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The 'New' View of Investment Decisions and Public Policy Analysis: An Application to Green Lights and Cold Refrigerators

Gilbert E. Metcalf, *Tufts University*
Donald Rosenthal

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Abstract

Recent research in investment theory emphasizes the importance of sunk investment costs, uncertainty in returns, and flexibility in investment timing. Allowing for the presence of these characteristics alters traditional discounted cash flow rules for when to invest. Those rules will recommend investing at lower rate-of-return thresholds than is optimal. This article describes this research and suggests the range of potential situations to which the theory applies. It also discusses the implications for policy analysis and suggests that government programs to encourage investment may, in some cases, be inappropriate. After discussing a wide array of possible applications, we focus on one in particular: programs to encourage energy-efficient investment. The examples suggest the importance of applying the new investment theory for economic analysis of investment in energy-efficient technologies.

INTRODUCTION

In recent years, a number of economists have argued that traditional rules for choosing the appropriate time to make investments ignore important costs. Because these costs are not considered, the traditional rules advocate investing at a lower rate-of-return threshold than is optimal. The theory underlying these additional costs can be characterized as a "new" view of investment. This article describes this new theory and suggests the range of potential situations to which the theory applies. Although there is an extensive literature in this area,[1] it tends to be highly technical and the results have not been readily accessible to policy analysts. Thus, we also discuss implications of this theory for policymakers; to that end, we present two examples in the energy conservation area: energy-efficient refrigerators and commercial lighting. The examples suggest the importance of applying the new investment theory for economic analysis of investment in energy-effi-

[1] See, for example, Pindyck [1991] for a survey of this literature.

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cient technologies. Moreover, the lesson from the examples is that it may be appropriate to rethink public policy toward programs designed to encourage more rapid energy conservation investment.

When investments have the characteristics of irreversibility, uncertainty, and flexibility, then the "new" theory will suggest different investment strategies than the "old" theory. Irreversibility, in this context, means the existence of sunk costs.[2] An irreversible investment is permanent. It cannot be undone regardless of the return that ultimately is realized. Uncertainty refers to the possibility of different future returns from this investment. Because of uncertainty about future returns, the investment ex post may provide a low (possibly negative) rate of return. Flexibility means that investors have some choice about the timing of the investment. Flexibility in timing provides an opportunity to postpone the investment and see if more information comes along that helps in determining if the investment will provide a high rate of return ex post. When investments are irreversible, uncertain, and flexible, the new theory shows that a more cautious approach to undertaking investments is optimal.

In the next section, we describe this notion of caution and sketch out the model of irreversible investment under uncertainty. In the following section, we provide examples to illustrate the broad applicability of the model. Following that we consider one of the examples in more detail: energy conservation investment.

A striking finding in the energy conservation literature is the presence of high discount rates used by investors when considering investments in energy-efficient capital. We argue that the high discount rates are overstated and are at least partially attributable to the inappropriate application of traditional discounted-cash-flow analyses to investments that are irreversible, uncertain, and flexible. Next, the paper considers two conservation investments in more detail and provides empirical support for the model. The final section concludes the article.

MODELING IRREVERSIBLE INVESTMENT UNDER UNCERTAINTY

Consider an automobile manufacturer that would like to purchase a machine to make an engine block for new car engines (e.g., Wankel engines). Because these new engine blocks would be unconventional, there is no salvage value for the firm if the engine turns out to be unpopular. Output from this machine is sold at price P_t in each time period t. Because of uncertainty in demand, the output price P is random. Let us assume that prices follow a random walk in logs. In other words

$$\ln P_t = \ln P_{t-1} + \varepsilon_t \tag{1}$$

where ε is a normally distributed random variable with mean 0 and variance σ^2. If the firm uses a discount rate of ρ, the expected present discounted value of the value of output from this machine equals P_t/ρ. If the costs of the capital equipment equals P_k, then the conventional net present value rule would be

[2] Sunk costs are fixed set-up costs of investment that cannot be recouped if the piece of capital is later resold.

to invest when:

$$\frac{P_t}{\rho} = P_k \tag{2}$$

Equation (2) simply says to invest when the present discounted value of benefits (B) equals the present discounted value of cost (C).[3]

We can generalize this approach in a number of ways. First, there could be a trend in prices (either upward or downward). Second, capital costs could be uncertain. For example, random technological progress might lower the cost of the machine over time. Finally, we can introduce different assumptions about the time series property of the price. None of these modifications are significant enough to alter the basic rationale of equation (2).

However, the rule to invest when equation (2) just holds will be incorrect. The problem lies in the irreversible nature of the investment. If prices rise, then the investment will ex post turn out to be profitable. On the other hand, if prices fall, the investment will be unprofitable ex post. Despite the machine's unprofitability, the owner will be unable to "undo" the purchase. He is stuck with it—the investment is irreversible. Therefore, it behooves the potential investor to wait a bit to see whether prices will go up or down. If they go down, then the investor can forego the investment and avoid a low return ex post. If prices go up, then he can make the investment with a greater degree of confidence that the return will exceed his discount rate (which may simply reflect the return that he can earn on some other investment).

A picture may help illustrate this point. Figure 1 presents one realization of a continuous-time price that is trending upward exponentially at a rate of 5.2 percent with a standard deviation of 0.109 (as a percent of price). Although the trend is upward, there may be long periods during which the price falls or is low relative to the trend. It is optimal to delay investment until the return is sufficiently high that the investor reduces his risk of incurring a long period of low return after making the investment.

How high must the return be before it is optimal to invest? It turns out that there is a value β (>1) such that the investor should make the investment when price (P_t) has risen to the point where[4]:

$$\frac{P_t}{\rho} = \left(\frac{\beta}{\beta - 1}\right) P_K \tag{3}$$

Equation (3) differs from equation (2) by the inclusion of the bracketed term on the cost side. This term is a "mark up" over the physical cost.

To understand equation (3), consider what happens if equation (2) just held. In that case, according to the traditional net-present-value rule, which ignores the irreversible nature of the investment, the investor would be equally willing to invest today as tomorrow. If the investor waits until to-

[3] This expectation follows from taking the limit as the time interval approaches zero. Strictly speaking, one should invest when the benefits exceed the costs. Assuming we start at a price at which benefits fall short of costs, it will be optimal to invest when price rises such that benefits just equal costs.

[4] This is a standard result and is available from the authors on request. Alternatively, the interested reader should consult a source such as Dixit and Pindyck [1994].

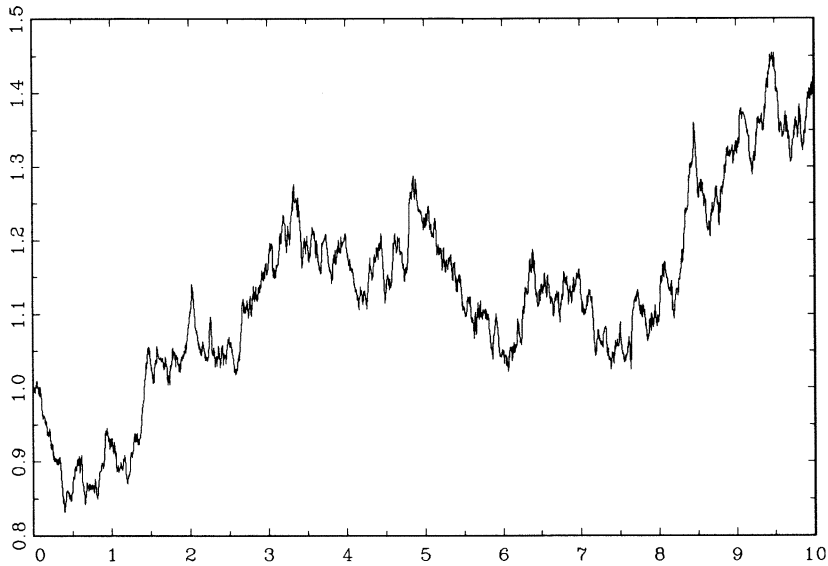

Figure 1. Sample random price process.

morrow to decide whether to invest, three things can happen. First, the output price may not change. If this occurs, then waiting and investing in the next time period is just as profitable as investing today. The rate of return on the investment equals ρ whether the investment is made today or tomorrow. Second, the price may rise. If this occurs, then waiting and investing in the next period entails a small economic cost because of foregone profits. Third, prices may fall. Should this occur, then waiting and not investing in the next period will make the investor better off than investing (and being stuck with a poor investment) tomorrow.

If the firm invests today, the assumed rate of return equals ρ. If we assume that each of the three possible future price outcomes is equally likely, then it is easy to show that the investor should postpone his investment decision. If the investment is delayed one time period and either the first or third outcome occurs, then the rate of return continues to equal ρ.[5] For the second outcome, the rate of return now exceeds ρ. The average return from these three equally likely outcomes exceeds ρ, and thus it is beneficial to wait to invest even if equation (2) just holds.

At some point, continuing to wait is no longer profitable. Although waiting increases the chances of raising the expected rate of return (benefit of waiting), this benefit comes at a cost of foregoing profitable investments if P is rising (cost of waiting). The value β in equation (3) is chosen to maximize the expected value of the investment inclusive of the *net* benefit of waiting.

Another (complementary) interpretation for the mark-up term in (3) follows from rewriting equation (3). Let $\omega = P_K/(\beta - 1)$. The term ω is a function

[5] This is true for the third outcome because if one decides not to invest tomorrow one can invest in an alternative investment and earn ρ.

of: (1) the physical cost of the investment; (2) the discount rate; and (3) the variance in future prices (contained in β). The marginal condition now becomes:

$$\frac{P_t}{\rho} = P_K + \omega \tag{4}$$

We have now split the cost of the investment into two components: the physical cost (P_K), and a second cost represented by ω. This second cost represents the cost of exercising a financial option. Before making a purchase, the investor has an option to make an investment (the new engine-manufacturing machine). Because the investment is irreversible, once the investment is made the option is no longer available. As long as the return on the investment and future capital costs are uncertain, the option has some value. Hence, part of the cost of making the investment is the value of the option that is lost when the option is killed. It is easy to show that the value of option increases when the return on the investment is more variable. This is consistent with option-pricing principles in finance; the ability to exercise an option is more valuable if there is greater uncertainty over the future state of the world.

SOME EXAMPLES OF INVESTMENT UNDER UNCERTAINTY

We have described the model in terms of an investment in physical capital. Pindyck [1988] has developed this model in detail. However, the theory is quite general and we turn now to some other examples. Consider a small hardware store that is looking to hire a new worker. Conventional theory suggests that the store owner should hire a worker if the value of marginal product equals (or exceeds) the wage rate. However, there are probably sunk costs in training the worker. Time is lost as the worker learns where parts are stored. Stocking mistakes are made and customers are annoyed by perplexed clerks. Moreover, there is some uncertainty about the overall productivity of the potential employee (even after training). Finally, the employer does not have to fill the vacancy right away. If he waits to hire, a more qualified applicant may turn up. The analysis above suggests that the store will only hire a new worker when the value of marginal product exceeds the wage it has to pay by some positive amount. The present discounted value of the difference between the value of marginal product and wage costs should just equal the cost of exercising the option to keep the position vacant a bit longer.

This analysis suggests that firms may be slow to hire workers in an economic recovery. The situation is exacerbated if wages are sticky (so that they do not fall immediately to induce the firm to hire). Bentolila and Bertola [1990] have extended this explanation to explain why firms may be slow to lay-off workers when marginal product falls or demand decreases. Firing workers entails costs (e.g., severance pay) and exposes the firm to the possibility of having to pay the sunk costs of rehiring workers should demand later increase. As a result, when worker productivity falls, firms are reluctant to fire workers immediately.

One way to picture the phenomenon described above is to imagine that there is some variable X which is random and moves up and down (call this

productivity). In the absence of any sunk costs, a firm would hire (fire) a worker when X exceeds (falls below) W, the wage. Adding sunk costs leads to a band of inaction. Productivity must fall below some lower bound ($W_L < W$) before a worker is fired and needs to exceed an upper bound ($W^U > W$) before a worker is hired. In the band between W_L and W^U firms will do nothing. Because of this band of inaction, firms may not rehire laid-off workers even if productivity returns to a level at least as high as the wage rate ($X \geq W$) where the worker was previously employed.

This failure of an economy to return to its former state (level of employment) after a temporary change in the economic environment (decline in productivity) is termed hysteresis. It has been used to explain the persistently high unemployment rate in Europe [Bentolila and Bertola, 1990] and the continuing U.S. trade deficit in response to changes in the value of the dollar in the 1980s [e.g., Dixit, 1989].

The examples considered thus far have demonstrated the reluctance of firms to make irreversible commitments because of the cost of giving up an option. Conversely, firms can also place a high value on obtaining an option. The Minerals Management Service (MMS) of the U.S. Department of the Interior administers the offshore oil and gas leasing program for the United States. During the mid-1980s, the bids received from oil companies for the right to explore and develop oil and gas resources in deep water and arctic tracts were often higher than a simple discounted cash flow (DCF) analysis of the potential oil deposits indicated. For many of those tracts, the discrepancy between bids and the valuation can be reconciled by considering the option value of an oil and gas lease.[6]

The leases sold by the MMS gave the purchaser the right to begin exploration of the tract for up to 5 years—and in some cases 10 years—after the least purchase date. If commercial oil deposits were found, the lease holder could also develop those deposits. Many of the leases purchased in deep water and in arctic environments in the mid-1980s appeared uneconomic given the existing expectations of oil prices and geology. However, when the option value of holding the lease for 5 or 10 years is factored in, these lease purchases may be profitable (in terms of expected return) for the oil companies.[7] In effect, the firm is purchasing a call option. The option has an exercise price equal to the cost of exploring the tract and expires at the end of the lease term. The underlying value of the option is the expected value of oil reserves. Unlike the previous examples, increased uncertainty (e.g., in future oil prices) makes the option more valuable and increases the amount that the bidder is willing to pay for the lease.

From a policy perspective, determining whether to account for the option value of a lease is important because the MMS is under a legal mandate to sell the leases at fair market value. One can imagine similar considerations for sales of other government assets such as licenses for bandwidth on the electromagnetic spectrum for nascent communication technologies.

A final example is the purchase of energy-efficient appliances and energy-conserving capital (e.g., wall and ceiling insulation for housing). Whether the costs of these investments are truly sunk, as with improvements to one's

[6] This section is based on the work Donald Rosenthal did while he was employed as an economist at MMS.

[7] Paddock, Siegel, and Smith [1988] have considered this issue in detail.

home, or only partially sunk, as with appliances due to the lemon's problem [namely, Akerlof, 1970], an element of irreversibility is involved in the investment. In addition, the return on the investment is uncertain. The return depends on future energy prices, which may rise or fall. Finally, there is typically some flexibility as to the timing of the purchase. In the next section, we develop this example more fully and argue that this new view of investment can help explain an energy paradox that has puzzled energy analysts for 20 years.

DISCOUNT RATES AND ENERGY CONSERVATION INVESTMENT

A striking finding in the energy conservation investment literature is the high discount rates used by investors to rationalize investments in energy-saving capital. Following Hausman's [1979] pioneering work, which found discount rates ranging from 20 to 30 percent, other researchers have found similarly high discount rates. Train [1985] summarizes the extensive literature on this subject. Discount rates for energy efficiency in refrigerators range from 40 to over 100 percent. The pattern persists for other types of investments. Discount rates for thermal integrity (e.g., wall and ceiling insulation) range from 10 to 30 percent, for space heaters from 5 to 35 percent, and so on. Train's study shows a persistently large discount rate for investments in energy efficiency.

In setting policy, it is important to determine if the high discount rates are because of short-sightedness on the part of consumers or because of capital constraints. If these explanations of high discount rates for energy conservation investment are accepted, then many will argue that government policies are needed for encouraging investment in energy efficiency. Conversely, if the reluctance to invest in energy efficient capital can be explained, at least in part, by the arguments presented in the previous section, then the case for activist government policies is less compelling.

Support for tougher policies in the area of energy efficiency remains strong. These policies can range from simply providing information as with appliance labels, to adopting tougher measures such as minimum energy efficiency standards for all new appliances. For example, the energy standards program administered by DOE was given renewed emphasis and broader scope under the recently passed Energy Policy Act of 1992 [Department of Energy, 1992]. Underlying the support for policies that mandate increases in energy efficiency is the belief that decisionmakers are somehow making the wrong choice.

When a consumer purchases an energy-efficient durable good, he or she is trading off an increased purchase price today for reduced operating costs in the future. For example, consider two air conditioners, one of which costs $400 and the other $600. The second air conditioner is expected to save $25 in energy costs per year. In effect, by purchasing the more expensive air conditioner, the consumer is making a $200 investment that pays $25 per year. If the air conditioner lasts for 10 years, the after-tax rate of return on this investment is 4.3 percent. If the consumer is indifferent between these two air conditioner options, then this rate of return corresponds to the discount rate he or she uses for investments. In general, if we have information about the trade-off between increased capital costs and decreased operating costs

(as well as information on the length of life of the appliance), we can calculate individual discount rates.

An obvious explanation for the high measured discount rates is that researchers did not explicitly incorporate the option value associated with delaying investment and that the measured discount rate is a combination of a true discount rate plus a mark-up to incorporate the option value. An econometrician observing investment behavior uses the relationship in equation (3) to determine the consumer's underlying discount rate. If the econometrician ignores the irreversible nature of the decision, then he will compute the discount rate on the basis of equation (2) rather than equation (3). If $\tilde{\rho}$ is the measured discount rate from equation (2), this measured rate will be biased upward; consumer discount rates will look unusually high. The relationship between the true discount rate and the measured rate is given by

$$\tilde{\rho} = \left[\frac{\beta}{\beta - 1}\right] \rho > \rho \tag{5}$$

One interpretation of the higher discount rates measured by researchers in the past is that they are measuring $\tilde{\rho}$ rather than ρ.[8]

At this point, it is probably useful to consider alternative explanations for the high measured discount rates in the literature before settling on the irreversible investment view. We then turn to estimating $\tilde{\rho}$ for two conservation technologies to consider the importance of irreversibility.

One explanation that has been put forward is that investments in conservation capital are risky and that discount rates should be adjusted upward as a result. In a standard neoclassical model of investment when the return is known with certainty, theory indicates that returns across all investments should be equalized. Once risk is considered, the return on investments can be explained through a theory such as the Capital Asset Pricing Model (CAP-M). The CAP-M model says that the return on an investment relative to the market return should be positively correlated with the stock's beta, the sensitivity of a stock's price to market volatility.[9] Allowing for risk only makes the high discount rates even more puzzling. High energy prices are negatively correlated with the stock market (e.g., Standard and Poor's 500).[10] However, returns on energy efficient appliances are higher when energy prices rise. Hence, the beta on energy investments is negative and people should be willing to accept a lower than market return on energy efficiency investments in return for the ability to reduce risk in their overall portfolio. We must turn to some other explanation of high discount rates.

One possibility is that consumers are constrained in capital markets. They might like to purchase the most efficient appliance in the store but simply cannot borrow enough money to finance the purchase. There are two problems with this theory. First, consumers often purchase appliances on credit. The additional cost of purchasing an energy-efficient appliance is small relative to the overall cost of the appliance. This fact suggests that the appropriate discount rate would be the cost of financing the purchase. This suggests

[8] Summers [1987] provides support for this view in an analysis of corporate investment.

[9] Sharpe [1964] and Lintner [1965] are early proponents of beta.

[10] The correlation between 1953 and 1992 of the Standard and Poor's 500 index and the CPI household fuel and other utilities index is −0.28. Its β equals −0.093 with a t-statistic of 1.90.

that the correct discount rate would be about 18 percent (nominal), not 25 to 100 percent as documented by Train [1985]. A second problem with this explanation is the existence of high discount rates for high-income people in the empirical work. Hausman [1979], for example, estimated a discount rate of 17 percent for households with income of roughly $62,000 in current dollars. Capital market constraints seem an unlikely explanation for high discount rates for this income group.

A second explanation is that consumers are simply short-sighted and do not take account of the future benefits that they will receive by investing in energy efficiency.[11] For example, Hirst [1986–1987] writes "In actuality, people do not think in terms of the time value of money" (p. 59). Although this argument may have an element of truth, it is difficult to accept as the entire explanation. People make intertemporal trade-offs all the time (Do I go to college? Should I rent or purchase a home?). To argue that people simply do not make intertemporal trade-offs rationally is to beg the larger question of how they do make trade-offs.[12]

The discussion surrounding equation (5) provides an alternative explanation of this paradox. Rather than measuring ρ, the true discount rate, econometricians and other analysts may be measuring $\tilde{\rho}$, which is a combination of the true discount rate and the option value to delaying investment.

TWO CONSERVATION TECHNOLOGIES

In this section we provide some illustrative calculations of the investment decision for two technologies: energy-efficient refrigerators, and commercial fluorescent lighting. We selected these technologies because their use could significantly reduce U.S. energy consumption. Lower energy consumption is required in order to meet President Clinton's Earth Day 1993 commitment of returning U.S. greenhouse gas emissions to 1990 levels by the year 2000. Reducing greenhouse gas emissions, including carbon dioxide emissions associated with burning fossil fuels for energy, is essential for reducing the risk of global warming.

In October 1993, President Clinton announced the *Climate Change Action Plan*, which identified a series of policy actions for reducing greenhouse gas emissions. A key component of the plan was using energy-efficient lighting in commercial and residential applications. Some of this lighting would be installed in new buildings; however, the majority of the applications would be retrofits of existing lighting systems.

In the case of a retrofit, the investor has considerable latitude regarding when to install the new, energy-efficient lights. The same latitude exists regarding when to replace a refrigerator model. In both of these cases, the rate of diffusion of the new technologies is influenced by when individuals decide to retrofit their older models. Given the emphasis placed by the United States on the diffusion of new technologies as a way to mitigate the

[11] A related explanation is that consumers do not have reliable information about the level of savings they can expect. Extensive information programs and experience with conservation investments in the marketplace reduce the plausibility of this argument.

[12] Moreover, once irrationality has been introduced there is no reason to expect investors to delay investment. They might also irrationally respond to seductive advertising that makes wild claims for the benefits of a conservation technology and invest more rapidly than is optimal.

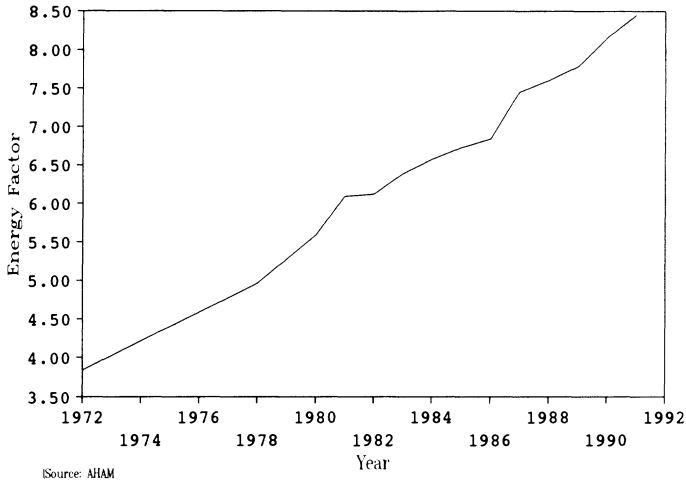

Figure 2. Energy efficiency for refrigerators.

right of global warming, it is important to understand the economic principles underlying retrofit decisions.

Energy-Efficient Refrigerators

Considerable progress has been made in energy efficiency in refrigeration since the early 1970s. Figure 2 shows the steady growth in energy efficiency for refrigerators over this period. We define the energy factor as the amount of space that can be cooled per unit of electricity per day. For example, an energy factor of 4 indicates that 4 cubic feet can be cooled for one day by one kilowatt-hour of electricity. The energy factor has grown at an annual rate of 6.2 percent between 1972 and 1991. During this time refrigerator prices have fallen slightly. Figure 3 presents the producer price for refrigerators between 1967 and 1990. If we do not control for changes in energy efficiency in refrigerators, the real price of refrigerators has fallen 1.6 percent per year.[13]

Adjusting for refrigerator quality arising because of increased energy efficiency, real prices have decreased even further. To give a sense of the decrease in prices, we have included a second price line in Figure 3. We take the level of energy consumption for a 20-cubic-foot refrigerator in 1978 as the base and subtract from the producer price the present discounted value of energy saved as refrigerators become more efficient in subsequent years.[14] By this measure, the real price of refrigerators has fallen at an annual rate of 4.4 percent. This is conservative because gains in refrigerator efficiency began well before 1978.[15]

[13] Nominal price is the producer value of shipments from the Current Industrial Reports divided by shipments. We then convert this into real 1982–1984 dollars using the CPI deflator. We thank Jim McMahon at the Lawrence Berkeley Laboratory for providing us with these data.

[14] We assume a life for the refrigerator of 10 years and a discount rate of 16 percent. We also assume a constant mark-up for refrigerators of 56 percent. Hence, we reduce the producer price by 1/(1.56). Our mark-up comes from the ratio of the average consumer price of refrigerators divided by average producer price in the LBL data.

[15] Gaps in our data prevent us from starting the adjustment in 1972.

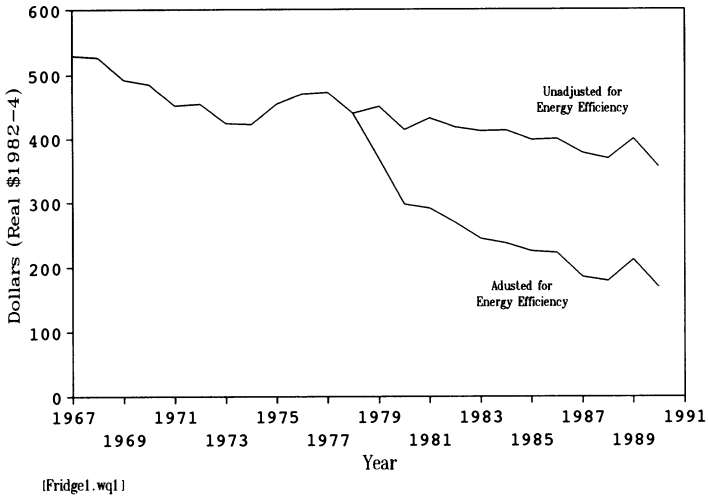

Figure 3. Producer price of refrigerators.

At the same time that refrigerator prices were falling, residential, electricity prices were first rising and then falling, with a peak in 1984 (see Figure 4). Looking at the period between 1978 and 1991, there is almost no trend in electricity prices (0.6 percent per year real).

If consumers in the 1970s and 1980s had been able to predict the mean and variance of the price distributions for electricity and refrigerators, they would have concluded that electricity prices (and hence the return on an investment in an energy efficient refrigerator) would be roughly constant (though exhibit variation over time), while refrigerator prices would be falling. The return per dollar invested (electricity price divided by the quality-adjusted refrigerator price) would be rising over time at a rate of 5.2 percent per year and would vary about 11 percent per year.

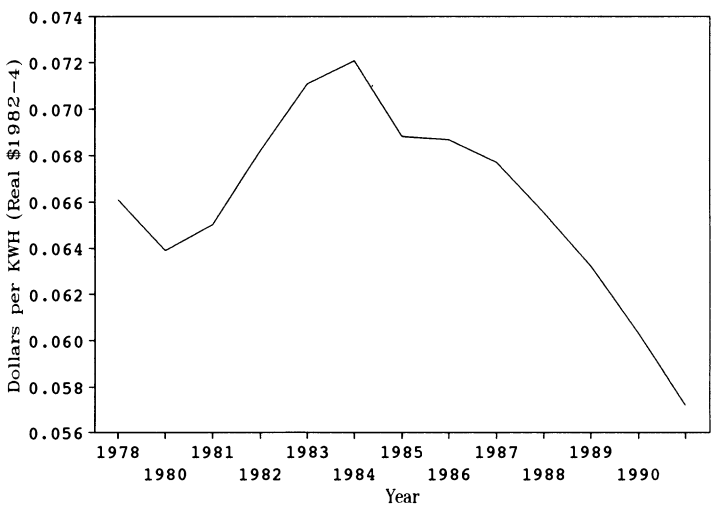

Figure 4. Residential electricity prices.

Based on these parameters values, we compute a value of β equal to 1.678 and a value of $\beta/(\beta - 1)$ of 2.48.[16] The expected present discounted value of the return on an energy conservation investment in a refrigerator (i.e., the hurdle rate) has to be roughly 2.5 times as large as it would if there were no uncertainty in the price of electricity or refrigerators. To make the point slightly differently, if the true real discount rate is 5 percent, then the measured discount rate ($\tilde{\rho}$) would be 11.6 percent.

Fluorescent Lighting

Lighting technology, especially in commercial buildings, has undergone a revolution during the last decade. Compared to the existing T-12 fluorescent lights and magnetic ballasts used in most commercial buildings, new T-8 fluorescent lights with electronic ballasts reduce energy consumption by approximately 65 percent. In addition to saving energy, the new T-8 lights have a better color spectrum. The energy savings from these new lights are significant for the commercial sector because lighting accounts for approximately 40 percent of electricity consumption in commercial buildings.

To spur the adoption of T-8 lights and electronic ballasts, the Environmental Protection Agency (EPA) sponsors the "Green Lights" program. Green Lights "partners" sign a contract with EPA in which they agree to proceed with lighting system upgrades when the rate of return from the upgrade equals or exceeds the prime rate plus 6 percent. With the prime rate currently at 7.25 percent (late May 1994) Green Light partners are obliged to invest in upgrades when the rate of return equals or exceeds 13.25 percent (nominal).

From the previous discussion, it is apparent that this prime rate plus 6 percent rule is not optimal for the Green Light partners. The rate of return that must be earned in order to invest in a lighting upgrade is given by equation (5). That equation shows that the required rate of return is affected by trends in energy prices, trends in the price of new lighting capital, energy price uncertainty, and uncertainty in the price of new lighting capital. Although we do not have detailed data on price trends for fluorescent lights, the informal data we do have indicates that, during the last decade, the quality-adjusted price of lights has fallen more rapidly than the price for refrigerators. This suggests that properly accounting for uncertainty and irreversibility could significantly affect investments in new lighting technologies.

Table 1 presents a set of adjusted discount rates as a function of different values of parameters affecting equation (5). These discount rates can be viewed as the hurdle rates Green Lights partners should use. Alternatively, they can be interpreted as the discount rate researchers studying energy investments would measure if they ignored uncertainty and irreversibility.

[16] The formula for β is as follows:

$$\beta = \frac{0.5\sigma_0^2 - \alpha + \sqrt{(0.5\sigma_0^2 - \alpha)^2 + 2(\rho - \mu_k)}}{\sigma_0^2}$$

where α is the trend in the ratio of return per dollar invested, μ_k the trend in refrigerator prices, and ρ the discount rate. We set ρ equal to 0.05.

Table 1. Adjusted discount rates.

Trend			$\rho = 0.05$		$\rho = 0.10$	
α_E	α_R	σ_0	β	$\tilde{\rho}$	β	$\tilde{\rho}$
0.006	−0.044	0.109	1.668	0.116	2.377	0.168
0.006	−0.044	0.055	1.756	0.108	2.627	0.158
0.006	−0.044	0.218	1.476	0.143	1.932	0.201
0.040	−0.044	0.109	1.082	0.172	1.601	0.200
−0.033	−0.044	0.109	3.385	0.085	4.321	0.140
0.006	0.000	0.109	2.701	0.076	3.901	0.132
0.006	−0.088	0.109	1.397	0.161	1.853	0.210

This table reports values for β and the adjusted discount rate ($\tilde{\rho}$) for different parameter values. It assumes that the standard deviation of log refrigerator prices is 0.049. The parameter σ_0 is the standard deviation of the log of the ratio of electricity to refrigerator prices. The parameter α_E measures the trend in electricity prices and α_R measures the trend in capital prices.

The top row of the table provides the base case used in the refrigerator example for a true real discount rate of 5 percent and 10 percent. In the former case, the estimated real discount rate would be 11.6 percent, and in the latter case 16.8 percent. The estimated discount rate is more than double the true rate if ρ equals 5 percent and is 70 percent higher if ρ is 10 percent. The next two rows of Table 1 consider how altering the variation in the price data affects the measured discount rate. With a doubling of σ_0, the option value of waiting increases and the measured discount rate increases from 11.6 percent (16.8 percent) to 14.3 percent (20.1 percent) if ρ equals 5 percent (10 percent). Halving σ_0 has little effect on the measured discount rate. Increasing the trend in electricity prices (α_E) also increases the value of waiting and the measured discount rate can be two to three times the true discount rate. Varying the trend in capital prices (α_R) also affects the measured discount rate with more rapid decreases in capital prices causing higher adjusted discount rates.

Although discount rates are substantially biased upward when irreversibility and uncertainty are ignored, we have not completely explained the high discount rates estimated in the literature. The results of this section suggest, however, that a large fraction of the high rates can be explained by irreversibility.

A *conservative* hurdle rate to use for Green Lights partners can be calculated by assuming the α_R parameter for lighting is the same as for refrigerators: $\alpha_R = -0.044$. If their true discount rate is given by the current (as of May 1994) prime rate less an assumed inflation rate of 3 percent—4.25 percent—then the proper hurdle rate for lighting upgrades is 10.8 percent real, or 13.8 percent nominal. The prime plus 6 percent rule is commonly thought of as allowing a generous margin for error in lighting investments; in fact, this example suggests that the rule will result in suboptimal, premature upgrades: The prime plus 6 rate equals 13.25 percent while the optimal rate is 13.8 percent. The actual value for the hurdle rate will depend on investors' expectations of α. More work is needed to determine the value of this key parameter.

CONCLUSIONS

In this article we have described the new view of investment that has been popularized by Dixit, Pindyck, and others. We argue that there are a large number of situations to which the theory applies, and have discussed one area (energy conservation investment) in some detail. Several policy issues raised by the theory are worth mentioning at this point.

First, policymakers attempting to encourage investment may in fact exacerbate slow rates of investment through prolonged policy discussions of various investment incentive options. Entertaining and discussing a wide range of investment inducements may increase the uncertainty surrounding the returns from or costs of investment and lead to increased delay. Similarly, frequently reopening discussion of specific incentives can also increase return or cost uncertainty.[17] Second, what appears to be suboptimal investment behavior (low take-up of energy-efficient appliances and other investments in energy conservation capital) may in fact be optimal from the individual's point of view. If so, many government programs to encourage investment in energy conservation may, in some cases, be misguided. Third, explicitly measuring option value (either on the benefit or the cost side) will help the government in fair pricing of many types of assets that the United States government wishes to sell.

Although the mathematics of specific option pricing applications may be daunting, the underlying concepts are not. The reluctance of investors to jump at new investment opportunities is, in many cases, consistent with a sophisticated intertemporal investment strategy. Decisionmakers do not have to understand the mathematics behind this strategy explicitly in order to employ it. Investors who commit too soon only to have prices later drop are taught the benefits of maintaining options.

Policymakers, on the other hand, need to understand the fundamental concepts behind the new investment theory. Those in a position to influence policy often do not have the benefit of years of investing experience in a certain industry or technology behind them. In the absence of such experience, it is tempting to employ simplistic economic models such as discounted cash flow (DCF) analysis to see if there are "barriers" to investment. A naive DCF analysis, which ignores the benefits of maintaining options and the corresponding high hurdle rates needed to justify investment, might incorrectly include government actions or policies to spur investment are needed. These policies, while well intentioned, might do more harm than good.

There is no simple formula or rule for determining how much the results of a simplistic DCF investment analysis will change when it is recast in a new investment theory framework. Policymakers should be alert for the three characteristics of investments on which this new theory hinges: irreversibility, uncertainty, and flexibility in the timing of investments. When these characteristics are present, careful analysis that accounts for the value of maintaining options is needed before policies aimed at removing barriers to investment can be justified.

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[17] Hassett and Metcalf [1994] explore this issue in some detail.

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GILBERT E. METCALF is Assistant Professor of Economics at Tufts University.

DONALD ROSENTHAL is an Economist with American Management Systems.

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