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FOR EVALUATING TECHNICAL INNOVATION AND DIFFUSION:
THE CASE OF ELECTRONIC BALLASTS FOR COMMERCIAL BUILDINGS**

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**A DECISION ANALYTICAL FRAMEWORK
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THE CASE OF ELECTRONIC BALLASTS FOR COMMERCIAL BUILDINGS**

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Abstract: We present a decision analytical framework for studying the decision to purchase new energy-efficient magnetic ballasts for commercial buildings as a special case study for understanding the decision environment that could either encourage or retard the penetration of new carbon-saving technologies. The framework is particularly germane to situations where uncertainty in the investment outcome prevails as a dominant dimension of the problem. It allows the policy analyst to consider policies that operate through other considerations than through the price alone. A key effect is how a policy will either truncate a probability distribution to remove the worst outcomes or cause the probability distribution to narrow. Such considerations appear important when studying information programs, vendor warranty, and other factors that condition the investment decision.

INTRODUCTION

Technical innovation and diffusion lies at the core of future efforts to control future greenhouse gas emissions. Incorporating such considerations into policy modeling has proven to be a significant challenge. Aggregate modeling such as found in many integrated assessment analytical frameworks often represents innovation and diffusion implicitly through aggregate parameters. Detailed technology-based analysis distinguish between technology types but does not incorporate the important decision environment that often conditions the investment opportunities.

Over the last several years the Energy Modeling Forum has been engaged in several long-term efforts to improve the policy modeling of climate change responses. The Forum completed a major review of aggregate modeling of the costs associated with abating carbon dioxide emissions (EMF 12; see Weyant, 1993, and Gaskins and Weyant, 1993) and is in the process of comparing the available integrated assessment models for evaluating the costs and benefits of emissions reduction (EMF 14). During this time, the Forum also conducted a major examination of the so-called "bottom up", technology-based frameworks used for analyzing the potential energy savings and investment costs for specific technology types (EMF 13 1996). And finally, the Forum completed a major review of the previous methodologies that have been developed to study investment, innovation, and diffusion in the economics and finance literature (Huntington et al, 1994).

This paper reports on the second stage of this last effort to evaluate the vastly growing literature on technology issues. While individual technologies differ greatly from each other and thereby make the widespread application of a single approach suspect in this area, we concluded from the first-stage review that a careful evaluation of the decision analytical approach to

technology choices was warranted. We develop here a few basic "building block" frameworks to demonstrate the type of insights that such modeling might be capable of generating. This approach demands technology detail that will probably make it impractical to incorporate directly into large-scale integrated assessment frameworks. Nonetheless, it generates a number of useful ways to consider the technology issues and can therefore serve to augment existing aggregate modeling of the greenhouse gas problem. Moreover, we show that it is capable of examining a number of different policy options that extend well beyond the traditional price mechanisms, so often the only policy that can be directly analyzed by existing integrated assessment frameworks.

The paper focuses on a particular technology choice about the type of electronic ballast to use in commercial sector fluorescent lighting. The next section highlights several key insights about how the decision environment can influence the incentives for all decisionmakers, regardless of their attitude towards risk. This section uses simple examples of a risk-neutral decisionmaker to demonstrate how changes in information or in vendor-provided warranties significantly alter the economics of technology choice without changing either the equipment costs or the value of energy savings. Section III then applies a more comprehensive evaluation of the decision that incorporates differing risk attitudes. Section IV concludes with a brief assessment of how future modeling of this type might proceed.

Decisions Based Upon Deterministic NPVs

We focus on the choice of magnetic ballast for fluorescent lighting in commercial sector buildings. The decision involves replacing an older aluminum ballast in a fluorescent light fixture with a newer and more energy efficient copper ballast. The ballast controls the turning on of the

light bulb. It does not affect the quality of the light, which is determined by the fluorescent light bulb. Therefore, the building owner and tenants are not buying a different product with dissimilar attributes, as sometimes happens when more energy-efficient equipment replaces older technologies.

The dollar amount for each ballast appears small, particularly with reference to the large expenditures required for new carbon-free energy supply sources often discussed in the context of the global climate change problem. However, the technology is an interesting one to study because its attributes are well known and have been evaluated by Koomey et al (1994, 1995). Moreover, the investment is likely to be a decision to replace or install hundreds of ballasts throughout a building at one time, and this investment is likely to be multiplied many times over as each building owner considers the installation of the new units. While the example is conducted at the per unit level for simplicity, it should be clearly understood that actual investments involve considerably larger expenditures.

New energy-efficient copper ballasts for fluorescent lighting appear to reduce substantially the required energy usage in lighting commercial buildings versus the older aluminum ballasts. Koomey et al (1994, 1995) find the reluctance to purchase newer ballasts puzzling in light of its apparently favorable economics. Customers need only to spend an additional \$4.40 per ballast to generate extra electricity savings of \$2.15 per year. Over an infinite time period, the implied discount rate would be $\$2.15/\4.40 , or about 49%. The copper ballasts appear to pay for themselves in slightly more than two years.

The above computations are based upon a deterministic net present value calculation in which all outcomes are certain. This approach often forms the core of "bottom up" economic analyses of competing technologies of varying energy efficiencies. The point of interest here is

to examine how these estimates might change by introducing uncertainty into the decision. Uncertainty could have two separate effects. First, risk-averse customers would prefer to avoid particularly bad outcomes that generated very low energy savings relative to the initial purchase price of the ballast, even if those outcomes are very unlikely. And second, even if customers were risk neutral--equating any dollar saved or lost--they might prefer to avoid situations where the sunk costs of the initial investment make it impractical to shed the investment quickly or inexpensively should the actual energy savings realized after the uncertainty is resolved be substantially less than the expected savings prior to the resolution of the uncertainty. Under some conditions, these incentives could provide a rationale for waiting or delaying the investment until more information could be collected and assimilated.

Table 1 summarizes the important economic considerations in choosing between the two ballasts. Purchasing and installing the new energy-efficient copper ballast involves an initial expenditure of \$15.40 per ballast compared to \$11 for the standard aluminum ballast. Energy savings from the copper ballasts average 8 percent relative to the aluminum ballasts. Koomey et al estimate that an 8 percent saving corresponds to 29 kWh/year when the ballast is operated 2600 hours per year. Therefore, the standard technology uses 362.5 kWh/year, at a rate of 0.139 kWh/hour. Electricity prices are assumed to remain at 7.4 cents per kiloWatt-hours (kWh), or approximately the 1995 average U.S. (for the nation) commercial sector electricity price. There is no upward trend in electricity prices in this base formulation, although an annual positive or negative trend can easily be incorporated. The two options are assumed initially to last 15 years each and are evaluated with an 8% real discount rate, i.e., after adjusting for price inflation.

Ignoring uncertainty, commercial customers appear to be leaving almost \$14 per ballast on the table each time they decline to invest in the copper rather than the aluminum ballast. This

Table 1: Cost and Operating Characteristics of Competing Magnetic Ballasts

	Baseline Assumptions	Standard	Efficient	Difference
Energy use		362.5	333.5	-29
Energy\$/year		(\$26.83)	(\$24.68)	\$2.15
Energy\$ total (PV)		(\$229.61)	(\$211.24)	\$18.37
Equipment\$		(\$11.00)	(\$15.40)	(\$4.40)
Total\$		(\$240.61)	(\$226.64)	\$13.97
Discount rate	8%			
kWh savings (%)	8%			
kWh savings/year	29			
Periods (years)	15			
Price (cents/kWh)	7.4			

estimate is the net present value of the investment produced by a stream of certain energy savings over 15 years at an initial incremental cost of \$4.40 per ballast. In the absence of any market failures in the ballast market, it is also a direct estimate of the costs associated with market barriers that cause the investment not to be undertaken.

In this analysis, we do not attempt to argue whether these additional costs are justified. If policy can reduce these costs to society without imposing costs elsewhere, this wedge can legitimately be viewed as a market failure justifying government intervention that costs no more than \$13.97. If policy can reduce these costs to the individual customer only by imposing costs on other parties, this wedge should be viewed as a market barrier that is often found as a hidden cost in markets where transactions are costly. For example, a utility-sponsored rebate will reduce the cost to customers qualifying for a program by reallocating money away from other customers paying the utility's rate. Unless the program reduces the costs to other future investors by demonstrating the merits of the new technology, the rebate will not reduce societal costs.

Aggregate models of climate change project energy demand on the basis of energy prices, economic output, and exogenous parameters for technological progress. Only policies that affect energy prices can be evaluated. The framework described above adds several other dimensions of interest to policymakers, including rebates for the purchase of new equipment or information programs and equipment warranty plans that affect uncertainty in the decision. The following analysis demonstrates several of these possibilities.

Decisions With Energy Price Risks

Consider initially the possibility of obtaining more reliable information about future energy prices. Many economists have focused on this issue by developing models that estimate the option value for delaying an investment (Dixit and Pindyck, 1994). The fundamentals of this option value are that customers can wait a period to learn more about future energy prices (Hassett and Metcalf, 1993). If the price remains favorable to the investment, the customer can invest after having reduced the chances of an unfavorable outcome. If the price turns unfavorable during the year, the customer can scrap all plans for investing and thereby avoiding the costs of a bad outcome. Fundamental to this example is the possibility that delay can produce more reliable information and that the investment cannot be easily scrapped. In addition, the investor must have the ability to delay the investment, as would happen if he could block other investors from realizing the energy savings in his building.

Although energy prices are often discussed as a source for the option value associated with energy-using equipment, our example suggests that they have minimal effects on the magnetic ballast under consideration here. This observation may not generalize to other investment opportunities in energy-using equipment. However, the economics of this decision in a deterministic environment are so favorable for choosing the new energy-efficient unit that customers are unlikely to delay their decision on the basis of uncertainty about energy prices alone.

Table 2 outlines the problem when uncertainty about energy prices is incorporated. For simplicity, we have ignored the issue of postponing the investment a year and focus instead on the effect of obtaining more reliable information on electricity prices. Despite this simplification, the essence of the problem is the same as that analyzed in terms of the option value associated

Table 2: Energy Price Risks and the Magnetic Ballast Decision

Probability	%variation in price from base	Price	Risk-Neutral		Risk-Averse	
			Costs w.o. Info	Costs w. Info	Utility w.o. Info	Utility w. Info
0.005	-90%	0.0074	-2.56	0.00	2.60	2.77
0.005	-85%	0.0111	-1.64	0.00	2.66	2.77
0.005	-80%	0.0148	-0.73	0.00	2.73	2.77
0.005	-75%	0.0185	0.19	0.19	2.78	2.78
0.03	-50%	0.037	4.78	4.78	3.03	3.03
0.25	-20%	0.0592	10.29	10.29	3.27	3.27
0.4	0%	0.074	13.97	13.97	3.40	3.40
0.25	20%	0.0888	17.64	17.64	3.52	3.52
0.05	50%	0.111	23.15	23.15	3.67	3.67
1						
Costs:						
Mean			13.85	13.87	13.51	13.56
Gain			0.02		0.05	
Utility:						
Mean					3.38	3.39

Log-utility function used to represent risk aversity.

$U = \ln(X+16)$ where $X = \text{costs}$

with delaying an investment. If the economics remain favorable after the uncertainty is resolved, the customer will continue to invest in the new technology. The net benefit will be the same as when the information is not available. However, if the economics should turn unfavorable after the uncertainty is resolved, the customer will decide against the investment, choose the standard ballast, and replace those outcomes with a negative cost with a zero net benefit. In this way, he sheds negative costs but retains positive gains.

As observed in the table, energy prices need to fall by more than 75% of the base value before they change the decision of whether to invest in the copper ballast or not. For smaller declines (as well as for any increases), the customer should remain with his decision to buy the energy-efficient unit. Table 2 also shows a probability distribution showing the likelihood that energy prices will increase or decrease by any given percent. This distribution has been arbitrarily chosen but is based upon the assumption that 90% of the observations should lie in the range of -20% to +20%. If the distribution were normal (which it is not), such an assumption would imply a standard deviation of about + or - 12.5% ($20\%/1.6$). The actual distribution has been chosen for ease of presentation rather than to conform to any known distribution such as a normal one.

If the customer could obtain perfect information about future electricity prices under the conditions described above, his expected costs would decline by about 2 cents per ballast (shown in the row "Gain" under the middle set of columns). This gain or increase in value generated by reliable information is due entirely to the customer's ability to refrain from investing in the energy-efficient ballast if energy prices should be extremely low. If energy prices do not fall by more than 75%, the customer will invest in the new energy-efficient ballast as he would have done without the information. If prices fall by more than 75%, the customer switches to

the standard aluminum ballast, incurring a net cost (relative to the standard choice) of \$0. In the example, there is a relatively low probability that energy prices would fall by 75% or more, and thus, the value to the customer of having the uncertainty about future energy prices resolved before he makes a decision is not very great. Note that changes in the electricity price affect the future energy savings (the paybacks) equally in all years. Both near-term and far-term savings (prior to discounting) are reduced by the same percentage.

Energy Price Risks and Risk-Averse Decisionmakers

It is important to consider how a risk-averse customer might respond under these conditions. The logarithmic utility function, where a customer equates utility equal to the logarithm of the net benefits of the decision, is a relatively basic formulation that introduces declining marginal utility of income and is widely used in analytical models of risk-averse decisionmakers. If X is income and $U = \ln(X)$, then $dU/dX = 1/X$. Since logarithms of a negative number are undefined, we have scaled the argument (X) in the utility function $U = \ln(X)$ to remain positive under all conditions. The maximum loss from investing in the copper ballast (relative to the standard unit) occurs when the customer spends an additional \$4.50 above the cost of a standard unit and the unit is immediately inoperative. In this case, he receives no energy savings and must pay an additional \$10 to replace it (see the discussion below on this latter point). Thus, we added \$16 (\$14.40 + a minimal amount) to the net benefits to ensure a positive argument under all conditions.

Table 2 also includes the computations relevant to a customer who possesses the logarithmic utility function described above. Risk-averse customers value any avoided bad outcomes more highly than risk-neutral customers. The value of perfect information about future

electricity prices rises from 2 cents per ballast for the risk-neutral individual to 5 cents per ballast for the risk-averse one. The latter figure is the change in the certainty equivalent benefits resulting from the better information. Certainty equivalents are calculated from the inverse of the utility function described above. Despite the higher valuation by the risk-averse customer, the overall effect of resolving electricity price uncertainty remains minimal.

Ballast Reliability

The almost singular focus on energy price uncertainty appears misplaced, compared to other potential uncertainties that are likely to operate in this decision. Some initial reports on energy-efficient ballasts emphasized that the technology was plagued by serious reliability problems when they were first introduced (Piete et al., 1989). Newer units often failed prematurely, causing the investment payback period to shrink compared to that for the standard ballast. Although these reliability problems were experienced with electronic ballasts rather than magnetic ones (which today are very reliable, according to technology experts), the important consideration is how the customers view the product's reliability. If they possess the same knowledge that the experts have, reliability may not be an important consideration. If they are reluctant to invest because they or their colleagues in other buildings had bad experiences with "energy-efficient ballasts" in the past, reliability becomes substantially more important. It seems reasonable to assume that commercial building owners or renters do not generally differentiate between whether a ballast is magnetic or electronic and that the potential to confuse the reliabilities of the two ballast types is a very real possibility.

A comparison of two investment options with dissimilar payback periods (standard versus energy-efficient units) introduces a number of complexities that can obscure the fundamental

economic issues. To avoid these problems and to focus on key insights, we simplify the problem considerably. When a copper ballast fails, it is assumed that the customer replaces it with a standard aluminum ballast. Under these conditions, the investor foregoes any future net energy savings (relative to the standard unit) once the new copper ballast fails. We ignore the purchase cost of a new standard (aluminum) ballast as well as any effects on energy costs after the 15th year. However, it seems reasonable to assume that the commercial building owner will incur some additional installation expenses in replacing the failed copper with an aluminum ballast. When making the initial investment, the owner is likely to be considering a building-wide program of replacing standard with energy-efficient ballasts. This situation allows him to experience considerable economies of scale spread over many units rather than a single ballast. Such economies of scale are unlikely to operate when the owner must replace a ballast as it fails. Unscheduled replacements are almost always likely to be more expensive than scheduled maintenance.

To incorporate the additional costs of unscheduled maintenance, it is assumed that the owner must pay an additional \$10 for each ballast that must be replaced within the first five years. This extra \$10 cost could result from increased labor costs for the unscheduled installation and can be viewed as a negative scrappage value for equipment in place. Traditionally, investment analysis must incorporate any resale value of the equipment being replaced. In the lighting example, a failed ballast has a zero resale value (which appears reasonable), but in addition, the investor must also incur an additional cost to continue receiving lighting services. The later in this five-year period the ballast fails, the lower will be this replacement cost in present value terms due to the effects of discounting.

Table 3 outlines the investment decision under these new conditions. The probability distribution describing the customer's uncertainty about the number of years of service for the copper ballast is shown in the far left column. Although arbitrary, this distribution appears reasonable for a new technology. About 60% of the outcomes fall within a duration period of 6 to 20 years. In the customer's mind, there exists about a 10% chance that the copper ballast will fail within the first five years. The expected mean life of the energy-efficient ballast is 15 years, as in the previous examples above.

The investment payoff per ballast falls from \$13.97 in the completely deterministic case to \$10.22 under the new conditions described above, based upon an 8% discount rate. While this decline in value is not sufficient by itself to explain the customer's reluctance to invest in the new ballast, it strongly suggests the sensitivity of any net present value calculation to the uncertainty surrounding equipment reliability. If the customer could avoid any negative payout (relative to the standard technology) due to premature equipment failure problems, he would be better off by \$1.89 per ballast because the investment would now be worth \$12.11. This example demonstrates not only that reliability problems may substantially reduce the expected benefits of an investment in such a technology but also that efforts to minimize the impact of perceived problems in equipment reliability may be very worthwhile pursuing.

One approach for reducing the customer's concerns about reliability would be to guarantee that the customer would be fully compensated for any early failure problems. Vendor-provided warranty programs that relieve the customer of any expenses for repairing or replacing failed equipment were developed precisely for this reason. If there were vendors or other energy-efficiency experts who had a more optimistic assessment of the equipment's duration, it presumably would pay them to offer warranties that isolated customers from the worst cases.

Table 3: Reliability and the Ballast Decision for Risk-Neutral Agent

Probability	Duration	Customer's Costs w.o. Info	Costs w. Info	Probability	Expert's Costs w.o. Info	Costs w. Info
0.05	0	-14.40	0.00	0.02		
0.05	1	-11.67	0.00	0.02		
0.05	2	-9.15	0.00	0.02		
0.05	5	-2.64	0.00	0.02		
0.15	10	10.00	10.00	0.25		
0.25	15	13.97	13.97	0.34		
0.2	20	16.67	16.67	0.25		
0.15	25	18.51	18.51	0.04		
0.05	32	20.14	20.14	0.04		
1				1		
Costs:						
Mean	15	10.22	12.11	15.04	12.21	12.96
Gain			1.89			0.76

Table 3 also shows in the last full column of numbers another probability distribution for equipment failure that presumably might be more like that for the vendor or someone else knowledgeable about the technology. By substituting his narrower distribution for the customer's wider one, the expert essentially reduces the cost of accepting the possibility of early equipment failure. The expert expects that perfect information will raise his net payout per ballast from \$12.20 to \$12.96. Viewed differently, the expert incurs a net opportunity cost (decline in benefit) of \$0.76 per ballast by accepting the early-failure risks rather than waiting to resolve the uncertainty about equipment reliability. With the expert's opportunity cost (\$0.76 per ballast) being less than the customer's willingness to pay for protection for such risks, it only remains for the expert and the customer to find some common ground between their two valuations for negotiating an agreement.

Concerns about premature failure have a much larger impact on the investment's payoff in the ballast example than do concerns about future energy prices. Lower energy price reduce energy savings in all years equally. Equipment failure completely eliminates energy savings for all years after the date of failure. When failure occurs early in the investment period, the effects on the investment return can be dramatic, turning an apparently attractive investment into a loss.

Avoiding reliability problems is even more beneficial when the customer is risk averse rather than an expected return investor. Table 4 repeats the cost computations for the risk-averse customer. Under these conditions, the customer would raise his willingness to pay from \$1.89 in the risk-neutral case to \$5.62 in the risk-averse case. Even if the expert should have an identical reluctance to accept risk (which appears unlikely), his higher opportunity cost to accept these risks (\$2.52 per ballast) is still well below the customer's willingness to pay (\$5.62 per ballast). Opportunities to transfer the risk while benefitting both parties remain.

Table 4: Reliability and the Ballast Decision for Risk-Averse Agent

Probability	Customer's Utility w.o. Info	Utility w. Info	Probability	Expert's Utility w.o. Info	Utility w. Info
0.05	0.47	2.77	0.02		
0.05	1.47	2.77	0.02		
0.05	1.92	2.77	0.02		
0.05	2.59	2.77	0.02		
0.15	3.26	3.26	0.25		
0.25	3.40	3.40	0.34		
0.2	3.49	3.49	0.25		
0.15	3.54	3.54	0.04		
0.05	3.59	3.59	0.04		
1			1		
Utility:					
Mean	3.07	3.30		3.26	3.35
Equiv Cost	5.52	11.14		9.96	12.48
Gain		5.62			2.52

Log-utility function used to represent risk aversity.

$U = \ln(X+16)$ where $X = \text{costs}$

The above examples demonstrate a few of the interesting policy-related cases that can be analyzed with the decision analytical framework incorporating uncertainty into the standard net-present-value methodology for evaluating technologies. These examples emphasize that equipment cost, physical energy savings, and the price of energy may not be the critical variables determining investment rates and the diffusion of new carbon-saving technologies.

From a policy perspective, programs aimed toward improving information and protecting customers from bad outcomes may be more effective than the traditional approach of offering rebates for new equipment, taxing carbon-intensive equipment, or even mandating energy-efficiency standards on equipment.

An Enhanced NPV Application

This simple example can be extended by probing different assumptions about risk attitudes and by testing how sensitive the results are to different parameter values. Again, we focus on the basic problem as formulated by Koomey et al in their discussion of the economics of new energy-efficient copper ballasts for fluorescent lighting in commercial buildings versus the older aluminum ballasts. Their results are based upon a deterministic net present value calculation in which all outcomes are certain. This approach often forms the core of "bottom up" economic analyses of competing technologies of varying energy efficiencies. The point of interest here is to examine the robustness of such estimates to a range of parameter values that might comprise the degree of uncertainty surrounding the problem.

We implemented several different approaches based upon different computer software packages. Initially, we were attracted to the simulation methodology used in the program, @Risk. In this approach, each uncertain variable is represented by a full distribution of possible

values that is simulated numerous times in a Monte Carlo fashion. The user specifies the distribution for each parameter and the software generates the distribution for the different simulations. Although the richness of the approach is attractive, we found that the software became cumbersome to manipulate for all but the simplest problem. This problem limited its usefulness as a building block for more complicated problems and modeling often used in policy analysis.

Our second approach is based upon a discrete representation of each variable's distribution in the tradition of decision analysis. This approach was implemented using Applied Decision Analysis's proprietary software for decision analysis, Decision Programming Language (DPL). Rather than sampling from a tree, this approach computes a closed form solution. We found sufficient flexibility in this approach to offset any problems due to the fact that for computational purposes each distribution is represented by only a few discrete steps. Practitioners of decision analysis frequently find that many decisions can be adequately modeled with just a few steps in the distribution. For the remainder of the paper, we focus exclusively on this second approach. Detailed discussion of the first approach and comparing results with the second approach would add complexity without contributing useful insights.

The modeling framework is outlined in Figure 1. Squares denote decision nodes, while circles indicate chance or probability nodes. At the far left, one chooses between the old aluminum ballast (top half of the chart) and the newer copper ballast (bottom half). Useful life and energy prices are possible unknowns affecting each option's payout. For the analysis reported here, the problem has been simplified by assuming that the decisionmaker knows with certainty that the known technology will last 15 years. The newer copper ballast also entails the uncertainty about how much physical energy will be saved with its adoption. With the failure

Figure 1

of the new unit, the decisionmaker must make a new selection of ballast, which conceptually could be either copper or aluminum. Undoubtedly, his experience will condition this choice in ways that are difficult to model precisely. We have adopted the simplifying assumption here that he reverts back to the old technology.

The key assumptions in our basic problem formulation are several. The distribution for the electricity price is based upon inspection of the average U.S. (for the nation) commercial sector electricity price over the 1960-90 period. Electricity prices are distributed normally, centered at a mean of 7.4 cents per kiloWatt-hours (kWh), or approximately its 1995 value, with a standard deviation of 0.5 cents. There is no upward trend in electricity prices in this base formulation, although a Brownian Motion path with an annual trend can also be incorporated.

Energy savings from the aluminum ballasts average 8 percent relative to the copper ballasts. These savings are distributed normally with a standard deviation of 2 percent. Koomey et al estimate that an 8 percent saving corresponds to 29 kWh/year when the ballast is operated 2600 hours per year. Therefore, the standard technology uses 362.5 kWh/year, at a rate of 0.139 kWh/hour. In the DPL model, we use 3000 hours times 0.139 kWh/hour = 418.27 kWh.

If the ballast fails early, we replace it with the standard technology and thus do not realize any additional energy savings after the fifth year. An additional failure cost of \$20 is assumed. Although this failure cost may appear high at first, it should be recognized that these ballasts will need to be replaced individually as they fail rather than as part of a programmed maintenance to replace all ballasts in a building at the same time.

The decision is based upon equivalent annualized costs for each alternative. The two options are evaluated with an 8% real discount rate, i.e., after adjusting for price inflation.

We employ a utility function that easily incorporates varying risk aversions. This function is:

$$U(x) = - \frac{(-x)^{1-c}}{1-c} \quad x \leq 0, \quad c \leq 0 \quad (1)$$

where x represents costs (a negative number) and C is the risk aversion factor with $C=0$ corresponding to risk neutrality with utility equal to costs. In the base simulations, the decisionmaker has a risk aversion factor of -2.

Figure 2 shows the cumulative distribution of both alternatives. The chart shows what percent (on the vertical axis) of the outcomes result in equivalent annualized payouts (negative costs) equal to or less than the value shown on the horizontal axis. The equivalent payouts almost always lie above -40 (cumulative probability is approximately 0) but above -15 (cumulative probability approaches unity) for either option. Expected payouts lie in the -25 to -30 range for both options. The distribution of the two payouts appear very similar to each other. The newer copper ballast entails a lower expected cost (negative payoff) and hence is preferred.

The sensitivity of these results to various parameter values can be evaluated. Figure 3 considers how failure costs affect the results. The certain payoff equivalent is shown vertically as a function of the failure cost for replacing a dysfunctional copper ballast shown horizontally. As failure costs increase from \$0 to slightly more than \$50, the equivalent payoff for the copper ballast diminishes. Once failure costs exceed \$50, the economic choice shifts to the older aluminum ballast, and failure costs become irrelevant for the decision after that point. Since the

Figure 2

Figure 3

base value of \$20 is well below \$50, the decision does not appear very sensitive to this parameter.

Figure 4 displays the decision's sensitivity to hours of operation. The newer copper technology is cost effective down to about 1700 hours, which is well below the 3000 hours used in the base case analysis.

The probability of early failure affects the payout for the newer but not the older technology. In Figure 5, the economic choice is to select the new technology as long as the failure rate lies below 60%. The equivalent payoff decreases for the newer copper unit as the rate increases within this range. Above a 60% failure rate, the choice shifts toward the older aluminum unit, with a payoff equivalent that is invariant (obviously) to the failure rate. The 60% switching rate lies well above the 33% rate used in the base simulations.

All but the most risk averse of decisionmakers would select the new technology in this hypothetical example. A completely risk neutral decisionmaker resides in the far upper right (northeast) corner of Figure 6, where the risk aversion parameter equals 0. At that point, he selects the newer copper unit with an equivalent payout of approximately -27.5. He continues to select the newer unit until he surpasses a risk aversion parameter of over -100.

The much-discussed sensitivity to the discount rate is demonstrated in Figure 7. The newer option remains economic up through discount rates of about 18%. At higher rates, future energy savings are not valued sufficiently to justify the differences in current-year costs.

Figure 8 shows the effect of incorporating an annual trend in the electricity price variable. An upward drift in energy prices increases energy costs for either option. Hence, payout equivalents become more negative for larger positive trends. With no upward trend ($= 0$), the new technology is still cost effective relative to the old unit. For negative trends of about -1.5

Figure 4

Figure 5

Figure 6

Sensitivity of Outcome to Risk Attitude

Figure 7

Figure 8

percent per year or more, however, the choice shifts to the older unit. The value of future energy savings generated by the unit becomes too small to justify the current-year capital expenditures, holding other factors constant.

The base case analysis assumed average annual physical energy savings from adopting the copper ballast of 8 percent. Figure 9 shows that the equivalent payoff from the new technology falls as the mean physical savings decrease. At slightly below 4%, the choice shifts to the older technology.

The base case analysis assumed physical energy savings to be distributed normally with a standard deviation of 2%. Figure 10 shows that greater variation in physical energy savings reduces the equivalent payoff for the new technology. At about 22%, well above the base value, the choice shifts against the new technology.

An attractive feature of this approach is that a variety of policy instruments can be modeled explicitly. Most climate change policy analysis begins with the assumption that decisionmakers choose the best-practice technology (technical efficiency) and choose the correct input mix given prevailing input prices (allocative efficiency). Thus, only price instruments--policies that raise or subsidize energy prices--can be explicitly analyzed.

Economic analysis is placing increased emphasis on the critical role of information in investment and adoption decisions. Some policies are oriented specifically toward facilitating the flow of information about new technologies. Other analysts suggest that adoption decisions by others creates useful information for others considering the technology. These considerations make it desirable have the capacity to analyze the effects of information on technology decisions. Potential adopters learn about a new technology by observing and interacting with other customers in the market. As experience with a product grows and is shared with other potential

Figure 9

Figure 10

adopters, some of the technology parameters may become better known. For example, wider exposure to a product may decrease the variation in the failure rate, as the mean becomes known with greater certainty.

This framework conceptually allows for such dynamics and for direct linkages between past decisions to adopt a technology and the distribution of technology parameters facing new adopters. The analysis also suggests several other ways new innovation could be encouraged. Many policy programs assume that innovators need to be subsidized with a rebate to adopt a new but risky technology. A rebate would lower the mean initial net cost of the equipment (or its first costs). In contrast, a service warranty offered by the company selling the new technology to a potential adopter would reduce the largest of down-side payouts (or losses) associated with equipment that fails early. In essence, the equipment vendor replaces the customer's rather wide distribution on the reliability of the unit with his own more informed experience with the product. This would presumably result in a tighter distribution with less variance in the technological failure rate. The issue then becomes why the companies are not offering these contracts, and what if anything needs to be done to encourage such instruments to be made available.

Summary

We have shown how a decision analytical framework might be applied as a policy tool for evaluating programs that influence a range of price and nonprice decision variables. At this point, it seems unrealistic that analysis of individual technologies can be incorporated into global assessment models of the climate change problem. Nonetheless, the more microeconomic decision analytical frameworks appear to have their place, reminding model builders of the range of price and nonprice factors that will influence future decisions and helping to inform

policymakers about the effects of specific carbon-reduction policies that focus on technological diffusion and adoption.

Customers appear reluctant to invest in new energy-efficient magnetic ballasts despite what appears to be favorable economics. We made no attempts to quantify any market barriers that could be adding hidden costs to the decisionmaker. These costs would be important to incorporate in a full-scale technology assessment. Our example does demonstrate, however, the rather weak case for energy price risks as a powerful deterrent to future investment in this technology. Electricity prices would have to fall by a very significant amount before the more energy-efficient investment became a poor investment; the probability of such conditions appears rather low. Hence, our assessment that customers would place a pretty low value on receiving more accurate information about future energy prices, either by delaying their investment or through some other means of information gathering.

Our conclusions refer to how uncertainty about energy prices affect technology choice. As is well known, energy prices also operate on energy use through other mechanisms such as the mix of activities with varying energy intensities and the rate of utilization of existing capital equipment. Thus, our conclusions do not generalize easily to broad statements about the importance or unimportance of energy prices in energy demand. Moreover, there is a strong need to apply the decision analytical framework to other technologies to gauge the robustness of our conclusions based upon electronic ballasts. From our earlier work on this project, we have become acutely aware that diversity among technologies requires careful interpretation of conclusions from technology-based studies.

Perceived reliability problems associated with new technologies may be a much stronger deterrent to investment than energy price risks. In the ballast example, a premature failure in a

new ballast could essentially destroy any favorable economic position. The fear of early failures can be offset, however, by service warranty programs and other risk-reduction policies that protect the customer from these problems. Such policies are likely to be more effective than taxes and other pricing policies or energy investment rebate programs.

A useful extension of this approach would be to develop the technology diffusion aspects of the problem more fully. As a technology is adopted by more customers, experience with the product increases. If the customers have favorable experiences with the technology, risks associated with technical performance (like reliability) will become less, thereby improving the perceived economics of the new technologies. Such a model seems to provide a more realistic picture of the technology decision environment than the standard deterministic net present value assessment of a technology under today's conditions.

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