less expensive on the margin. Finally, the subset of feasible models that are actually offered for sale has shifted noticeably towards less energy-intensive models. We refer to these three kinds of shifts as overall technological change, directional technological change, and model substitution. We take the term "innovation" to encompass the combined effect of all these changes in the product menu.

Figure I is representative of what occurred (to varying degrees) between the early 1970s and the early 1990s in the technologies that we examined. In terms of the overall energy efficiency of the menu of models offered for sale, we have observed significant improvement. The Hicksian hypothesis is that this improvement is related to the rise in energy prices. The goal of this paper is to develop an empirical framework for measuring the extent to which that improvement can be

4. We also estimated translog versions. The decomposition of innovation discussed below is considerably more complex in the translog world, and we found that the translog estimation yielded similar results [Newell 1997]. For other products there are additional characteristics, which are accommodated by simply adding more logarithmic terms. For notational convenience, we generally suppress the model subscript i in subsequent equations.

5. An alternative would be to redefine all characteristics so that they were desirable, using energy efficiency rather than energy flow, for example. Given our interest in energy-saving technological change, however, we found it useful to formulate the problem in terms of capital inputs k and energy inputs f in a manner analogous to a standard production function when viewed from the perspective of the *user* of the product, be it a consumer or a firm.

associated with changes in energy prices; we also generalize the notion of "inducement" to include the possibility that government-mandated efficiency standards may have induced energy-efficiency innovation. In order to do this in a sensible way, we decompose the overall change in the energy efficiency of the menu into the parts due to overall technological change, directional technological change, and model substitution. The first two components are related to changes in the parameters of the transformation surface, represented by a functional relationship as in Equation (1). Model substitution corresponds to "movements along" this surface. In Section IV below, we show that this decomposition can be carried out in a straightforward way, once the parameters of the transformation surface and their changes over time have been estimated. We now turn to that estimation.

II.B Econometric Specification

We investigate technological change by estimating the parameters of the transformation surfaces, and simultaneously estimating how these parameters change over time. For room air conditioners, central air conditioners, and gas water heaters, respectively, we separately estimate the following versions of the transformation surface:

$$\ln k_{it} = \alpha + \beta_1 \ln f_{it} + \beta_2 \ln c_{it} + \beta_3 \mathit{2speed} + \beta_4 \mathit{3speed} + \varepsilon_{it} \tag{2}$$

$$\ln k_{it} = \alpha + \beta_1 \ln f_{it} + \beta_2 \ln c_{it} + \varepsilon_{it} \tag{3}$$

$$\ln k_{it} = \alpha + \beta_1 \ln f_{it} + \beta_2 \ln c_{it} + \beta_5 \ln g_{it} + \varepsilon_{it} \ , \tag{4}$$

where k is product cost, f is energy flow, c is cooling or heating capacity, *2 speed* and *3 speed* are dummy variables indicating the number of fan speed settings in room air conditioners, g is storage capability in gas water heaters, i indexes product models, t indexes time, and ε is an independently distributed error term with zero mean. Note that we have simplified notation by omitting product-specific subscripts on the α, β, and γ parameters; they are not restricted to be equal across products.

To allow for autonomous technological change, we allow the parameters of the surfaces to vary flexibly as second-order functions of time.[6] We introduce induced technological change by allowing the relevant parameters to vary as functions of the relative price of energy p and the level of energy efficiency standards s. We show in Section IV below that "overall" improvements in

6. It is of course possible that what we call "autonomous" and measure with t is at some deeper level itself endogenous, being associated with research investments, the state of knowledge and technical experience, or other factors for which we do not have measures.

technology are associated primarily with changes in α, while "directional" technological change relative to energy efficiency is associated with changes in β_1. It is not clear whether Hicks should be interpreted as saying that rising energy prices stimulate overall technological change, directional technological change favoring energy, or both. Newell [1997] shows that an effect of changing energy prices on the *direction* of technological change can be derived from a model of the firm's optimal investment in research. An effect on the overall rate of technological change could perhaps be motivated by a satisficing or evolutionary model in which any "shock" to the economic environment stimulates innovation. We will estimate versions in which inducement is permitted in both the α and β_1 terms, and also versions in which it is limited to affecting β_1.

Thus, the varying coefficients of the estimated surfaces take on the following form:

(5) $$\alpha = \alpha_0 + \alpha_1 t + \alpha_2 t^2 + \alpha_3 \ln q_t + \alpha_4 \ln p_{t-j} + \alpha_5 s$$

(6) $$\beta_1 = \beta_{10} + \beta_{11} t + \beta_{12} t^2 + \beta_{13} \ln p_{t-j} + \beta_{14} s$$

(7) $$\beta_2 = \beta_{20} + \beta_{21} t + \beta_{22} t^2 ,$$

where t is time, p is the relative price of energy, s is the level of energy efficiency standards, and q is aggregate product shipments.[7] To control for any effects of aggregate production levels on product cost, we allow the constant term to vary as a function of product shipments, q.[8] The subscript j indicates that the associated price occurred j years prior to year t. Based on assessments in the literature of the tooling and redesign time required to bring energy-saving product innovations

7. Traditional estimation of "neutral" technical change would allow only α to vary, and only as a linear function of time. We add quadratic terms to allow for acceleration or deceleration in technological change. We allow the β_1 and β_2 parameters to vary over time to permit autonomous changes in the slope of the function with respect to the important characteristics. We allow energy prices and standards to affect α and β_1 to test the inducement hypothesis; since there is no theoretical reason why energy prices or standards should affect the shape of the surface in the other characteristic dimensions, we do not enter these variables into β_2. Time interaction terms for the fan speed dummies for room air conditioners and for storage capability for gas water heaters were eliminated because we found them to be both very small and statistically insignificant.

8. It is not clear, *a priori*, whether we should expect the coefficient on $\ln q$ to be positive, due to an association with demand shocks or the business cycle, or negative, due to economies of scale in production. Because shipments for the products we investigated have been generally increasing over time, we also face the difficult issue of distinguishing scale effects from technological change. We therefore do not place too much interpretative emphasis on the effect of product shipments, viewing it rather as a useful control variable along the "price-quantity" dimension.

to market,[9] we estimate equations using the three-year lag in the relative price of energy (i.e., j=3). Note again that we have simplified notation on the α and β parameters, which are not restricted to be equal across products.

III. Estimation of the Transformation Surface Over Time

III.A Data

Using the Sears catalogue [Sears, Roebuck and Co. 1958–1993] and other publicly available data sources, we compiled a database of information on 735 room air conditioner models offered for sale from 1958 through 1993; 275 central air conditioner models from 1967 through 1988; and 415 gas water heater models from 1962 through 1993. The catalogues contain a wide variety of product models over many decades, a comprehensive set of descriptive data on product characteristics, and importantly, transaction prices, as opposed to list prices (which may be subject to discount).[10] Below, we describe the variables used in the analysis and summarize their construction. Table I provides descriptive statistics and units of measurement; see Newell [1997] for additional detail on data sources and methods of variable construction.[11] Note that all references to "mean" or "average" values for characteristics refer to the mean value of models *offered for sale*; the means are not weighted by the number of units sold, for example.

Model Characteristics. We assembled data on the cooling/heating capacity, energy flow, energy efficiency, nominal price, and other characteristics of all models of room and central air conditioners and gas water heaters from the Sears catalogue over the 36-year period from 1958 to 1993. We also included storage capability for gas water heaters and dummy variables indicating whether a room air conditioner had multiple fan speeds (i.e., 2 or 3 rather than 1). The mean capacity of available models of all three products changed very little over the sample period, falling

9. An Energy Information Administration [1980] study found that major tooling and redesign changes to incorporate energy-saving design options require lead times of about 1½–2 years for a single model and longer for an entire product line. Thus, a typical cycle for introducing new appliance models can be three or more years. This time frame is consistent with other assessments in the literature of the time required to develop and bring new product innovations to market [Levin, Klevorick, Nelson, and Winter 1987].

10. There are, however, occasional sales on products in the Sears catalogue. See Gordon [1990] for a thorough review of the advantages and disadvantages of using various data sources for such analysis.

11. To facilitate interpretation of the parameter estimates of the characteristic transformation surfaces, we normalized the time variable to equal zero in 1975 and we normalized all other purely time-series variables (i.e., energy prices and product shipments) to equal unity in 1975, or zero after taking natural logarithms. We normalized all other variables so their normalized means equal unity, or zero after taking natural logarithms.

on average by less than 0.3 percent per year. Energy flows fell faster, leading to a net rise in the mean energy efficiency of the three products (Figure II). Central air conditioners experienced the greatest annualized rates of change in energy efficiency (2.6 percent), followed by room air conditioners (1.2 percent), and gas water heaters (0.3 percent).

The transformation surface has as a dependent variable an index of the quantity of real inputs necessary to produce the particular product model. We do not observe model-specific input quantities. We do, however, observe model-specific prices. The nominal price of a given product model can be thought of as its production cost multiplied by a price/cost markup. Further, the production cost can be thought of as the quantities of physical inputs needed to produce that model, multiplied by the prices of those inputs. Thus, to use the model price as a proxy for the model's product cost, we must assume that the price/cost markup is constant across models and time for a particular product.[12] To the extent that this is untrue, our computation of the rate of product cost reductions could be biased. We address this issue econometrically by including national annual product shipments[13] for each technology in the transformation surface estimation. This provides a control for possible markup changes due to economies of scale or demand fluctuations, although it does not control for possible changes in industrial structure or economic regulation.

Assuming constant markups converts the model's price into a proxy for its nominal product cost. To convert nominal product cost into an index of input quantity, we deflate each model's nominal unit price (from the Sears Catalogue) by an index of input prices. We developed

12. Given data on nominal product prices, we construct a measure of real product cost, and over time a measure of technological change, by controlling for changes in input prices. Thus, our measure of product cost k is calculated as $k_{it}=p_{it}/p_{xt}$, where p_{it} is the nominal price of product model i at time t and p_{xt} is an input price index for that product at time t (subscripting for product models and time is suppressed in what follows). To clarify the procedure we used, including its possible limitations, consider the relationship $p=\mu c'$, where c' is the product's nominal marginal cost and μ is the markup of price above marginal cost. We thank an anonymous referee for pointing out that the markup can be decomposed into components representing pure profit π and the degree of returns to scale γ, leading to $p=\pi\gamma c'$, where $\pi=p/\overline{c}$, $\gamma=\overline{c}/c'$, and $\overline{c}$ is average cost. Our input cost deflation procedure can be represented explicitly within this framework by expressing marginal cost as the product of the input price index and an input index x: $p=\pi\gamma p_x x$ or $p/p_x=k=\pi\gamma x$. Over time, this implies that $\dot{k}/k=\dot{\pi}/\pi+\dot{\gamma}/\gamma+\dot{x}/x$, confirming that our measure of real product cost can provide an unbiased measure of technological change (i.e., reductions in the amount of inputs used to produce a given output) so long as the components of markup are together relatively constant over time.

13. We could not obtain model-specific data on product shipments; aggregate data are from Bureau of the Census [1959–1994,1947–1958].

separate input price indices for air conditioners and gas water heaters, based primarily on Census data on capital, labor, and materials for the corresponding 4-digit SIC industries.[14]

To summarize, the (real) product cost for each product model is taken to be its Catalogue price, divided by an index of input prices that varies across time, and is calculated separately for air conditioners and water heaters, but does not vary across models. The mean nominal prices of the three products rose at lower rates than their respective input price indices over the sample periods, implying that their mean real product costs fell by an annualized 2.2 percent, 1.8 percent, and 0.9 percent, respectively, for room air conditioners, central air conditioners, and gas water heaters (Table I).

Relative Price of Energy. We assume that the inducement mechanism is driven by the price of energy *relative* to the price of product inputs. We estimate this relative price by dividing the Consumer Price Index [Bureau of the Census 1975, 1996] for electricity (for room and central air conditioners) and natural gas (for water heaters) by the input price indices described above. The relative price indices for electricity and natural gas have varied substantially over the past four decades, falling during much of the period, but rising sharply in the mid-1970s and early-1980s, coinciding with the Arab oil embargo of 1973–1974, several major domestic natural gas shortages, and other energy shocks (Figure III). Both fuels experienced their lowest price levels in the early 1970s, with the peak electricity and natural gas price levels of the mid-1980s being about 35 percent and 85 percent higher, respectively, than their lowest levels.

Our use of past energy prices as a measure of consumers' expectations about the future path of energy prices raises the possibility of a conservative bias in our estimates. This could arise from an "errors in variables" problem associated with using actual energy prices that exhibit greater variation than the true price expectations for which they act as proxy, thereby imputing a coefficient bias toward zero relative to the true effect of expected energy price changes. In addition to the expected path of energy prices, the relevant "price" of energy flow in the consumer's choice of optimal energy efficiency will be influenced by the consumer's discount rate, their expected utilization of the product, and how long they expect to have the good in service. Omission of these

14. We constructed Divisia price indices having rates of growth equal to a weighted average of the rates of growth of labor, capital, and material prices; the weights are the relative shares of each component in total value. The data are primarily from the Census [Bureau of the Census 1954–1993] using Standard Industrial Classification (SIC) Code 3585, Refrigeration and Heating Equipment for room and central air conditioners, and SIC Code 3639, Household Appliances—Not Elsewhere Classified for gas water heaters.

additional variables from our analysis will only bias our results, however, if they have *changed* over time in a manner that is systematically correlated with the variables we include. Although this possibility exists, we believe that any bias is likely to be small and in the direction of making our results *understate* the true inducement effects.[15]

Energy Efficiency Standards. The National Appliance Energy Conservation Act of 1987 (NAECA) mandated that minimum energy efficiency standards be met by room air conditioners and gas water heaters after January 1, 1990, and central air conditioners after January 1, 1992 or 1993 [*United States Code of Federal Regulations* 1995b]. Since manufacturers did not wait until the deadline to meet the standards, we model the effect of efficiency standards as cumulative over the period of time between passage and enforcement, that is, we let $s = 0, 1, 2, 3, 4$ for $t<1987$, $t=1987$, $t=1988$, $t=1989$, and $t \geq 1990$, respectively. We do not analyze the effect of efficiency standards on central air conditioners because the compliance deadlines were beyond the time frame of the data available to us.

III.B. Estimation Issues

Although we do not focus on the equilibrium that determines which product models are offered in a given year, the existence of this equilibrium process raises the possibility of an endogeneity problem in using the product characteristics as regressors. We interpret the regression function as tracing out the transformation surface, which could be thought of as a "supply function" for characteristics. There is, of course, a large literature on hedonic price regression, in which model prices are regressed on characteristics, and the regression function is sometimes used as the basis for estimating a demand function for characteristics.[16] It is well known that a regression of

15. The "price" of energy flow to an optimizing consumer, p_f, can be written as $p_f = pu\rho$, where p is the price of energy per unit time, u is the utilization level (e.g., hours), and ρ is a present value factor (which takes into account the discount rate and product service life) [Newell 1997]. Given this relationship, if expected utilization is negatively correlated with expected energy prices (as we might expect) an estimated coefficient involving the price of energy alone could be biased *downward* relative to the true value. In practice, Hausman [1979] estimated the elasticity of air conditioner utilization with respect to the price of electricity to be -0.04, suggesting that any such bias would likely be quite small. In any event, the utilization data that would be necessary for our analysis do not exist. Regarding discount factors, one could use market interest rates as a proxy, but it is not clear what interest rate to use. If the nominal credit card rate is the relevant discount rate, this suggests that the discount rate has changed very little because nominal credit card rates have been remarkably stable over the last three decades. *Real* interest rates, on the other hand, have historically been positively correlated with real energy prices, suggesting that any potential bias from their omission would again *underestimate* the effect of energy prices (recall that the discount rate is inversely related to the present value factor). Finally, we found no evidence for significant trends in the service lifetimes for these appliances based on communications with industry experts and other information sources at our disposal. In practice, we found that our results were generally robust to a wide variety of alternative specifications for the energy "price" variable, including specifications that included market interest rates.

16. Gordon [1990], for example, uses hedonics to generate quality-adjusted price indices for a large number of durable goods, including room air conditioners and gas water heaters.

prices on characteristics embodies a variant of the classic supply/demand simultaneity problem, in which the regression coefficients are not, in general, identified as parameters of either the supply or demand function [Rosen 1974; see also Epple 1987 and Triplett 1987]. The ordinary hedonics interpretation of a regression of model prices on characteristics as a demand function requires an assumption that the data are generated by heterogeneous suppliers' distinct supply functions tracing out the demand curve of homogeneous consumers. Conversely, our interpretation of the deflated price (i.e., product cost) regression as a supply function requires an assumption of heterogenous consumers' distinct demand functions tracing out the supply curve of a homogenous production sector.

This latter interpretation is plausible in the current context. Indeed, all models in the sample are supplied by the same firm, although the models in Sears' catalogue span the space of available models. Different consumers purchase different models with different efficiencies, presumably because they have different discount rates, different anticipated intensities of usage, or face different energy prices. Further, energy efficiency is different from other characteristics that are typically the focus of hedonic analysis. In general, we expect a given consumer to have a downward sloping demand curve for a given characteristic; for example, at some point additional computer memory has little value, particularly holding constant other attributes. In contrast, the value of energy savings is essentially constant for any given discount rate and expected usage. Hence, each consumers' demand curve is infinitely elastic, so that there is unlikely to be simultaneity bias in interpreting our estimates as parameters of the supply structure.

Finally, to compensate for heteroskedasticity, we compute robust standard errors using White's [1980] method. There was no evidence of autocorrelation of residuals along the time series dimension of the estimated equations. To avoid problems associated with the potential endogeneity of aggregate shipments, we estimate the surfaces using two-stage least squares, instrumenting for the log of the quantity of shipments using levels and changes in the log of housing starts [Bureau of the Census 1975, 1996] and real household income [Bureau of the Census 1975, Council of Economic Advisors 1997], in addition to the other explanatory variables.[17]

17. Shipments of many durable goods, including air conditioners and water heaters, are correlated with both housing starts and real household income. Housing starts tend to be correlated with demand for most appliances for two primary reasons: almost every new house requires a new set of appliances; and housing starts are a good indicator of a healthy economy, which would encourage replacement and discretionary purchase of appliances.

III.C. Results of Estimation of Characteristics Transformation Surfaces

The estimation results for the three technologies are presented in Tables II, III, and IV. We present results for a "pure" autonomous technological change model and the induced innovation model. Since it is not obvious theoretically that the inducement mechanism should affect the intercept term, and these effects are indeed generally insignificant, we also present the results when these terms are suppressed. Overall, the results are consistent with the economic interpretation of the parameters. The estimated elasticities for the various characteristics all have the expected signs and reasonable magnitudes; and the coefficient on time is negative in all cases, indicating positive autonomous technological change. The results confirm that the cost of durable goods increases with increasing energy efficiency, capacity, and other desirable characteristics, and that the cost of producing a given bundle of characteristics tends to fall over time as a result of technological change in production techniques and product design.

The coefficient on $\ln f$ (i.e., β_{10}) in each table measures the elasticity of product cost with respect to energy flow in 1975; the elasticity for other years depends on the year and the magnitudes of β_{11}, β_{12}, β_{13}, and β_{14}.[18] The elasticity is negative for all three products, as expected, indicating that reductions in energy flow come at the expense of higher product cost. However, the magnitude of this tradeoff varies significantly among the technologies; a 10 percent decrease in energy flow (or increase in energy efficiency) was associated with a 4 percent increase in product cost for room air conditioners, a 12 percent increase for central air conditioners, and a 40 percent increase in product cost for gas water heaters (in 1975). The estimates also indicate that multiple fan speeds and increases in capacity are costly, although, not surprisingly, there are "economies of product scale" as cost increases less than proportionately with capacity.[19]

The coefficients α_1 in each table indicate the rate of change of the intercept in 1975; the rate of change in other years depends on α_2. The quantitative significance of these changes is

18. Recall that, to facilitate interpretation of the parameter estimates of the transformation surfaces, we normalized the variables; see footnote 11. Coefficients on those variables that do not involve interactions with t, t^2, $\ln p$, or s, have the interpretation of being the elasticity for that variable in 1975.

19. The response of product cost to changes in capacity is best measured by adding β_1 and β_2, which gives the elasticity of product cost with respect to capacity holding constant energy efficiency, rather than energy flow. Thus, a 10 percent increase in capacity was associated with a 5 percent increase in product cost for room air conditioners, an 8 percent increase for central air conditioners, and a 7 percent increase in product cost for gas water heaters (in 1975). Multiple fan-speed room air conditioners were estimated to cost 20 percent and 30 percent more, respectively, for a two- or three-speed than for a one-speed model (see β_3 and β_4). To some extent, the multiple fan-speed dummies may be picking up characteristics not included in the analysis that are also associated with higher-quality room air conditioners (e.g., adjustable thermostats, rotating louvers, and filter monitors).

discussed further in the following section; we note here only that all three technologies have α_1 significantly negative, meaning that there is autonomous overall technological change.

There is also evidence of autonomous "directional" change, i.e., changes over time in the slope of the transformation surface. For example, the results indicate that in 1975 (t=0) the absolute magnitude of the elasticity of product cost with respect to energy flow was decreasing autonomously by 0.10 and 0.06 annually for central air conditioners and gas water heaters, respectively, indicating an autonomous "bias"of technological change *against* energy efficiency. In all three cases, however, this component has shifted over the course of time toward favoring energy-efficiency.

Turning to the induced innovation specifications, there is little evidence of significant inducement effects on overall technological change. Although four of the five coefficients (α_5 in Tables II and III; α_4 and α_5 in Table IV) are negative, none are statistically significant at conventional levels. In terms of energy-price-induced changes in the slope, indicated by β_{13}, there is a statistically significant and robust effect in the predicted direction for room air conditioners.[20] For central air conditioners, the energy price effect is in the predicted direction; it is statistically significant at only the 0.10 level in the full specification, but is significant at the 0.05 level after the α_4 term is deleted.[21] For gas water heaters, the inducement effects are always insignificant. Since many of the specific technological changes that foster efficiency are common between room and central air conditioners, while water heaters are quite different, these results suggest that changes in energy prices probably did affect technological change in cooling technology, but not in water heating technology.

Results regarding the effect of energy-efficiency standards on the direction of technological change (β_{14}) are qualitatively similar. The direction of technological change shifted substantially in favor of energy efficiency during the period that Federal energy efficiency standards were being implemented for room air conditioners, but not gas water heaters.[22] Of course, the concern remains that the representation of changing regulatory standards by a constant time dummy

20. A positive coefficient for the inducement effect means that an increase in the energy price or standard makes β_1 less negative, thereby reducing the elasticity of product cost with respect to energy flow.

21. These effects are also of modestly significant magnitude. For example, the estimate for β_{13} in Table II of 0.41 means that a 10 percent increase in energy prices is associated with a change in the elasticity of product cost with respect to energy flow of about 0.04. The base elasticity (β_{10}) is about -0.4, so this represents a reduction of about 10 percent in absolute magnitude. The relative magnitude is similar for central air conditioners.

22. Recall that we cannot estimate a standards-inducement effect for central air conditioners because there were no standards during the period of our data.

is a blunt instrument that could potentially act as a proxy for factors other than energy efficiency standards that were influential during the same time period.

IV. Overall Changes in the Menu of Models Offered

The results of the previous section indicate that, for all three technologies, there were changes in the position and slope of the transformation surfaces over time. We now turn to the question of whether the changes in the menu of products actually offered can be related to these estimated changes in the positions of the curves, as well as to "movements along the curves." The question is illustrated by Figure IV, which shows the position and slope of the estimated surface for room air conditioners at five-year intervals, based on the estimates of the previous section. The heavy dot on each line is the mean of the characteristics of all models offered in that year. Consistent with the previous section, the surfaces move toward the origin and become flatter over time. The figure also shows that the mean model offered for sale got much cheaper and slightly more energy efficient from 1960 to 1980, and then got much more energy efficient and slightly cheaper from 1980 to 1990. We would like to explain the movements in this mean model as being driven by the inward shift of the curve (overall innovation), the change in the slope of the curve (directional innovation), and movements along the curve at a point in time (model substitution).

IV.A. Decomposition of Characteristics Innovation

Because the transformation surface for any given product is continually shifting, tilting, and changing its composition, there is no unique way to measure these separate effects. We adapt to the current context a standard approach to decomposition from the aggregate technical change literature. Figure V presents another projection of the transformation surface onto the product cost/energy flow plane, holding constant capacity (and other characteristics, if relevant). For the time being, assume there is a single consumer whose optimal product cost/energy flow combination at time t_0, given technical possibilities represented by ψ_0, is at point **a**. The line p_f^0 represents the relative "price" of energy relevant for the choice of optimal energy efficiency; it is determined by the expected path of energy prices, the discount rate, and the expected utilization and service life of the capital good. Assume that at some time t_1, technical possibilities have improved, as represented by the shift of the transformation surface from ψ_0 to ψ_1, and that energy prices have also changed so that the price line now has the slope of p_f^1 instead of p_f^0. Accordingly, optimal energy flow and product cost are now located at point **d**.

Measured in terms of energy flow, we can decompose the improvement between points **a** and **d** into the distances labeled *R*, *D*, and *P* on the horizontal axis, which correspond respectively to the movements from **a** to **b**, from **b** to **c**, and from **c** to **d**. Point **b** is the point on the new transformation surface that lies on a ray to the origin from the initial point **a**. Hence, the movement from **a** to **b** represents equi-proportionate improvement in up-front product costs and energy operating costs, and the distance *R* corresponding to this movement is a measure of the rate of overall technological change. In percentage terms, it is the rate of decrease in the total cost of the good to its user (i.e., product cost plus energy cost). Point **c** lies at the tangency between the new transformation surface and the old price line. Thus, the horizontal distance *D* between **b** and **c** measures the effect on energy use of the tilt in the transformation surface between time t_0 and t_1, i.e., what we call "directional technological change." Finally, point **d** is the new optimum and the movement from **c** to **d**, which we label *P*, is the "model substitution" effect (given the new technology) brought about by the change in prices from p_f^0 to p_f^1.[23]

Expressions for *R*, *D*, and *P* can be derived in continuous time by taking the first-order condition that corresponds to the tangency shown in Figure V, and differentiating it with respect to time. If the transformation surface is expressed as a log-linear function like those estimated in the previous section, then it is shown in the Theory Appendix that the rate of change in energy flow for the optimal product model will be given by:

$$(8) \qquad \dot{f}^*/f^* = 1/(1-\beta_1)\cdot(\dot{\alpha} + \dot{\beta}_1 \ln f^* + \dot{\beta}_2 \ln c^*) + 1/(1-\beta_1)\cdot(\dot{\beta}_1/\beta_1) - 1/(1-\beta_1)\cdot(\dot{p}_f/p_f),$$

where optimal values are indicated by the * and p_f is the discounted present value of the expected stream of relative energy prices, as in Figure V. The last term in Equation (8) corresponds to *P* in Figure V; it indicates that the optimal rate of change of energy flow has a term that is proportional to the rate of change of the effective energy price. The middle term captures optimal responses to changes in the slope of the surface; it corresponds to *D*. The first term includes changes in the intercept, as well as a weighted average of changes in β_1 and β_2. (Recall that β_2 relates to the capacity characteristic, which is held constant in Figure V.) It is shown in the Theory Appendix that this term is, in fact, the rate of change of f^* (and of k^*) if these rates of change are set equal to each other. Thus it is equal to what is labeled *R* in Figure V. The factor $1/(1-\beta_1)$ appearing in each term

23. We call *P* model "substitution" because of its similarity to the concept of input substitution along a production isoquant or output substitution along a production possibility frontier, recognizing that this term is not strictly appropriate because the range of model offerings can be expanded or enriched without a new model always displacing an old one.

indicates that the optimal responsiveness of energy efficiency to any of these changes depends on the "costliness" of energy efficiency. β_1 is negative; when it is large in absolute magnitude, energy efficiency is expensive, so the energy-efficiency response to any of these changes is muted.

IV.B. Decomposition of Annual Changes in Energy Efficiency

Using the values of the parameters estimated in Section III, and data on changes in energy prices, it is possible to calculate each of the terms on the right-hand side of Equation (8) for any time period.[24] There is, of course, nothing that ensures that *actual* changes in mean efficiency of models offered for sale will correspond to the calculated changes in *optimal* efficiency. We explore this issue by approximating Equation (8) in discrete time and treating it as a regression equation. In this way, we allow explicitly for error between the computed "optimal" changes and the actual changes in energy efficiency. We can also generalize to allow for effects of the minimum efficiency standards described above, as well as labeling standards that require prominent display of energy efficiency information for all product models.[25] We conjecture that these labeling standards may have affected consumers' actual responsiveness to energy prices, and thereby affected the extent to which firms faced incentives to offer more energy efficient models as energy prices rose.

To allow for all these effects, we estimate for each product a time-series regression of the form:

$$\Delta \ln \bar{e}_t = \sigma + \mu R_t + \xi D_t + l_{0t} \sum_{j=0}^{\hat{j}} \tau_{0j} \frac{1}{1-\beta_{1t}} \Delta \ln p_{t-j} + l_{1t} \sum_{j=0}^{\hat{j}} \tau_{1j} \frac{1}{1-\beta_{1t}} \Delta \ln p_{t-j} + \theta \Delta s_t + \varepsilon_t, \tag{9}$$

where the dependent variable is the rate of change in mean energy-efficiency of models offered for sale, t indicates values in year t, Δ indicates annual changes from year t-1 to year t, ln is the natural

24. Since energy use per unit of capacity has been falling, and it becomes awkward to constantly talk about the absolute value of negative numbers, at this point we will switch from looking at changes in energy flow (f), to changes in "energy efficiency," which we denote e. Since all of our analyses are carried out holding other characteristics (including capacity) constant, the rate of change of energy efficiency is simply the negative of the rate of change of energy flow.

25. Title V of the Energy Policy and Conservation Act of 1975 (EPCA) requires product labels providing information on the energy efficiency, estimated annual energy costs, and operating cost ranges for similar products for 13 categories of appliances and equipment [Office of Technology Assessment 1992, *United States Code of Federal Regulations* 1995a]. The compliance deadline was May, 1980, for room air conditioners and water heaters, but was delayed until February, 1988, for central air conditioners. The Sears catalogue includes label information in tabular form. We model the potential effect of product labeling on energy efficiency changes by allowing the coefficient on the relative price of energy to change from the pre-labeling to the post-labeling period, where the change occurs in 1981 for room air conditioners and 1977 for water heaters.

logarithm, R and D are the overall and directional changes in the transformation surface based on the estimated parameters in that year, p is the relative price of electricity or natural gas to production inputs, l_0 is a dummy variable indicating that energy-efficiency labeling *was not* yet in effect, l_1 is a dummy variable indicating that labeling *was* in effect, Δs is a dummy variable indicating that energy-efficiency standards had been legislated but not yet achieved (i.e., s equals 1 for $1987 \leq t \leq 1990$), and ε is an independently distributed error term with zero mean. The subscript j indicates that the associated price change occurred j years prior to year t, where j=0 is the contemporaneous price and $j = \hat{j}$ is the most distant price lag included in the lag structure.[26] We use this distributed lag because we do not have a theoretical basis on which to determine how quickly the menu of product offerings should change in response to energy price changes.

To summarize, if the mean model is optimal for the typical consumer, the theory behind Equation (8) says that σ should be zero, that μ, ξ, should each be unity, and the τ_1 terms should sum to unity. Our specification allows for this but does not impose it, and also allows for the possibility that labeling regulation increases the elasticity of average efficiency with respect to energy price, and that minimum efficiency regulations have an independent effect on average efficiency. The estimation results are summarized in Table V, while the results for the full distributed lag version are provided in the Statistical Appendix.

Because of the dynamic nature of the equations, as well as the existence of inducement effects on movements both *of* and *along* the surfaces, it is difficult to assess fully the empirical significance of the price and standards effects on the basis of the parameter estimates themselves. As an overall estimate of those effects, we therefore carry out dynamic simulations using the estimated parameters of Equation (8) in which total changes in energy efficiency are compared, with and without the historical changes in prices, and with and without minimum efficiency standards. The results are presented in Table VI, including standard errors based on the underlying parameter

26. Three conventional methods for selecting the number of lags (i.e., the Akaike Information Criterion, the Schwarz Bayesian Information Criterion, and the adjusted R^2) recommended the same distributed lag structure for our estimated equations: 5 years for room air conditioners, 1 year for central air conditioners, and 3 years for gas water heaters.

estimates.[27] We first carry out a "baseline" simulation that fits the model to the actual data,[28] and then compare the baseline to counter-factual simulations that isolate the effects of energy price changes and energy efficiency standards, as well as autonomous influences.

Effect of Changes in the Relative Price of Energy. In general, the results suggest that there is a substantial positive relationship between changes in the price of energy relative to production inputs and the rate of energy-efficiency improvements. We also find that there was a marked *change* in the responsiveness of energy-efficiency innovation to relative prices from the period before to the period after energy-efficiency labeling of room air conditioners and gas water heaters took effect. In the cases of both room air conditioners and water heaters, these parameters are statistically and economically significant for the period after energy-efficiency labeling took effect, but the effects are smaller and not significantly different from zero during the pre-labeling period. Indeed, the post-labeling effect for both products is not statistically distinguishable from the theoretically predicted value of unity.[29] Labeling for central air conditioners did not take effect until after the period covered by our data, so the table presents a single price elasticity estimate; it approximates the theoretical value of unity.[30]

To assess the cumulative effect of energy price changes, we compare the baseline simulations to counter-factual simulations which hold real energy prices at their 1973 levels,

27. Recall that we have allowed for inducement effects in the overall movement of the surface, the change in the slope of the surface, and the movement along the frontier. The first of these was insignificant and the second was significant in some specifications for some products. Hence the inducement effects we simulate and present in Table VI are based on the parameter estimates from Table V in conjunction with any induced influences of energy prices and standards on the measures of *R* and *D*, which are in turn based on parameter estimates for Specification 2 from Tables II, III, and IV.

28. The baseline simulation replicates actual experience quite well, including capturing turning points in the innovation trajectory. This is supported by a conventional quantitative measure for dynamic goodness of fit, 1-*U*, where *U* is Theil's *U* statistic [Theil 1961]. In addition, decomposing *U* into its component sources revealed that the vast majority of the simulation error for the three products was due to unsystematic error—a desirable property for simulation models [Newell 1997].

29. The $1/(1-\beta_1)$ elasticity adjustment is quite important here; the unadjusted price elasticity for gas water heaters is much lower than for air conditioners (η_1=0.87, 0.73, and 0.14 for room air conditioners, central air conditioners, and gas water heaters, respectively) [Newell 1997]. This is as expected given the less favorable product cost tradeoff inherent in central air and gas water heater technology.

30. The elasticity estimate for central air without labeling suggests that the labeling effect for the other two technologies may be due to some sectoral shift other than the labeling itself. To test this, we estimated an equation for central air conditioners with dummy variables for pre- and post-1981 observations as for the other products. Because there were no labeling requirements for central air, these periods should not differ if labeling is the true explanation for the shifts found for the other technologies. The result is that the post-labeling coefficient is higher than the pre-labeling coefficient, but the difference is small and insignificant. This suggests that while the difference we ascribe to labeling in the room air conditioner and water heater equations may be partly due to other (unobserved) factors (e.g., other information sources), labeling does seem to have some effect. Possibly, the fact that central air is a "bigger" purchase makes consumers (and hence manufacturers) sensitive to price tradeoffs even without mandatory labeling, but this is only speculation.

approximately their minimum for our study period.[31] The relative prices of electricity and natural gas rose 24 percent and 69 percent, respectively, over the simulation period (1973–1993). If the relative prices of electricity and natural gas had remained at their low 1973 levels, the model says that about one-quarter to one-half of the increase in the energy-efficiency of the available menu experienced since then would not have occurred. Energy-efficiency would have been about 8 percent lower for room air conditioners, 16 percent lower for central air conditioners, and about 5 percent lower for gas water heaters.

Effect of Energy-Efficiency Standards. Direct energy-efficiency standards appear to have had a modest positive effect on energy-efficiency changes during the compliance period from enactment of legislation to the time of the compliance deadline (1987–1990). For both room air conditioners and gas water heaters, the point estimate implies that energy efficiency improved about 2 percent per year faster during this implementation period than would otherwise have occurred, implying a cumulative effect of 7 percent for room air conditioners and 8 percent for water heaters based on the simulations. Note that while the "direct" effect of standards on average efficiency levels in room air conditioners is statistically insignificant in the regression, the overall effect of standards *is* significant when combined with the "indirect" effect of standards through D and R, as shown through the simulations. This analysis does not reveal the extent to which this occurred because inefficient models were dropped versus new efficient models added, although new, more efficient models *were* being added during the compliance period.[32]

Effects of the Rate and Direction of Technological Change. The parameter estimates for the influence of R and D on changes in mean energy efficiency do not provide any consistent support for the theoretical prediction of unitary coefficients. It is possible that this failure is due to the arbitrariness of the mean model as representative of the preferences of the typical consumer. Another problem is that the predicted changes due to the direction of technological change are extremely sensitive to the estimated curvature of the surface, particularly given the relatively slight

31. The simulations assume that product labeling occurred as it did historically, as measured in our regressions by a shift in the coefficient on energy prices from a pre- to a post-labeling level.

32. An important limitation of our approach that bears consideration, especially in the context of the effect of standards, is our reliance on changes in the mean energy efficiency of the menu as our measure of energy efficiency improvements. Obviously, the mean efficiency can rise because of the disappearance of inefficient models, without any introduction of new models. The elimination of inefficient models was, in fact, the primary intention of these regulations. Inspection of the distribution of the efficiencies of room air conditioners and gas water heaters over the time period when these standards were taking effect suggests that the primary effect was the elimination of the distribution's lower tail.

curvature that we find in some cases. More generally, it is empirically difficult to distinguish the effects of *R* and *D*, because of a high degree of correlation between the rate and direction of technological change, as well as relatively constant rates of overall technological change, which makes *R* difficult to distinguish from the constant term.

On the other hand, the simulations indicate that a substantial portion of the overall change in energy efficiency for all three products cannot be associated with either price changes or government regulations. The autonomous drivers of energy-efficiency changes (including the constant term) explain up to 62 percent of the total change in energy efficiency. Thus we can view the inducement hypothesis as either half-full or half-empty; a substantial portion of energy-efficiency changes appear to be induced, but a large portion cannot be explained in this way. Of course, as with the "residual" in standard analyses of technological change, the association of these non-induced changes with "time" means only that we cannot explain exactly where they come from. To the extent that they are driven by forces such as government funded research, some portion of what we label autonomous is probably endogenous in a broader sense.

V. Conclusion

The re-emergence of energy efficiency as a policy concern has drawn new attention to an old question: To what extent does the innovation process respond to economic incentives, making it systematically easier over time to economize on inputs that become more expensive? A natural way to approach this question is to think of capital goods as products, and their resource-consuming properties as product characteristics. In this way, we place microeconomic structure on the induced innovation hypothesis. In principle, this structure permits econometric identification of the extent to which the pace of technological advance, the direction of technological advance, and changes in the "menu" of offered product models each respond to changes in resource prices.

Our application of this analytical framework to the evolution of three energy-using household durable goods yields several important findings. First, the substantial observed increases in the energy efficiency of two of the three products over the last several decades appear to have been associated with overall technological advance. In the early part of the period, autonomous improvement in these products appears to have been biased away from energy-efficiency. That is, the up-front costs of the products was decreasing faster than their operating costs. But the significant increase in energy prices that occurred in the 1970s and 1980s had noticeable effects, slowing or reversing this process. Second, increasing energy prices had an observable effect on which technically feasible models were offered for sale. Third, this effect of energy-price increases on "model substitution" was particularly strong after product-labeling requirements went into effect. Indeed, our simulations suggest that the post-1973 energy price increases account for one-quarter to one-half of the observed improvements in the mean energy efficiency of models offered for sale over the last two decades. Fourth and finally, government energy efficiency standards also had a significant impact on the average energy efficiency of the product menu.

The recent resurgence in interest in endogenous technological change has focused attention on the mechanisms by which economic agents' optimizing decisions affect the overall pace of technological change. But the endogeneity of the direction or composition of technological change is surely at least as significant. Further, whereas empirical implementation of endogenous growth models has been hampered by the difficulty of measuring the underlying exogenous factors that drive the system, variations in relative prices provide interesting "natural experiments" that permit empirical investigation of induced changes in the direction of technological change. We suggest that the product characteristics approach provides a useful framework in which to look at these natural experiments.

THEORY APPENDIX

A straightforward model of consumer optimization over the product cost *k* and energy flow *f* of a durable good shows that the consumer will desire a model for which the marginal cost of *f* is equal to the consumer's willingness to pay for *f* (i.e., p_f). This first order condition can be represented in elasticity form, as follows:

$$\text{(A1)} \qquad -(\partial k^*/k^*)/(\partial f^*/f^*) \;=\; \epsilon_{kf} \;=\; p_f f^*/k^*,$$

where ϵ_{kf} is the elasticity of product cost with respect to energy flow. This condition shows that the consumer would like to purchase a model such that the ratio of operating costs to product costs (in present value terms) implied by the purchase is equal to the elasticity of the transformation surface, i.e., a point of tangency such as is shown in Figure V.

Solving Equation (A1) for f^* and taking natural logs:

$$\text{(A2)} \qquad \ln f^* \;=\; \ln k^* \;+\; \ln\epsilon_{kf} \;-\; \ln p_f.$$

The transformation surface (Equation (1)) gives $\ln k^*$ as a function of *f*, so we can use that to solve out both $\ln k^*$ and ϵ, and, assuming $\beta_1<0$, we get:

$$\text{(A3)} \qquad \ln f^* \;=\; \alpha \;+\; \beta_1 \ln f^* \;+\; \beta_2 \ln c^* \;+\; \ln(-\beta_1) \;-\; \ln p_f.$$

By taking the derivative of Equation (A3) with respect to time, holding capacity constant, we get Equation (8) in the text, which shows how consumers' desired levels for *f*, and therefore *k*, might change over time:

$$\text{(8)} \qquad \dot{f}^*/f^* \;=\; 1/(1-\beta_1)\cdot(\dot{\alpha}+\dot{\beta}_1\ln f^*+\dot{\beta}_2\ln c^*) \;+\; 1/(1-\beta_1)\cdot(\dot{\beta}_1/\beta_1) \;-\; 1/(1-\beta_1)\cdot(\dot{p}_f/p_f),$$

where time subscripts on all variables and parameters are suppressed for notational convenience.

As described further in the text, the three terms of Equation (8) correspond to *R*, *D*, and *P* in Figure V. To see this, return to the basic transformation surface of Equation (1), and differentiate with respect to time, considering both the characteristics and the parameters as functions of time:

$$\text{(A4)} \qquad \dot{k}/k \;=\; \beta_1\cdot(\dot{f}/f) \;+\; \beta_2\cdot(\dot{c}/c) \;+\; \dot{\alpha} \;+\; \dot{\beta}_1 \ln f \;+\; \dot{\beta}_2 \ln c.$$

Now recall that *R* is the overall rate of technological change, defined as the percent reduction in *k* and *f* that is implied by movements of the transformation surface, assuming these reductions occur proportionately, and holding other characteristics constant. If $\dot{k}/k = \dot{f}/f = R$, then this equation can be solved for R to yield

$$R \;=\; -1/(1-\beta_1)\cdot(\dot{\alpha} + \dot{\beta}_1 \ln f^{\,*} + \dot{\beta}_2 \ln c^{\,*}),$$

where the minus sign indicates that cost reductions represent positive innovation.[33]

33. As is clear from the definition of R, the rate of technological change will depend on where measurements take place along the transformation surface. The usual approach to addressing this measurement issue is to create a productivity index using the mean of the distances from the old to the new surface that are found using rays from the origin through the realized point on the old and on the new surfaces (which will not generally lie on the same ray). In the typical aggregate or firm level context, the points on the old and new surfaces will correspond to points of tangency between the surface and a price hyperplane. In the empirical application we calculate the rate of innovation as the mean of the rates found using the mean characteristic levels at the initial and subsequent points in time.

STATISTICAL APPENDIX: FACTORS AFFECTING ENERGY-EFFICIENCY INNOVATION
(Full distributed lag)

Parameter	Variable	Description	Room a.c.	Central a.c.	Gas water heaters
		Pre-labeling			
η_{00}	$\frac{1}{1-\beta_{1t}} l_0 \Delta \ln p_t$	percent change in relative price of energy	-0.271 (0.194)	0.670 (0.270)	0.059 (0.414)
η_{01}		1-year lag	0.127 (0.189)	0.724 (0.341)	-0.113 (0.458)
η_{02}		2-year lag	0.309 (0.236)	—	-0.230 (0.466)
η_{03}		3-year lag	-0.573 (0.323)	—	0.611 (0.356)
η_{04}		4-year lag	-0.116 (0.215)	—	—
η_{05}		5-year lag	0.526 (0.268)	—	—
η_0		Total pre-labeling price effect	0.001 (0.630)	1.394 (0.423)	0.327 (0.529)
		Post-labeling			
η_{10}	$\frac{1}{1-\beta_{1t}} l_1 \Delta \ln p_t$	percent change in relative price of energy	-0.062 (0.191)	—	0.317 (0.183)
η_{11}		1-year lag	0.098 (0.194)	—	-0.140 (0.233)
η_{12}		2-year lag	0.235 (0.314)	—	0.159 (0.234)
η_{13}		3-year lag	0.743 (0.277)	—	0.242 (0.214)
η_{14}		4-year lag	-0.429 (0.224)	—	—
η_{15}		5-year lag	0.590 (0.194)	—	—
η_1		Total post-labeling price effect	1.175 (0.391)	—	0.577 (0.277)
θ	Δs	standards	0.024 (0.025)	—	0.017 (0.007)
μ	R_t	rate of innovation	0.055 (0.417)	0.844 (0.882)	-2.045 (2.872)
ξ	D_t	direction of innovation	-0.053 (0.145)	0.047 (0.059)	0.479 (0.761)
σ	*constant*		0.007 (0.007)	0.001 (0.026)	0.007 (0.009)
		# observations	35	21	31
	1-U	goodness of fit	0.67	0.66	0.61

Dependent variable is the rate of change of mean energy efficiency of models offered for sale ($\Delta \ln \bar{e}$). Estimation method is ordinary least squares. Robust standard errors are reported in parentheses.

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TABLE I
SUMMARY STATISTICS FOR VARIABLES

Variable	Symbol	Overall		Initial year		Final year		Mean growth rate
		mean	std dev	mean	std dev	mean	std dev	
Room Air Conditioners (1958–1993; N=735)								
Energy flow (1,000 watt)	f	1.5	1.0	1.9	0.6	1.2	0.8	-1.3%
Energy efficiency (Btu/hr/watt)	e	7.6	1.4	5.9	1.0	9.0	0.6	1.2%
Cooling capacity (1,000 Btu/hr)	c	11.4	6.7	10.8	3.1	10.6	6.2	-0.1%
Nominal price ($)		376	166	248	64	548	166	2.3%
Product cost (overall normalized mean=1)	k	1.00	0.46	1.85	0.47	0.86	0.26	-2.2%
Shipments (millions/year)	q	3.39	1.21	1.67	—	3.08	—	1.8%
Relative price of electricity (1975=1)	p_f	1.08	0.10	1.25	—	1.14	—	-0.3%
Central Air Conditioners (1967–1988; N=275)								
Energy flow (1,000 watt)	f	4.4	1.5	6.1	1.8	3.5	1.4	-2.6%
Energy efficiency (Btu/hr/watt)	e	8.3	1.7	6.4	0.1	10.8	0.4	2.5%
Cooling capacity (1,000 Btu/hr)	c	35.1	10.0	39.3	12.1	37.2	14.0	-0.3%
Nominal price ($)		911	404	531	158	1299	313	4.4%
Product cost (overall normalized mean=1)	k	1.00	0.26	1.23	0.37	0.85	0.21	-1.8%
Shipments (millions/year)	q	2.66	0.91	1.01	—	4.35	—	7.2%
Relative price of electricity (1975=1)	p_f	1.04	0.10	1.02	—	1.11	—	0.3%

TABLE I
(CONTINUED)

Variable	Symbol	Overall		Initial year		Final year		Mean growth rate
		mean	std dev	mean	std dev	mean	std dev	
Gas Water Heaters (1962–1993; N=415)								
Energy flow (1,000 Btu)	f	44.1	12.2	47.0	12.0	40.0	7.7	-0.5%
Energy efficiency (90º gal/1,000 Btu)	e	0.98	0.05	0.94	0.03	1.05	0.05	0.3%
Heating capacity (90º gal/hr)	c	43.0	11.0	44.4	11.6	42.0	8.5	-0.2%
Storage capability (gallons)	g	41.8	11.1	36.3	7.4	46.8	14.0	0.8%
Nominal price ($)		173	96	79	21	284	104	4.2%
Product cost (overall normalized mean=1)	k	1.00	0.30	1.20	0.31	0.90	0.33	-0.9%
Shipments (millions/year)	q	3.56	0.45	3.22	—	4.54	—	1.1%
Relative price of natural gas (1975=1)	p_f	1.29	0.33	1.13	—	1.54	—	0.9%
Other Variables (1958–1993)								
Housing starts (millions/year)		1.51	0.32	1.34	—	1.29	—	-0.1%
Median household income ($1994)		36,196	4,149	26,055	—	37,905	—	1.1%

Means are for models offered for sale; they are not weighted by units sold, for example. Growth rates are geometric means over the period available for each technology. Product cost is equal to the nominal price divided by an input price index.

TABLE II

TRANSFORMATION SURFACE ESTIMATES: ROOM AIR CONDITIONERS

Parameter	Explanatory variable	Autonomous innovation	Induced innovation Specification 1	Induced innovation Specification 2
β_{10}	ln*f*	- 0.387 (0.027)	- 0.362 (0.026)	-0.383 (0.026)
β_{11}	*t*ln*f*	0.80e-3 (2.68e-3)	1.17e-3 (2.88e-3)	1.51e-3 (2.94e-3)
β_{12}	t^2ln*f*	8.33e-4 (2.42e-4)	0.70e-4 (3.14e-4)	3.28e-4 (2.98e-4)
β_{13}	ln*p*ln*f*	—	0.410 (0.125)	0.361 (0.127)
β_{14}	*s*ln*f*	—	0.028 (0.011)	0.034 (0.012)
β_{20}	ln*c*	0.919 (0.028)	0.914 (0.027)	0.937 (0.027)
β_{21}	*t*ln*c*	-2.73e-3 (2.95e-3)	-1.04e-3 (3.05e-3)	-1.16e-3 (3.10e-3)
β_{22}	t^2ln*c*	-6.78e-4 (2.68e-4)	-5.90e-4 (2.93e-4)	-8.69e-4 (2.75e-4)
β_3	*2-speed*	0.197 (0.016)	0.202 (0.016)	0.201 (0.016)
β_4	*3-speed*	0.300 (0.016)	0.299 (0.016)	0.298 (0.016)
α_0	*constant*	-0.215 (0.017)	-0.234 (0.019)	-0.220 (0.016)
α_1	*t*	-0.026 (0.001)	-0.026 (0.001)	-0.027 (0.001)
α_2	t^2	1.05e-3 (0.19e-3)	1.05e-3 (0.19e-3)	0.93e-3 (0.06e-3)
α_3	ln*q*	-0.083 (0.024)	-0.083 (0.024)	-0.102 (0.016)
α_4	ln*p*	—	0.043 (0.088)	—
α_5	*s*	—	-0.016 (0.010)	—
	# observations	735	735	735
	R^2	0.96	0.96	0.96

Dependent variable is the log of product cost (ln*k*). Variables are described in more detail in Table I and in the text. Estimation method is two-stage least squares, with instrumentation for shipments (ln*q*) using levels and changes in the log of housing starts and real household income in addition to the other explanatory variables. Robust standard errors are reported in parentheses.

TABLE III

TRANSFORMATION SURFACE ESTIMATES: CENTRAL AIR CONDITIONERS

Parameter	Explanatory variable	Autonomous innovation	Induced innovation Specification 1	Induced innovation Specification 2
β_{10}	ln*f*	-1.247 (0.077)	-1.205 (0.087)	-1.177 (0.082)
β_{11}	*t*ln*f*	-0.103 (0.014)	-0.107 (0.016)	-0.103 (0.014)
β_{12}	t^2ln*f*	4.87e-3 (1.41e-3)	4.04e-3 (2.14e-3)	2.81e-3 (1.67e-3)
β_{13}	ln*p*ln*f*	—	0.968 (0.566)	1.291 (0.558)
β_{20}	ln*c*	1.978 (0.079)	1.991 (0.083)	1.978 (0.078)
β_{21}	*t*ln*c*	0.101 (0.013)	0.107 (0.015)	0.105 (0.014)
β_{22}	t^2ln*c*	-4.43e-3 (1.41e-3)	-5.26e-3 (1.80e-3)	-4.60e-3 (1.42e-3)
α_0	*constant*	0.086 (0.010)	0.064 (0.018)	0.086 (0.010)
α_1	*t*	-0.051 (0.004)	-0.055 (0.005)	-0.052 (0.004)
α_2	t^2	-1.48e-3 (0.32e-3)	-0.64e-3 (0.65e-3)	-1.49e-3 (0.31e-3)
α_3	ln*q*	0.320 (0.055)	0.385 (0.082)	0.339 (0.055)
α_4	ln*p*	—	-0.421 (0.286)	—
	# observations	275	275	275
	R^2	0.90	0.90	0.90

Dependent variable is the log of product cost (ln*k*). Variables are described in more detail in Table I and in the text. Estimation method is two-stage least squares, with instrumentation for shipments (ln*q*) using levels and changes in the log of housing starts and real household income in addition to the other explanatory variables. Robust standard errors are reported in parentheses.

TABLE IV

TRANSFORMATION SURFACE ESTIMATES: GAS WATER HEATERS

Parameter	Explanatory variable	Autonomous innovation	Induced innovation Specification 1	Induced innovation Specification 2
β_{10}	$\ln f$	-3.918 (0.235)	-3.829 (0.267)	-3.925 (0.221)
β_{11}	$t \ln f$	-0.055 (0.032)	-0.074 (0.023)	-0.061 (0.028)
β_{12}	$t^2 \ln f$	0.012 (0.002)	0.013 (0.002)	0.013 (0.002)
β_{13}	$\ln p \ln f$	—	-0.056 (0.263)	-0.088 (0.227)
β_{14}	$s \ln f$	—	-0.079 (0.058)	-0.032 (0.051)
β_{20}	$\ln c$	4.670 (0.238)	4.557 (0.271)	4.659 (0.226)
β_{21}	$t \ln c$	0.071 (0.032)	0.094 (0.023)	0.077 (0.028)
β_{22}	$t^2 \ln c$	-0.011 (0.002)	-0.012 (0.002)	-0.011 (0.002)
β_5	$\ln g$	0.381 (0.024)	0.383 (0.025)	0.383 (0.025)
α_0	*constant*	-0.006 (0.012)	-0.010 (0.012)	-0.004 (0.012)
α_1	t	-0.018 (0.002)	-0.014 (0.003)	-0.018 (0.002)
α_2	t^2	1.156e-4 (1.05e-4)	4.02e-4 (2.37e-4)	0.74e-4 (1.01e-4)
α_3	$\ln q$	0.640 (0.092)	0.594 (0.103)	0.646 (0.092)
α_4	$\ln p$	—	-0.073 (0.065)	—
α_5	s	—	-0.025 (0.015)	—
	# observations	415	415	415
	R^2	0.92	0.92	0.92

Dependent variable is the log of product cost ($\ln k$). Variables are described in more detail in Table I and in the text. Estimation method is two-stage least squares, with instrumentation for shipments ($\ln q$) using levels and changes in the log of housing starts and real household income in addition to the other explanatory variables. Robust standard errors are reported in parentheses.

TABLE V
FACTORS AFFECTING CHANGES IN ENERGY EFFICIENCY

Parameter	Explanatory variable	Description	Room air conditioners	Central air conditioners	Gas water heaters
η_0	$\frac{1}{1-\beta_1} l_0 \Delta \ln p$	pre-labeling price effect	0.001 (0.630)	1.394 (0.423)	0.326 (0.529)
η_1	$\frac{1}{1-\beta_1} l_1 \Delta \ln p$	post-labeling price effect	1.175 (0.391)	—	0.577 (0.277)
θ	Δs	standards	0.024 (0.025)	—	0.017 (0.007)
μ	R_t	rate of innovation	0.055 (0.417)	0.844 (0.882)	-2.045 (2.872)
ξ	D_t	direction of innovation	-0.053 (0.145)	0.047 (0.059)	0.479 (0.761)
σ	*constant*		0.007 (0.007)	0.001 (0.026)	0.007 (0.009)
		# observations	35	21	31
	1-U	goodness of fit	0.67	0.66	0.61

Dependent variable is the rate of change of mean energy efficiency of models offered for sale ($\Delta \ln \bar{e}$). Estimation method is ordinary least squares. Robust standard errors are reported in parentheses. U is Theil's U statistic, where 1-U is a measure of dynamic goodness of fit. See the Statistical Appendix for parameter estimates of the individual distributed lag price effects.

TABLE VI

HISTORICAL EFFECTS OF PRICE CHANGES AND EFFICIENCY STANDARDS ON ENERGY-EFFICIENCY (1973–1993)

(Historical simulations of cumulative percent change in energy efficiency)

	Room air conditioners		Central air conditioners		Water heaters	
	Relative to 1973	Share of total change	Relative to 1973	Share of total change	Relative to 1973	Share of total change
Total change (%) (baseline)	29.7 (4.5)	—	58.9 (3.5)	—	11.2 (2.4)	—
Price-induced portion (%)	8.2 (5.0)	28	16.1 (5.0)	27	5.1 (2.4)	46
Standards-induced portion (%)	7.1 (3.1)	24	—	—	7.6 (1.8)	68
Autonomous portion (%)	12.7 (2.7)	43	36.8 (3.7)	62	-1.1 (1.9)	-10

The baseline simulation uses the coefficient estimates from Table V to estimate the cumulative change in energy-efficiency of models offered for sale from 1973–1993, assuming energy prices and efficiency standards took their historical values (simulations for central air conditioners extend only to 1988). We decompose the total change into price-induced, standards-induced, and autonomous portions using the parts of the estimated model corresponding to these effects, and including any induced influences on the movement of the transformation surfaces (based on parameter estimates for Specification 2 from Tables II, III, and IV). The portions do not sum to the total change due to the non-linear nature of the model. Standard errors are reported in parentheses.

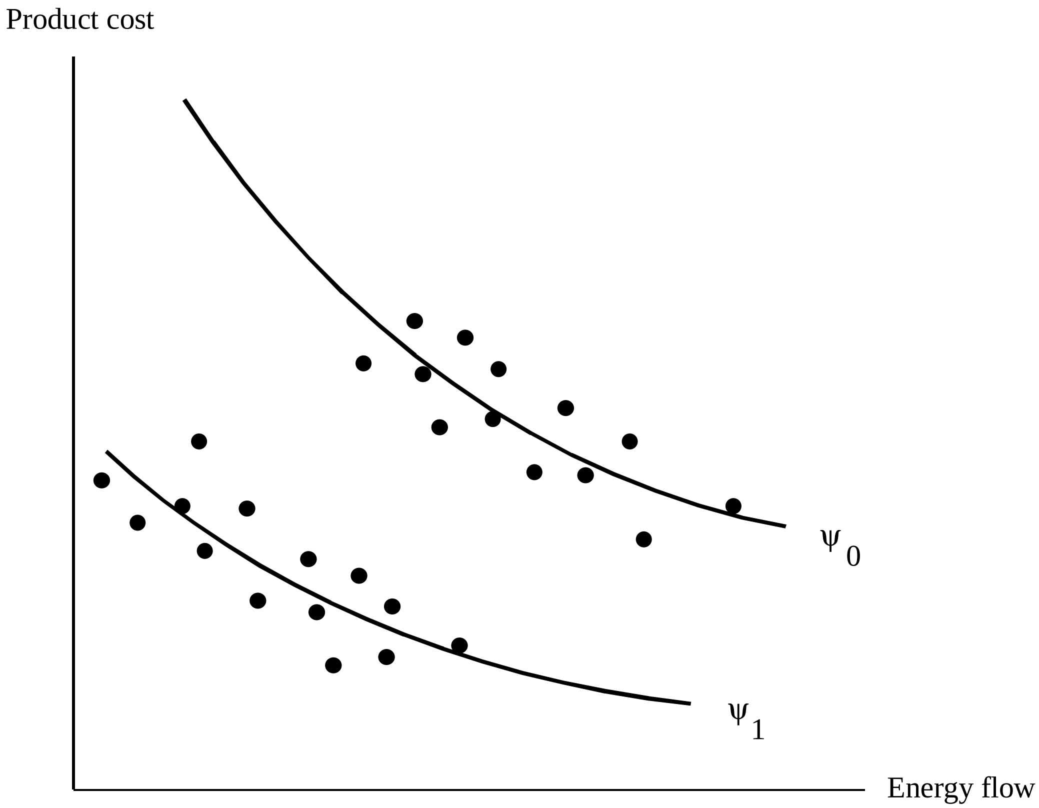

FIGURE I
Innovation in the Characteristics Transformation Surface

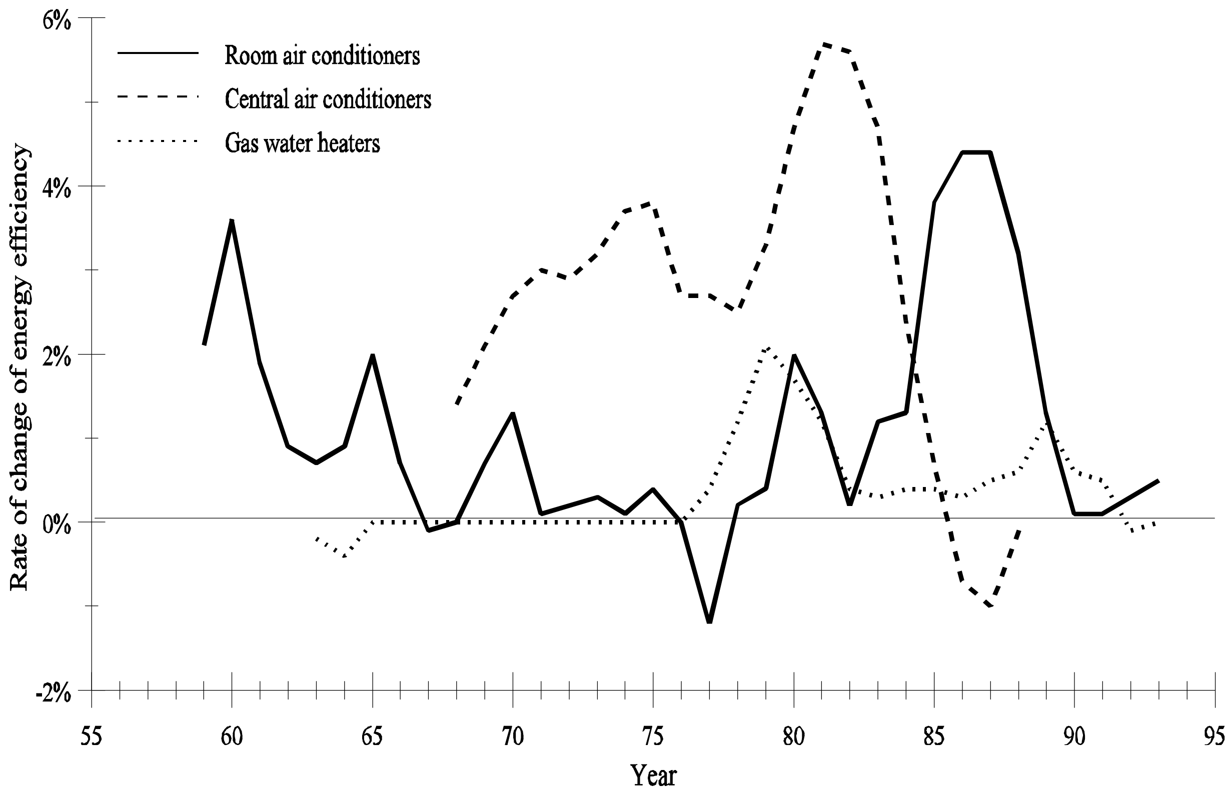

FIGURE II
Changes in Energy Efficiency

The figures shows a three-year moving average of the annual rate of change of mean energy efficiency of models offered for sale.

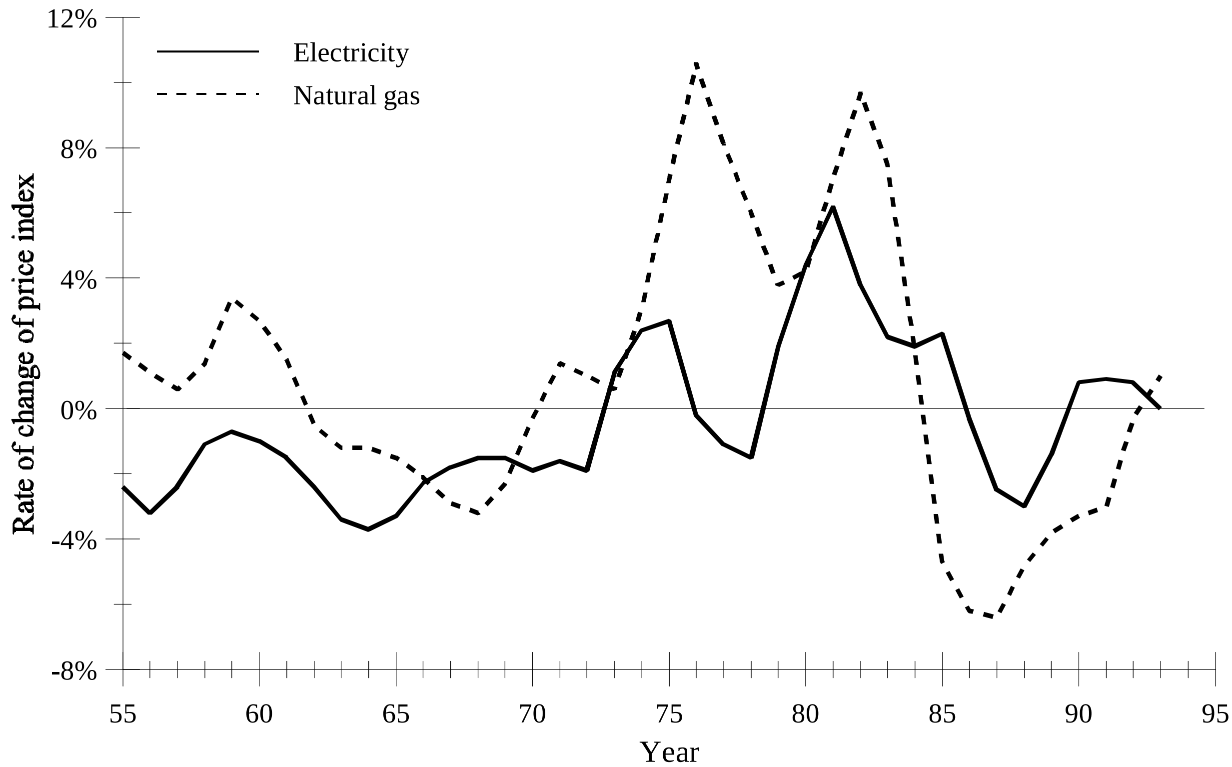

FIGURE III
Changes in Electricity and Natural Gas Prices

Figure shows a three-year moving average of the rate of change of the relative price index. See text for detail on data construction.

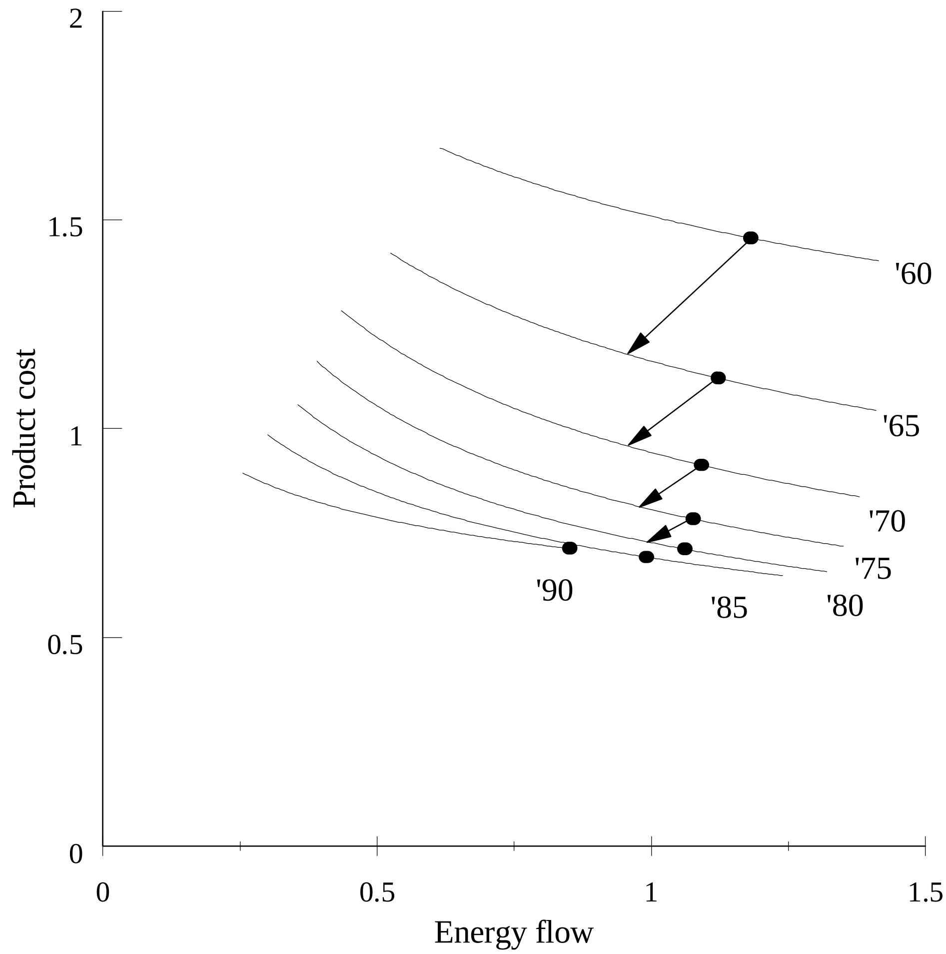

FIGURE IV
Innovation in Characteristics Transformation Surface: Room Air Conditioners

Figure illustrates the estimated transformation surfaces over 5-year intervals. Variables are normalized to equal 1 at their grand means. The dots represent the mean characteristics bundle of models offered for sale at each point in time and the arrows represent the overall rate of innovation, measured radially from the origin.

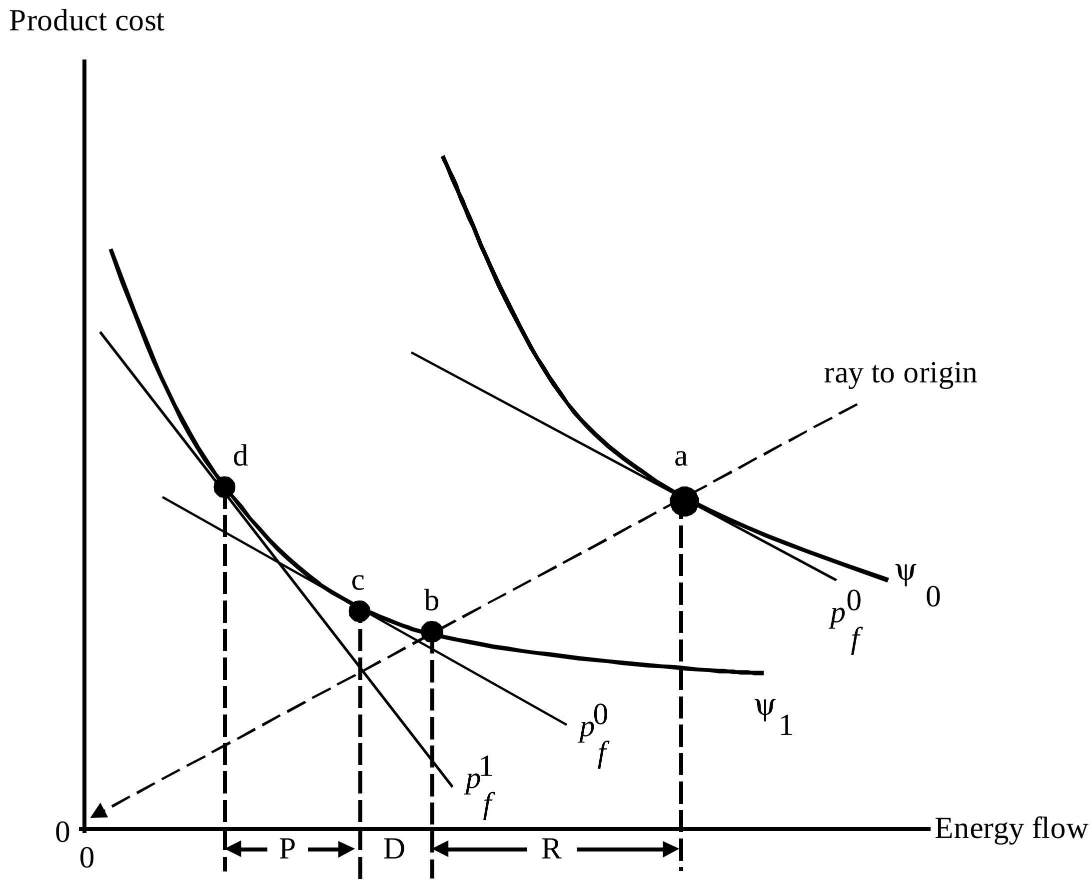

FIGURE V
Decomposition of Characteristics Innovation