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Measurement Issues for Energy Efficient Commercial Buildings: Productivity and Performance

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ABSTRACT

In previous reports, we have identified two potentially important issues, solutions to which would increase the attractiveness of DOE-developed technologies in commercial buildings energy systems. One issue concerns the fact that in addition to saving energy, many new technologies offer non-energy benefits that contribute to building productivity (firm profitability). The second issue is that new technologies are typically unproven in the eyes of decision makers and must bear risk premiums that offset cost advantages resulting from laboratory calculations. Even though a compelling case can be made for the importance of these issues, for building decision makers to incorporate them in business decisions and for DOE to use them in R&D program planning there must be robust empirical evidence of their existence and size. This paper investigates how such measurements could be made and offers recommendations as to preferred options.

There is currently little systematic information on either of these concepts in the literature. Of the two there is somewhat more information on non-energy benefits, but little as regards office buildings. Office building productivity impacts can be observed casually, but must be estimated statistically, because buildings have many interacting attributes and observations based on direct behavior can easily confuse the process of attribution. For example, absenteeism can be easily observed. However, absenteeism may be down because a more healthy space conditioning system was put into place, because the weather was milder, or because firm policy regarding sick days had changed. There is also a general dearth of appropriate information for purposes of estimation. To overcome these difficulties, we propose developing a new data base and applying the technique of hedonic price analysis. This technique has been used extensively in the analysis of residential dwellings. There is also a literature on its application to commercial and industrial buildings. Commercially available data bases exist that, if supplemented with engineering survey for equipment and materials use, could be analyzed statistically with a hedonic price model for the valuation of both the energy-saving and productivity effects of building technologies.

Uncertainties about technology performance can cause investors to delay deploying new technologies. This behavior is explained by the “investment under uncertainty” literature. This literature suggests that under conditions of irrecoverable (“sunk”) costs, uncertain outcomes, and the ability to defer deployment, decision makers focus on potential losses and demand risk premiums and a few support the notion of focusing on losses, the so-called “bad news principle.” We describe a series of approaches to isolating buyer perceptions of uncertainty and means for reducing uncertainty.

EXECUTIVE SUMMARY

This report develops suggestions for measuring the non-energy contributions to economic productivity by advanced building technologies and suggestions for measuring sources of technical uncertainty that cause decision makers to reduce rates of technology deployment. Better estimates of non-energy contributions to productivity amount to measuring incremental contributions to profitability and provide guidance to business decision makers and real estate appraisers about the subtle, but very real, contributions to well being that can be assigned to specific types of technological changes. This can also provide DOE with information about the value of alternative R&D activities that purposefully link energy and non-energy benefits to increase the attractiveness of advanced technologies. One way to improve DOE's ability to plan is to develop tools that link technical attributes that factor into design specifications, such as cubic feet per second of air flow, with users' perceptions of productivity, such as better control of noise, to provide better linkages between the design and use attributes.

Users' perceptions of uncertainties are important because user choices determine investment outcomes. For the class of investment decisions that includes advanced building technologies, those characterized by sunk costs, uncertainty that is abated over time, and ability to defer investment, investors tend to focus on the profits (losses) from the least favorable outcome, reflecting what is known as "the bad news principle." This is behavior is sometimes characterized as adding an "option premium" to the costs of uncertain technologies. It should be stressed that investor perceptions may differ from laboratory measurements or from DOE expectations of technical performance. The point to be made is that from the investor's perspective, cost-effectiveness takes into account the various forces and uncertainties of the real workplace and tend to be formed on the basis of workplace experience.

To measure contributions to profitability by non-energy attributes of advanced building technologies statistical analysis based on an approach referred to as the hedonic pricing model is proposed. This model has used extensively in the analysis of differentiated products such as buildings and automobiles, and it has been applied to the valuation of a number of characteristics of commercial buildings. The technique decomposes the price of a differentiated product into the unit prices of a number of its characteristics. In the case of a commercial building that price could be a sale price, an assessed value, or the annual rent on a suite of building space. To date, however, the hedonic model has not been used to study the market valuation of mechanical and electrical equipment and advanced materials in commercial buildings, although energy efficient residential equipment has been studied with hedonic pricing methods. The hedonic model applied to commercial buildings, particularly office buildings, has focused on how that market values characteristics such as the buildings age, its accessibility, amenities within the building and in the surrounding neighborhood, and even the view from a suite of offices. Attention to structural characteristics has been limited to date to the number of floors, and a single study including the type of material used in the frame and on external walls.

Commercially available data bases exist for office real estate, containing price and rent information, locational information on the individual buildings, the building's age, and a number of its physical characteristics. Some surveys also include information on energy use and energy bills.

These data bases, however, do not contain detailed information on equipment and materials used in the structures. Nonetheless, individual buildings can be identified in some of these data bases, and engineering surveys could supply the information on technology deployment required to conduct a hedonic pricing analysis of the productivity and energy-efficiency effects of a number of building technologies.

To identify and measure sources of uncertainty we propose employing a set of tools derived from the economic and social sciences that rely on questioning decision agents about the manner in which they form values. Decision agents in the commercial buildings industry, especially owners and people involved in lending, may perceive uncertainties in either the technical or market performance of new equipment and materials. Their investment decisions tend to rely on assumptions that the least favorable possible performance will emerge. This reasoning, and related circmstances, can lead to high hurdle rates required for investment and to deferral of investments in new technologies until uncertainties are clarified. The perceptions of the lending agents are important, in addition to those of owners and users, because of their influence over lending for new construction. Performance uncertainties involved with technologies having higher first costs but lower life-cycle costs can make first cost, which traditionally has been the primary bottom-line target of lenders, a rational investment criterion. Understanding the views of these agents can offer information that would be useful in designing advanced equipment and materials.

1. INTRODUCTION: WHAT WE WANT TO KNOW

How much value do advanced building technologies contribute to the firms occupying building space that uses these technologies? This is the question that both the developers and the users of these technologies want to know. The developers (DOE) want the information so they can tailor their R&D toward items that users will find more attractive. Users want some evidence they can accept as valid that resources they might pay for are worth their cost. This report develops suggestions for measuring the economic productivity of advanced building technologies, which amounts to measuring incremental profitability.

Developers and users of building technologies think about the characteristics of desirable building features in different terms. The developers of technology tend to think of the characteristics of their products in terms like cubic feet per second of air flow, lumens per square foot for lighting, analogous measurements for auditory and heat-transmission characteristics. Commercial building occupants show clear concern for the physical characteristics of their space, but most of them would be hard pressed to map magnitudes of these various characteristics onto how much they want the technologies that provide them. The private firms occupying commercial buildings—a definition that excludes government agencies and schools—think in terms of how much money they make and how their various expenditures repay themselves in terms of the "bottom line."

Studies of office productivity have tended to associate quantitative measures of physical activities with different functional attributes of office interiors. Typing speed has been a popular measure, probably because of the ease of its measurement. Employee health and related absenteeism measures also have been targeted for examination, although the health links may be more complicated. Less tangible indicators of employee morale have been cited as improved by certain features of building space. Such physical measures may or may not reflect the additional profit that employers can capture from the contributing technologies, so these measures may not encourage widespread adoption of the technologies that are found to be associated with higher levels of physical productivity measures.

Second, what technological or business uncertainties do potential buyers of advanced buildings technologies perceive in them, and how much are these uncertainties slowing down deployment? In making investments for which costs are sunk, outcomes are uncertain, and waiting is inexpensive, investors compare the known performance of existing technologies with the worst possible outcomes associated with using lesser-known technologies. This view of investment opportunities, deriving from irreversible investment theory and called the "bad news principle," predicts high hurdle rates for technologies with uncertain performance characteristics and investments in new technologies deferred in favor of older, better-known technologies.

Examinations of the real option values associated with energy-efficient technologies have emphasized uncertainties in energy prices and options with infinite strike dates (when the option expires). Technical performance uncertainties may be more important than energy price uncertainties because the parameters of their variability are less well-known and because those uncertainties are more amenable to policy action than are energy price uncertainties. Shorter terms to expiration on a real option, which are consistent with many of the technologies under consideration, raise the hurdle rate on an investment for any degree of uncertainty. This is simply to say that when technological change is discrete, but frequent, as in generations of computer technology, an investor who skips the purchase of this season's superior technology may be confident that next year's superior technology may offer even more advantage.

Knowing more clearly what uncertainties buyers perceive in new buildings technologies could help research engineers adjust various technical features in new versions of equipment and materials. It may be possible that the business environment heightens the importance of some features over others in ways that would not be obvious outside the market. Moreover, there are also various other ways of dealing with downside uncertainty.

Section 2 discusses several approaches to measuring the economic productivity of these technologies and reveals a number of technical difficulties in statistically estimating productivity of technologies with empirical data. The hedonic pricing approach to commercial buildings appears to be the most appropriate method for estimating productivity effects. Consequently in section 3 we discuss the hedonic, or implicit, price model and the results to date found in the literature studying commercial buildings with that pricing model. Section 4 identifies opportunities for measuring both the capitalization of energy-saving and productivity benefits and the performance uncertainties perceived by potential users of advanced buildings technologies. Sub-section 4.1 outlines some recommendations for developing a data base on commercial buildings that would yield the information needed to statistically analysis contributions to productivity by advanced buildings technologies. Sub-section 4.2 sketches the relationship between technology characteristics, uncertainties, and investment choices and recommends industry and user surveys to identify specific uncertainties.

2. APPROACHES TO MEASURING PRODUCTIVITY IN COMMERCIAL BUILDINGS

In a technical sense, the empirical measurement of the productivity effects of specific technology applications in commercial buildings is a test of the null hypothesis that those technologies have no such effect. This fact should be borne in mind as a quality assurance check, because it is easy to construct statistical models that appear to test these hypotheses but which in fact do not, because they fail to adequately account for the behavioral interactions involved in the technology selection and use.

This section begins with a review of the economic concept of productivity and then turns to several possible ways to examine productivity empirically. As an example of potential pitfalls, an intuitively appealing method that actually fails to test the null hypothesis at all is described.

2.1. Define Productivity

How much output can be obtained from a given quantity of inputs is the heart of productivity. There are several options for measuring this concept. News reports commonly focus on aggregate productivity in the entire economy rather than productivity in making specific goods and services, though for present purposes it is specific applications in buildings that is of interest. We seek to measure the productivity of a single inputs—called single-factor productivity measurements—while recognizing that several inputs are used in making a product. The value of identifying individual contributions to productivity, such as the value of having a conference room with a quiet environment, lies in the fact that the business community wishes to use additional inputs whose contributions to profits exceed their costs and reduce the use of those whose contribution is exceeded by their cost. This is just another way of saying that factors must pay their own way. This focus on the attribution of parts of output or profits to specific inputs leads to the concept of marginal productivity, or the contribution of a particular input to total production, making allowance for the contributions of each other input.

Carried to its logical conclusion, the marginal measures of productivity can also be used to predict business behavior. As business people strive to maximize profits, they will try to equate the marginal productivity of each of their inputs, in value terms,[1] to its marginal cost to them. This equality implies that the marginal productivity of a unit of each input should equal its price to the firm when the firm has maximized profits. If the marginal revenue product (MRP) of an input is higher than the price a firm must pay for it, the firm should use more of it, and vice versa if the MRP is less than the input's unit price.

2.2. The Subtleties of Measurement and Estimation

The marginal productivities of inputs to production processes cannot be easily measured because it is difficult to design natural experiments in which the multitude of inputs not under consideration are held constant and the single input of concern is systematically varied. Instead, measurement requires using statistical estimation of well-posed hypotheses using data drawn from observations of a range of firms that make different operating decisions. A statistical technical called multiple regression analysis is used for this purpose. Multiple regression analysis provides a "quasi-experiential control" by allowing the analyst to artificially hold constant some effects while allowing others to vary thus identifying the marginal productivities of the factors under consideration. However, it is entirely possible to conduct statistical tests for productivity in which the estimated statistics have no valid, interpretable meaning related to productivity. The following subsections offer examples of this problem and ways to avoid it.

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[1]This version of the productivity measure is called "marginal revenue product."

2.2.1. Directly Estimating Contributions to Profits

Suppose that we could obtain data for individual firms on their profits—revenue less costs—for a given time period. Also suppose that each firm will report the value of its output and how much of a number of inputs it used during that time period—labor, office equipment of various types, materials, electricity, building space, and possibly other items. Included in the data they report on their building space are binary data (1 or 0 for presence or absence) on various types of advanced equipment and materials present in their building space. Finally, suppose that we have a large sample of firms occupying a sufficiently wide variety of building space that the building data have variances large enough to yield statistically significant estimates of coefficients.

We regress profits on the output variable and the input variables. The regression equation would look something like:

Profits = Constant + a_1 Output + a_2 Labor + a_3 Equipment + a_4 Electricity + . . . + a_j Technology j + a_{j+1} Technology j+1 + . . . + error term.

In a regression equation, the regression coefficients (the a_i) on the independent variables tell the change that will occur in the dependent variable (profits) per unit change in the respective independent variable.[2] So the values of these coefficients should tell the contribution to profits that the employment of each of these inputs and building technologies makes. We would look to find positive values for these coefficients and hope for statistical significance.

In fact, because of the behavior of the firms generating these data, the value of each of these coefficients should be zero. This does not mean that none of these inputs contributes anything to profits, but rather that this specification of the regression equation does not test the hypothesis we want to test. The primary condition for profit maximization by a firm is that it uses each input in an amount that makes its incremental contribution to profit zero. The incremental contribution of each input to gross revenue should equal the incremental cost of hiring or otherwise using that input. That is, the incremental benefits should exactly offset the incremental costs. This equality probably will not occur exactly for each firm, so the regression equation would generate some statistical noise, but the regression coefficients should be small in value (either positive or negative) and generally statistically insignificant. With a large number of independent variables on the right-hand side of the regression, we might find one or two statistically significant, but they could equally well be of negative sign as positive, but either way, they would be meaningless. This is the first example of the difficulty of testing the hypothesis that the use of advanced building technologies makes a positive contribution to profits for private business firms.

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[2]With a particular specification of the variables (logarithmic), these coefficients can tell the percent change in the dependent variable caused by a one-percent change in each independent variable.

In this light it is useful to consider the finding by Heschong et al. (1999) relating skylighting in retail stores to improvements on sales. That study obtained observations on a large number of stores of a retail chain in the Pacific Northwest, some of which had installed skylighting, and others of which had not. Using a multiple regression analysis to control for a number of factors that could have been responsible for differences in sales revenue, they determined that the presence of skylighting in a store made a statistically significant contribution to sales revenue, in fact raising revenues in the stores with skylighting forty percent above stores without. In stores operated by the same management, this difference in sales performance is striking. Let us follow how this revenue effect comes about. It is reasonable to suppose that the aggregate demand for the products sold in these stores was not affected by the skylighting in some of this chain's outlets. Thus, sales appear to have been diverted from stores, either of the same chain or of other ownership, without skylighting to these stores with skylighting. The greater aesthetic appeal of skylighting to shoppers is a reasonable conclusion.

In this circumstance, stores without skylighting have an incentive to install skylighting to retrieve some of their sales.[3] Suppose that all the stores initially without skylighting invest in skylighting. What will happen to aggregate sales at the total group of stores? It should not change, because the demand for those goods has not changed. To the extent that shopping is more pleasurable with skylighting than without, shoppers may be enticed to purchase more of those goods than other goods sold in yet other stores still without skylighting, but that should effect should be of second-order magnitude. Once all the stores that sell these particular goods have adopted skylighting, their sales revenue will return very close to what is was before, but their cost of operation will have increased to the extent of the mortgage payments on the skylighting investments, less any possible reduction in lighting bills. Under competitive conditions, these retail firms will pass on at least part of these higher costs to consumers. The principal benefits will go to consumers in the form of more desirable aesthetics for shopping, and to the extent that the skylighting reduces the demand for lighting, some environmental improvements from reduced electricity demand will result. The principal observation is that the forty-percent increase in sales in the stores installing skylighting is a diversion effect from other stores, not a genuine increase in productivity of a business operation. Even if other stores do not respond by installing skylighting, the increase in sales at this chain's stores with skylighting will be matched by reductions in sales of the same goods at other stores.

Production theory in economics does generate a relationship known as a profit function, but it is a function of the *prices* of the firm's product and its inputs, not their quantities (Chambers 1988, Chapter 4; Cornes 1992, section 5.4, 5.7). In many industries,

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[3]These chain stores with skylighting are likely to have represented a small proportion of the stores selling the goods they offer, and a correspondingly small percentage of sales of those goods. Consequently, the reductions in sales in stores without skylighting could be a relatively small fraction of their sales. Whether they would have been distinguishable from statistical noise in a formal analysis of their sales is an open question. Also an open question is whether the adoption of skylighting would be an economically justified investment to recover the lost sales, given the potentially small percentage of sales that could be involved. In the text above, we assume that these stores decide that such investments are justified.

at any particular time, most firms will face the same prices, so this relationship is difficult to test empirically without observations over different time periods, during which prices have the opportunity to change. In some instances however, interregional variations in prices are sufficient to permit statistical implementation, and among firms with bargaining power over many of their important inputs, prices may vary at a given time. One practical question in implementing the properly specified cost function to study building technologies is whether the prices of those technologies vary enough across regions to permit statistical estimation. Whether profit data could be obtained at the firm level would pose another practical hurdle for the profit function.

2.2.2. Estimating Contributions to Cost Reduction

Advanced building technologies can contribute to firms' productivity by reducing some of their costs. For example, providing superior fresh air flow in a building can improve health and reduce absenteeism due to a number of respiratory illnesses. More energy-efficient lighting and HVAC equipment obviously can reduce electricity costs. Demonstrating these effects on a more systematic basis than a series of anecdotes might be accomplished by estimating a cost function for a series of firms.

A cost function is estimated in a manner similar to a profit function in that the independent variables are the firm's output (not its output *price*) and the prices of its inputs rather than their quantities (Chambers 1988, Chapters 2-3; Cornes 1992, section 5.2). The firm's total cost of doing business is the dependent variable (the variable on the left-hand side of the regression equation). Again, variation among firms in the prices of inputs is required for statistical estimation, and data on businesses' costs could be difficult to obtain. Cost data might be less sensitive than profit data however, and the approach need not be discarded out of hand.

2.3. Technology's Contribution to Production

In general, firms employ inputs to produce output. The building space a business firm uses is one such input. Accordingly, advanced building technologies, which offer improved services in a number of types of equipment and materials, contribute directly to production. This direct relationship offers another route for examining the productivity of these new technologies.

2.3.1. The Production Function Concept

A production function specifies the technological relationship between the quantities of inputs used in a production process (the independent variables) and the quantity of the firm's output. Production functions give information not only the quantitative relationship between inputs and outputs but also on the possibilities for substituting one input for another to produce a given amount of a product. The parameters of a production function tell how much the output will be increased by a unit increment in each input, holding unchanged the quantities of all other inputs.[4] This is clearly direct, physical productivity information.

This method of characterizing production processes is an especially useful reminder of the fact that real resources are required to produce goods and services and that increased supplies of goods and services require increased quantities of inputs. Technological progress is the sole way to relax the otherwise ironclad rule that no increases in output occur without corresponding increases in inputs, and of course technological progress in building equipment, materials, and design methods is the ultimate subject of the present research effort.

Improving an input's direct contribution to production is equivalent to reducing costs.[5] Expressed quite simply, less can be more, or at least the same. It is possible that less of a more productive version of some input—say, a particular type of equipment—can yield the same or even more output than a larger quantity of an older version can produce. Consider another example. Advanced roofing materials and design techniques might use more materials and cost more initially, but the new roofs may last longer and better protect other building components from moisture, thus "producing" "more roof" in an economic sense and simultaneously enhancing the productivity of related inputs.

Statistical estimation of production functions is complicated by the fact that the optimal quantity of each input is chosen in conjunction with the optimal quantities of all the other inputs, and often in conjunction with the desired quantity of the output as well. This behavioral feature of profit maximization in production requires that the statistical estimation take into account the simultaneity of these choices. Doing that often leads analysts to use simultaneous estimation of multiple regression equations. Additionally, since the optimal choices of inputs and outputs depend on the prices of the inputs and the output, statistical estimation needs some variability in input and output prices across the observations, which usually are individual firms, just as was the case with cost and profit functions.

Again, the profit-maximizing behavior underlying production choices complicates the statistical estimation of the production function, and the need for price data is not avoided, despite the fact that the production function relates quantities to quantities. However, the production function allows one to decompose the output of a good or service into the contributions of each input used in producing it. The cost function allows

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[4]In some production function specifications these parameters take the handy form of "output elasticities," which tell the percent increase in the output yielded by a one-percent increase in a particular input, again holding unchanged the quantities of all other inputs.

[5]In fact, the cost function is derived from a production function. We can find the profit-maximizing quantities of inputs, express them in terms of their prices, and substitute them back into the production function to get a cost function (after a few manipulations and cancellations of terms). Production and cost functions are said to have a "primal-dual" relationship to each other. The cost function is the dual of the production function, and the production function is the primal, or quantity, form of the input-output relationship.

one to decompose the cost of producing a good or service into the costs of the separate inputs. Both of these insights come together in the hedonic pricing model used to study heterogeneous, non-standardized products such as automobiles and buildings.

2.3.2. Hedonic Pricing

The hedonic, or implicit, pricing model decomposes the overall price of a multi-attribute product into the implicit prices for each of the components. It has proven quite useful for comparing the prices of highly differentiated products that contain different features or similar features in different quantities or qualities. The unit price of such a product will be the sum of price-times-quantity for each of the attributes—the unit implicit price of the attribute, times the quantity or number of units of the attribute. An example of such a readily measurable attribute is the number of bathrooms in a residential house. Some attributes may be a combination of continuous and binary measures, such as HVAC systems which could be both of different sizes, in terms of tons, and different efficiencies, such as "standard" and "advanced."

The observations in a hedonic price model are products rather than firms. This focus enormously simplifies the data requirements for the analysis of commercial buildings, which may be occupied by any number of separate business firms. Commercial building space is an input to the production processes (and therefore the production functions) of firms using it, and the price of a commercial building—or the rents for space within a building—is determined by its productivity to firms.[6] The aggregate building price, as well as the rentals which serve as the basis for the price, is composed of the separate effects of many building characteristics, so we are able to get at the productivity effects that firms derive from the separate building components by looking at how much they are willing to pay for buildings or in rents. Data on building prices and space rentals are much more readily available than are data on profits and costs of private firms, which generally consider that information privileged. The buildings and space within them are the subject of relatively public transactions.

The implicit prices estimated in a regression of product price on product attributes are the intersections of buyers' demand curves for those attributes and producers' supply curves for them. If buyers have a high demand for a particular attribute, given the attribute's supply conditions, its unit price will be high. If buyers find the presence of a particular attribute a nuisance, the implicit price of the attribute will be negative and a multi-attribute product containing it will sell at a discount. The supply curve for the attribute could be interpreted as the cost of getting rid of that attribute. While the estimation of the underlying demand and supply functions for the attributes is a relatively intricate statistical procedure, the satisfactory estimation of the implicit prices—the implicit supply-demand intersection points—is more straightforward. Taking the example

[6]Of course, capital asset prices are also influenced by interest rates determined in the capital market as well as by the immediate productivity of an individual asset itself, but the influence of interest rate fluctuations on building prices is of secondary concern to the present productivity problem.

of commercial buildings, the price of a building will vary across observations (individual buildings) because the characteristics of the buildings differ, so there is no problem with getting sufficient variation in the only price used in the regression, even if all building prices are observed at the same time.[7] The hedonic regression uses the building price as the dependent variable (the one on the left side of the equals sign) and building characteristics as the independent variables: e.g., floor space, number of floors, location, age of the building, and a number of equipment and materials variables. The optimization actions conducted by both buyers and sellers are represented by the supply-demand intersections for each characteristic and thus are fully contained in the estimated implicit prices of characteristics.

3. HEDONIC PRICING IN COMMERCIAL BUILDINGS

Extensive hedonic price analysis of the residential dwelling market has demonstrated the usefulness and practicality of the hedonic technique in identifying specific components of market value of buildings. A considerably smaller literature is devoted to hedonic price analysis of commercial and industrial buildings, but predominantly office buildings.[8] The common attributes of interest in these studies have included the building's location and neighborhood amenities, square footage and number of floors, age, rental contract terms, and in-building conveniences such as banking facilities, day care, and restaurants. The literature generally has given less attention to structural characteristics and mechanical equipment than has the residential hedonic literature, which has explored the capitalization of energy-efficient equipment such as HVAC systems.

Sivatanidou (1996) provides the only hedonic study of commercial buildings we have found that considers any structural features of buildings other than square footage. She uses dummy (binary) variables for whether the building has a metal frame, whether it has glass walls, and whether it has external wooden walls, and an integer variable for the number of elevators in the building. The dependent variable, using data from the Los Angeles area, is assessed property value per square foot of land under the building (not per square foot of floor space—a departure from the usual practice in the hedonic analysis of buildings).[9] The coefficients of each of these structural features were statistically significant. Metal frame and wood exterior depressed assessed value, and glass exterior and a larger number of elevators raised it. Building age depressed assessed value.

[7]Space occupied by separate tenants within a building equally well could be the unit of observation. In that case, the rental of that space, per square foot, would be the dependent variable.

[8]Lockwood and Rutherford (1996) is the only hedonic study of industrial buildings we have located, and it studies the effects of location relative to points of transportation access more than structural characteristics of the building itself.

[9]She estimated the regressions on sale prices of a smaller sample of 308 properties but encountered multicollinearity problems (high correlation among independent variables). However, she found a rank correlation coefficient of 0.98 between the assessed values and sale prices of the properties in both samples. There were 539 properties in the sample of assessed values.

In another study using asking rent[10] per square foot as the dependent variable, Sivatanidou (1995) examined the influence of neighborhood characteristics on commercial building rents, again in the Los Angeles area. Better shopping opportunities nearby raised office rents, and higher crime rates depressed them. She used no structural characteristics of the buildings, other than age and rentable area per floor in the analysis. Age depressed rents, and rentable area per floor had very small positive effects, of marginal statistical significance.

Mills (1992) examines the effects of several on-site amenities on office asking rents in Chicago in a hedonic price model. The presence of a banking facility and a restaurant in an office building raised office rent with statistical significance. Presence of shopping opportunities, day care, and health clubs all had positive coefficients—i.e., raised rents—but were either of marginal statistical significance or not significant. The existence of a stop clause on net rents had a positive effect on rents, while its absence from a net rent contract depressed rent.[11] Rents per square foot were higher in larger office buildings, but no other structural features were examined. He found that the first year's rent was as informative as a dependent variable as the more complicated present discounted value of the rental contract that accounted for various contractual features. That finding simplifies empirical work. In an earlier study of the Chicago office market, Brennan et al. (1984) found results similar to Mills', using transaction rentals on units within a building, but without the in-building amenity variables. They also found a positive effect of vertical location within a building, indicating a price premium for a view.

In an example of the hedonic pricing model's ability to identify users' valuations of building features that some observers would be inclined to dismiss as being incapable of affecting rents, Vandell and Lane (1989) report positive valuations of design aspects of architectural features on commercial buildings in Boston. They solicited the opinions of a panel of architects regarding the aesthetics of design features on specific buildings, controlled for various physical characteristics of the buildings, and entered the quality of the design features as a discrete variable taking values between 1 and 5, representing the lowest and highest aesthetic assessments. The coefficient on that variable was positive and statistically significant. They used the same design variable in a regression of the determinants of vacancies (the vacancy rate times average rental in a building yields its income), and it did not depress building occupancy in response to the higher rent.

4. MEASURING PRODUCTIVITY AND ASSESSING BARRIERS

[10]"Asking rent" is the posted rent advertising the availability of the building space. Negotiations between tenant and landlord may yield a different contracted rent, but data on contracted (or "transaction") rents are more difficult to obtain, so many studies use asking rents as dependent variables in hedonic studies of commercial buildings.

[11]A stop clause specifies a ceiling on operating costs that a tenant must pay.

This section identifies two directions for measurement activities to contribute to enhanced deployment of new buildings technologies. The first activity describes the estimation of the capitalization of energy-saving and productivity benefits of these technologies into commercial building rents. The second activity focuses on identifying technological uncertainties that can defer the date at which buyers would feel justified in investing in new building technologies.

4.1. A suggested approach to estimating productivity effects of commercial buildings technologies

This section suggests a method for estimating the productivity effects of building technologies separately from the capitalization of their energy-savings effects, using a hedonic pricing model. We would use a commercially available data base of commercial buildings, containing various economic and locational data for identifiable buildings and would supplement that data base with direct engineering survey for equipment and materials characteristics, and possibly energy use.

We offer an outline of the regression specification, using rent per square foot as the dependent variable. The regression should control for location of the building, identifying both the metropolitan area and the building's location within that area, i.e., central city or suburb. Interactive use of an energy savings index and a dummy variable for specific equipment/material use will permit distinction between the value of productivity effects and the value of energy saving. The regression should control for the influences of a number of other variables, such as age of the building, rental contract terms, possibly number of floors, and in-building and neighborhood amenities. The form of a regression with these variables is:

$$\text{Rent/ft}^2 = a_0 + a_1\,\text{location} + \sum_{i=2}^{1+j} a_i D_j\,(\text{Energy Savings Index}) + \sum_{i=j+1}^{2j+1} a_i D_j + \sum_{i=2j+1}^{k} a_i Y_i + \;.$$

In this expression, D_j is a dummy for equipment or material of type j. The Energy Savings Index = [(Energy Bill)* - (Energy Bill)$_k$]/(Energy Bill)*, where (Energy Bill)* is the highest energy bill/ft^2 in the sample of buildings and (Energy Bill)$_k$ is the energy bill/ft^2 recorded for building observation k. We may want to (be able to) substitute Btu for energy bill, depending on the data set. Y_i represents an array of other control variables.

In this specification, the interaction of the equipment/material dummy with the energy savings index captures the energy savings permitted by this particular technology. The equipment/material dummy used alone captures all other effects on the building rental, and it seems reasonable to call these “productivity effects.”

There are several sources for data bases on commercial buildings (or for the office-building subset). Each of the data bases contains price data and sufficient information on the buildings to at least calculate rentals or sale prices per square foot, and probably to identify the number of floors in the building. They probably vary in the availability of further physical detail. We would need identification of the properties that would allow us to survey the buildings for further information on their use of various building technologies, which means the address of the building and the name of its owner or property manager.

First there is the annual BOMA survey, if the individual buildings in it can be accessed. It has rent per square foot, considerable detail on location, age, and overall building size, and details on energy use. However, not all variables are available for all buildings.

Second are the Torto-Wheaton data bases. Torto-Wheaton Research (TWR) is a commercial realty consulting firm founded by two real estate economists, William Wheaton of M.I.T. and Raymond Torto of Boston University. TWR has time series rental data on office buildings from 71 metropolitan areas: 35,000 multi-tenant office buildings over 10,000 square feet (a 100-percent sample) and 20,000 single-tenant office buildings. Their data base contains information on size, age, and location as well as unit rentals.

Third are the NCRIEF (National Council of Real Estate Investment Fiduciaries) data. These data attach values to buildings, rather than rentals, but they appear to be dominated by appraisal data rather than transaction prices. These data are property-specific and include some physical information on buildings. Some description of these data is available on the NCRIEF web site.

If a base economic building data set can be acquired from one or some combination of these sources, and the buildings can be identified by location and owner, ORNL possesses the engineering capability to survey the buildings to fill the remaining information on structural components needed to conduct the suggested hedonic price analysis. Some particular information such as the type of glazing or details on a control system, may be difficult to obtain even with such a survey procedure, but most of the information on equipment and material deployment will be amenable to engineering survey.

4.2. Uncertainties and Technology Deployment

All investments are made under uncertainty, because they involve making current expenditures to put into place capital equipment that is expected to deliver a stream of net benefits over some period in the future that is at least sufficient to cover all current and future charges associated with the investment. Uncertainty can derive from the market, i.e., whether demand for the products the investment produces will prevail as expected, or from the technology itself, whether the equipment will perform as expected. Uncertainty may also stem from the need to purchase inputs to make use of the investment, such as energy, raw materials, or labor.

When an uncertain investment can be deferred while uncertainty abates, but once made, is largely irrecoverable, a recently developed theory of investment gives superior insight into decisions than does the older and simpler, "Neoclassical" investment model. In particular, under the "irreversible" conditions, each contemplated investment has an associated real option value, which is the value of waiting to invest, to see if any of the current uncertainties will be clarified with the passage of time. Undertaking the investment requires exercising the option, or using it up, which involves an opportunity cost just as real as the purchase price of the capital equipment and the labor costs required to install it. The existence of this additional cost of investment gives rise to what has become called the "hurdle rate" that an investment must pass to be considered sufficiently profitable to be undertaken. This hurdle rate is an interest rate or rate of return, but is higher than the rate of return that would be calculated only from the readily observable purchase price and installation costs of the equipment, because the cost of the "option" is added in. Uncertainties, either market or technological, can raise the option value and thus the cost of making an investment, consequently raising the hurdle rate to a point that justifies deferring investment rather than undertaking it presently (Jensen 1982, Dixit and Pindyck 1994, Alvarez and Stenbacka 2001).

Even though the theory is specified relative to a generic source of uncertainty, making the model operational required specifying and measuring the specific source of uncertainty to which the investment is subject. Virtually any key variable subject to uncertainty that affects the profitability of the investment could be specified and measured, so, in general, there could be several sources of relevant uncertainty. Whether or not these sources are key is another matter. Uncertainties over energy prices are unlikely to be a critical source of uncertainty in decisions to invest or not in energy-efficient building technologies, largely because history does not describe a highly volatile time path for energy prices, or at least one greatly different from that of other commodities. Waiting to see if energy prices are going to change in some fashion conducive or not to the use of a new technology is unlikely to offer permanent resolution to the inherent uncertainty in a commodity market. The expiration dates on real options are determined by the economic life span of the investment underlying them, while energy prices and variations in them have no temporal end point. No permanent clarification of any uncertainty regarding energy prices is gained by waiting.[12] The contrary is the case with technological uncertainty, which can be either resolved or reduced by waiting to observe performance of equipment or materials, either in the market or in controlled testing. Furthermore, an

[12]Of course, uncertainty over price paths can abate in the sense that prices can drift into a regime for which the uncertainty generating mechanism, coupled with discounting, yield a sufficient value for striking (using) the option.

important implication of the irreversible investment model is that when investors are studying the return they must make on an investment, they look at the most unfavorable possible outcome rather than use the probability-weighted average of good and bad possible outcomes. This result is known as the “bad news principle,” and it places an especially heavy burden on new, relatively unproven technologies. As a hypothetical example of this kind of investment problem, consider the installation of an advanced HVAC system in a twenty-story office building. Suppose that, for some reason, the system fails to perform close to expectations, and the owner contemplates replacing it. Tearing out the existing components and installing another system in an occupied building could cost an order of magnitude more than the original, installed cost of the existing HVAC system, making it a truly irreversible investment. A number of recent studies have identified the contribution of option values in determining commercial real estate investment behavior, along the lines predicted by the theory of irreversible invstments.[13]

In this setting, the concerns of potential buyers take on heightened significance for the deployment of advanced building technologies. It would be especially useful to systematically survey decision agents in the commercial building industry, particularly owners, to learn what technological uncertainties they may perceive with these new technologies. In some instances, technological uncertainties may interact with business practices in ways not contemplated during the design phase of the technology development. Information from such a survey could prove useful in making design trade-offs and in targeting specific aspects of performance for field testing.

The perceptions of lenders to the commercial buildings industry are equally important, since those agents hold the purse strings and heavily influence all choices affecting cost. Lenders traditionally have used first-cost criteria for evaluating and approving equipment and material choices in commercial buildings, and proponents of improving energy-efficiency long have criticized them for what appears to be excessive and unwarranted conservatism in their assessments. However, from the perspective offered by irreversible investment theory and its bad news principle, performance uncertainty in a new technology can collapse the distinction between first cost and life cycle cost as the worst possible outcome, rather than a statistically expected outcome, is used to evaluate profitability prospects. Understanding the views of this group of agents, and how they form and modify those views, is likely to be important to the deployment of advanced building technologies.

5. SUMMARY AND CONCLUSIONS

The productivity in which businesses are interested is the ability of an input to production to contribute to profits. Building owners and users need information on the expected profitability of advanced building technologies to make the business decisions involved in investments. At the same time, DOE R&D managers can make use of this

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[13]Holland et al. (1995), Sivitanidou and Sivitanides (2000), Bulan et al. (2000), and Sing and Patel (2001).

information in R&D planning. However, little systematic information on such profitability of building technologies is available currently. Productivity of technologies generally cannot be observed directly but must be estimated statistically. The profit-maximizing behavior guiding the choice of inputs, as well as availability of data, complicate the statistical estimation of productivity.

Hedonic price analysis of commercial buildings provides a useful method for estimating the productivity of building technologies for which the necessary data appear to be available. The technique has been used extensively in the analysis of residential dwellings, and a literature exists on its application to commercial and industrial buildings. The residential hedonic literature has studied the valuation of energy-efficient equipment successfully, but the valuation of building materials has been quite restricted in the commercial hedonic literature, and the valuation of building equipment, other than elevators, nonexistent to date.

Commercially available data bases exist that, if supplemented with engineering survey for equipment and materials use, could be analyzed with a hedonic price model for the valuation of both the energy-saving and productivity effects of building technologies.

Of equal importance is the need to gain greater understanding of the role of uncertainty in the investment decision making process. Surveys of the perceptions of commercial building owners and lenders about technology performance will provide the required information. These views exert powerful influence over the evaluation criteria these agents use for investment decisions and consequently over the rate of deployment of advanced technologies.

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