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LIFE-CYCLE COSTING GUIDE FOR ENERGY CONSERVATION IN BUILDINGS

Harold E. Marshall and
Rosalie T. Ruegg

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The purpose of this chapter is to provide practicing architects, mechanical engineers, building financiers, and others interested in the design process with a guide to life-cycle cost techniques for evaluating building designs for energy conservation.

The first section is an overview of the state of the art of life-cycle costing (LCC) of energy conservation design in buildings, provided in the format of a primer. The second section describes selected case examples and applications of LCC; and the concluding section a discussion of potential impediments to the immediate application of LCC techniques and the benefits to the building community that can be expected as LCC analysis gains wider acceptance.

Primer on Life-Cycle Costing

What is life-cycle costing? Life-cycle cost analysis is a variation of benefit-cost analysis, a technique for evaluating programs or investments by comparing all present and future expected benefits with all present and future costs.[1] To be worthwhile economically, the long-run benefits or cost savings produced by an investment must exceed the long-run costs. As one would expect from its name, the focus of LCC analysis is on costs. However, this does not preclude the treatment of benefits in an LCC analysis if the benefits can be conveniently stated as negative costs, as is the case with fuel cost savings.

LCC analysis, as applied to energy conservation features in buildings, is the evaluation of the net effect over time of reducing fuel costs by purchasing, installing, maintaining, operating, repairing, and replacing energy-conserving features. The results of LCC analysis may be expressed as (1) the total of conservation investment and energy consumption costs, (2) the net savings from the investment in energy conservation, or (3) the ratio of savings to costs. The choice will depend in part on the preference of the analyst and in part on the nature of the investment problem.[1] The net savings from energy conservation are computed as shown in Equation 1:

Net Savings (or losses) from energy conservation
Energy cost savings (benefits)
Acquisition and installation costs
Maintenance and operating costs
Repair and replacement costs

$$S = E - [A + M + R].$$

A positive value for S indicates that the energy-conserving feature results in net savings and is, therefore, economically efficient; a negative value indicates that it results in net losses and is, therefore, uneconomical.

1. More extensive treatments of benefit-cost and LCC analysis are provided in A. K. Dasgupta and D. W. Pearce: *Cost-Benefit Analysis: Theory and Practice,* Barnes and Noble, New York, 1972; Reynolds, Smith and Hills, Architects - Engineers - Planners, Inc.: *Life-Cycle Costing Emphasizing Energy Conservation: Guidelines for Investment Analysis,* rev. ed., Energy Research and Development Administration Manual 76/130, May 1977 (hereafter cited as *Life-Cycle Costing*) and R. T. Ruegg, J. S. McConnaughey et al. *Life-Cycle Costing, A Guide for Selecting Energy Conservation Projects for Public Buildings,* National Bureau of Standards Building Science Series 113, May 1978.

LCC analysis may be used to address two types of economic efficiency choices: first, how much of a single energy conservation feature to use (if at all), and second, how much of each of several energy conservation features to use in combination. By comparing the net life-cycle effects of successively increasing amounts of a given energy conservation feature, it is possible to determine which level of investment in this feature is most economical. The optimal combination of energy conservation features can be determined by substituting among alternatives until each is being used to the level at which its additional contribution to energy cost reduction per extra dollar spent is just equal to that for all the other alternatives.[2]

Discounting, Taxes, and Inflation The results obtained by LCC analysis and benefit-cost analysis are usually expressed in either present value terms or in uniform annual value terms. "Present value" means that all past, present, and future dollars of expenditures, receipts, or savings—that is, all cash flows—are converted to an equivalent value in today's dollars. "Uniform annual value" means that all past, present, and future cash flows are converted to an equivalent level amount recurring yearly.

It is important to note that the present value of net costs and cost savings from an investment is not found by merely summing the cash flows over the expected life. Nor is the uniform annual value found by dividing cumulative net cash flows by the number of years of expected life (that is, the uniform annual value is not the same as the average yearly value). This is because the value one places on money is time dependent. The time dependency of value reflects not only inflation, which may erode the buying power of the dollar, but also the fact that money can be invested to yield a return over time that is separate from inflation. Hence, to evaluate the profitability of investing in energy conservation—either to determine the desirability of a single investment or to compare alternative investments—it is necessary to adjust for the differences in the timing of expenditures and cost savings.

The conversion of differently timed cash flows to a common time equivalent may be done by a technique called discounting. This technique relies on the application of interest (discount) formulas or, to simplify the calculation, discount factors already calculated from the formulas, to adjust the cash flows.[3]

To apply the discount formulas or factors, it is necessary to select a discount rate. The discount rate should indicate one's time preference for money. For example, if a person had an annual discount rate of 10% (for example, he or she could earn 10% interest in a risk-free savings account at the bank), a given amount of money this year would be worth 10% more than that same amount next year. This person should therefore be indifferent to a choice between a given amount of money now and 10% more than that amount a year from now.

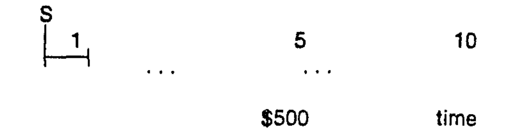
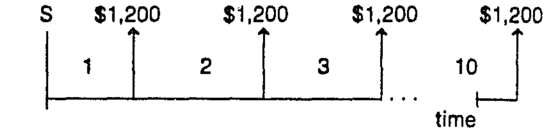
A discount rate may be either "nominal" or "real." A "nominal"

2. For a discussion of the determination of the optimal input combinations to minimize the cost of producing a given output or to maximize the output for a given cost, see E. Mansfield: *Microeconomics: Theory and Applications*, W. W. Norton, New York, 1970, pp. 148–156.

3. A familiar application of an interest, or discounting, formula is the use of the Uniform Capital Recovery (UCR) Formula to amortize the principal of a mortgage loan over a specified number of years at a given interest rate. This formula, together with the following five additional interest formulas, are those most frequently used in investment analysis: a) Single Compound Amount Formula (SCA), used to find the future value of a present amount, b) the Single Present Worth Formula (SPW), used to find the present value of a future amount, c) the Uniform Compound Amount Formula (UCA), used to find the future value of a series of uniform annual amounts, d) the Uniform Sinking Fund Formula (USF), used to find the annual amount which will result in a given total value at a future time, and e) the Uniform Present Worth Formula (UPW) used to find the present value of a series of uniform annual amounts. An in-depth explanation of discounting formulas and tables of discount factors calculated from the discount formulas for a range of years and discount rates are available in most engineering economics textbooks. See, for example, G. W. Smith: *Engineering Economy: Analysis of Capital Expenditures*, 2nd ed., Iowa State University Press, Ames, Iowa, 1977 (hereafter cited as *Capital Expenditures*); and E. L. Grant and W. Grant Ireson: *Principals of Engineering Economy*, The Ronald Press, New York, 1970 (hereafter cited as *Engineering Economy*).

TABLE 1

Discounting Cash Flows from an Energy Conservation Investment[a]

Type of cost or saving (1)	Cash-flow diagram (2)
Purchase and installation of an Energy-Conserving Feature	
Repair and Replacement of Parts	
Annual Fuel Savings[b]	
Net Total Savings (Fuel Savings Less Costs)	

discount rate reflects both the effects of inflation and the real earning power of money invested over time. A lower, "real" rate, reflecting only the real earning power of money, is appropriate for evaluating investments if inflation is removed from the cash flows prior to discounting, that is, if they are stated in constant dollars.

The discount rate may be based on any of several different measures, such as the rate of return which could be realized from the next best available investment, the interest rate on savings accounts, or the cost of borrowing. There may be a strong subjective element in the specification of the discount rate. The choice of a rate will likely vary depending on the investor's financial position and concern for the timing of expenditures and receipts (time preference).[4] The approach generally taken is to base the rate on a consideration of the factors at hand, and to test the outcome for sensitivity to the use of alternative discount rates where there is great uncertainty as to the correct choice.[5]

Table 1 provides several simple illustrations of the discounting of costs and savings typically associated with investments in energy conservation. The illustrations are based on a discount rate of 10% and a period of 10 years. The first column describes the type of costs or savings. The second column uses a cash-flow diagram to describe the timing of the cash outflows and inflows. The horizontal line with arrows represents a time scale progressing from left to right, on which S (for "start") indicates the present, the number on the scale indicates the number of years, each downward arrow represents an expenditure, and each upward arrow represents a cost saving. The third column shows the present value equivalent, and the fourth column, the annual value equivalent of each cost or saving.

4. For a discussion of subjectivity in selecting discount rates, see James J. Mutch: *Residential Water Heating, Fuel Conservation, Economics, and Public Policy,* prepared by the Rand Corporation for the National Science Foundation, Th 7512, M18, Appendix B, pp. 69–71.

5. When there is uncertainty as to the correct value of one or more important input parameters in an evaluation, such as the discount rate, it is useful to determine whether the outcome would change significantly if alternative values were used for the input parameters. Sensitivity analysis can be used to provide additional information for making economic choices. For a description and illustration of sensitivity analysis and the mathematics of probability in economic studies, see, Grant and Ireson, *Engineering Economy,* pp. 251–301.

Present value equivalent (P) (3)	Annual value equivalent (A) (4)
P_f = \$10,000	A_f = \$10,000 · (UCR, i = 10%, N = 10) = \$10,000 · 0.1628 = \$1,628
P_r = \$500 · (SPW, i = 10%, N = 5) = \$500 · 0.6209 = \$310	A = \$500 · (SPW, i = 10%, N = 5) · (UCR, i = 10%, N = 10) = \$500 · 0.6209 · 0.1628 = \$51
P_s = \$1,200 · (UPW, i = 10%, N = 10) = \$1,200 · 6.144 = \$7,373	A_s = \$1,200
$P_n = P_s - (P_f + P_r)$ = − \$2,937	$A_n = A_s - (A_f + A_r)$ = − \$479

*Nomenclature: S = Starting time (the present)
P = Present value equivalent
A = Annual value equivalent
F = Future value equivalent

Subscripts: f = first costs
r = repair and replacement costs
s = fuel savings
n = net of total costs and savings

UCR = Uniform Capital Recovery Formula, $A = P\dfrac{i(1+i)^N}{(1+i)^N - 1}$.

SPW = Single Present Worth Formula, $P = F\dfrac{1}{(1+i)^N}$.

UPW = Uniform Present Worth Formula, $P = A\dfrac{(1+i)^N - 1}{i(1+i)^N}$.

i = Discount rate per period
N = Number of interest periods

*Assumes no change in fuel prices. To include fuel price escalation, the formula becomes

$$P = C \times \sum_{j=1}^{N} \left(\frac{1+e}{1+i}\right)^j$$

where C = Fuel cost savings at outset, and e = fuel price escalation rate

Once the various cash flows have been discounted to a present value or to an annual value, they may then be combined to provide a net measure of the economic impact of an investment. In column 3 of Table 1, for example, the present value cost of \$10,000 for purchasing and installing the energy conservation feature, plus the present value cost of \$310 for repair and replacement, total \$10,310. The present value cost savings total \$7,373. Net savings of −\$2,937 result. This is equivalent to a net loss of \$479 per year in terms of annual value. Hence, this investment is not worthwhile even though net savings in undiscounted terms amount to \$1,500 (i.e., a total of \$10,500 for purchase, installation, repair, and replacement subtracted from \$12,000 in aggregate fuel savings equals \$1,500.)

Depending upon the degree of accuracy desired in an evaluation, it may be important to consider the impact of taxes. By affecting revenues and costs, taxes can dramatically alter the profitability of an investment.[6] Potentially important tax effects include deductions from taxable income of depreciation allowances on capital expenditures; investment tax credits which directly offset tax liabilities; property taxes on capital investments; and the loss of deductions from taxable income when current operating expenses are reduced by fuel savings.

It is usually not necessary to increase the estimates of cash flows to include inflation in each item of cost or savings. Inflation can often be handled in an LCC analysis by making the simplifying assumption that all costs and revenues, except fuel costs, inflate at the same general rate, and that they therefore remain constant in real terms.[7] Because fuel prices are a dominant factor in the analysis of energy conservation investments, and because they are widely expected to increase at a rate faster than over-all prices in the economy, it is important to adjust estimates of future fuel cost savings to reflect their expected differential rate of price increase, i.e., the rate of increase over and above the general rate of inflation.[8] With these assumptions, all future cash flows can be evaluated with a "real" discount rate. (It should be noted that the treatment of inflation in economic analysis is different from the treatment of inflation for budgeting. To develop reliable budgets, it is essential to take into account the inflation that can occur in planned costs during the lag between the time of the preparation of the economic analysis and the time of actual spending or obligating funds.)

It is not always necessary to go through an elaborate LCC analysis before investing in energy conservation. In some cases, where first costs are low and the potential for energy conservation is high, it will not be necessary to make an explicit evaluation. Weatherstripping around poorly fitting (or leaking) windows and doors is an example of an inexpensive approach to energy conservation which can generally be undertaken with little doubt as to its favorable impact on life-cycle costs.

In cases where first costs are high and/or significant costs and savings are unevenly distributed over time, it is often advisable to do an LCC analysis. Not all energy-conserving features will be economical to use. Their cost effectiveness will depend particularly upon climatic conditions, their purchase and installation costs, their durability and maintainability, their ability to save energy, and the present and future prices of fuel. As is illustrated in specific applications later in this chapter, LCC analysis appropriately used can result in substantial savings both in energy conservation investments and in building costs in general.

Related Methods of Evaluation There are several other methods of evaluating the economic efficiency of investment in energy conservation which are closely related to LCC analysis. Popular among these are the payback method and the internal rate-of-return method.

6. For a discussion of estimating the impact of taxes on investment decisions, see Grant and Ireson, *Engineering Economy*, pp. 337–382.
7. For a discussion of the conditions under which this assumption of evenly inflating costs and revenues is *not* appropriate, see Smith: *Capital Expenditures*, appen. G, pp. 542–552.
8. Reynolds, Smith and Hills, *Life-Cycle Costing*. Guidelines for using differential rates of fuel price increases have been adopted by the Energy Research and Development Administration, pp. II/10–II/11.

The *payback method* measures the elapsed time between the point of the initial investment and the point at which accumulated savings, net of other accumulated costs, are sufficient to offset the initial investment. (Although costs and savings should be discounted in calculating the payback period, in actual practice they are frequently left undiscounted.) Shorter payback periods are generally preferred to longer payback periods.

The popularity of the payback method probably reflects the fact that it is an easily understood concept and that it emphasizes the rapid recovery of the initial investment at a time when many organizations appear to place great emphasis on flexibility in investment strategy. However, the payback method has the weakness of failing to measure cash flows that occur beyond the point at which the initial investment costs are recovered. It is possible for a project with a longer payback period to yield higher net savings than a project with a shorter payback period. Hence, use of the payback method may lead to uneconomic conservation investments.

The algebraic formulation for determining discounted payback is the following:

$$C - \sum_{j=1}^{Y} \frac{B_j - K_j}{(1+i)^j} = 0$$

Equation No. 2

where C = the initial investment cost
Y = the number of years elapsed until the present value of cumulative net yearly savings just offsets the initial investment
B_j = cost savings or benefits in year j
K_j = costs in year j
i = discount rate

The objective is to find the number of years, Y, which solves the equation, given values of the other variables. This may be done by trial and error. Alternatively, for the special case in which the net yearly savings, $B_j - K_j$, is equal to a constant, A, the following expression of the payback equation can be used:

$$Y = \frac{-n(1 - iC/A)}{n(1+i)}$$

Equation No. 3

The *internal rate-of-return method* finds the rate of return that an investment is expected to yield. The rate of return is expressed as that compound interest rate for which the total discounted benefits become just equal to total discounted costs. The rate of return is generally calculated by a process of trial and error in which various interest rates are used to discount costs and benefits to present values. These discounted costs and benefits are compared with each other until that interest rate is found for which costs and benefits are equal and net benefits are, therefore, zero.

As an illustration, let us find the internal rate of return on an investment which requires an initial, one-time cost of $10,000, and yields a yearly recurring savings of $3,000 for 10 years. The initial investment of $10,000 is already in present value terms. We need now to calculate the net present value, *P*, of the $3,000 in yearly savings for various interest rates. First, let us calculate the value of *P* for, say, a compound interest rate of 25%. At this interest rate, the present value equivalent of the $3,000 for 10 years is equal to $10,713. Substracting the present value cost of $10,000 from the present value savings yields a net present value savings of $713. The fact that $713 exceeds zero means that 25% is less than the internal rate of return on this investment. Trying now a higher compound interest rate of 30%, the present value savings over the 10-year period equals $9,276. Net present value savings are now equal to $–724, an amount $724 less than the $10,000 cost. Since an interest rate of 30% results in net losses, this rate must be greater than the internal rate of return on this investment. Thus, we can conclude that the rate of return is bracketed by 25% and 30%. By interpolation, we can now estimate that the investment yields an internal rate of return of a little over 27%. The investment would be considered worthwhile if the 27% rate exceeds the rate of return which the investor could get from alternative investments.

This method of evaluation usually results in a measure consistent with an LCC approach, and somewhat more reliable than the payback method. However, the internal rate-of-return method does have the disadvantage of giving either no solution or multiple solutions under certain conditions.

The payback method, internal rate-of-return method, and LCC method all have particular advantages and disadvantages. Each will serve as a useful tool for investment decisions in certain cases.[9] For most problems of making economically efficient decisions in energy conservation, the LCC method will provide an adequate measure.

Case Applications of LCC to Energy Conservation

Let us examine four applications of LCC to energy conservation. The first deals with insulating an existing building to lower the undesirable heat loss and gain. The second deals with selecting window size, design, and orientation to reduce energy and lifetime building costs. The third deals with determining whether a solar heating system will be cost effective in reducing the consumption of nonrenewable energy resources. The fourth describes the use of LCC in developing energy conservation performance standards for buildings.

Retrofitting Existing Buildings[10] Promoting energy conservation in existing buildings is important for two reasons. First, the existing housing and commercial building stock is very large

9. For a discussion of the suitability of different evaluation methods for treating different kinds of investment decisions, see R. T. Ruegg: "Economics of Waste Heat Recovery," *Waste Heat Guidebook*, K. G. Kreider and M. B. McNeil, eds., National Bureau of Standards Handbook 121, February 1974, pp. 99–105.

10. Retrofitting an existing building for energy conservation means to add insulation, weatherstripping, storm windows, or replacement windows with insulated glass, or to do any other remodeling that contributes to the prevention of unwanted heat loss or gain.

relative to the number of new buildings added to that stock each year. Thus, the greatest potential for energy conservation in terms of numbers is in existing buildings. Second, older existing buildings generally have less insulation than do newer buildings. One cause of this is the historically low cost of fuel relative to other costs for operating buildings, and the consequent emphasis on a low first cost in weatherizing buildings. Furthermore, there had been no government controls to require insulation in buildings until the FHA Minimum Property Standards in 1960 called for increased insulation in FHA-insured residential construction.

A comprehensive handbook for determining the economically efficient amounts of insulation, weatherstripping, storm windows, and insulating glass to add to an existing home is *Making the Most of Your Energy Dollars,* by Madeleine Jacobs and Stephen R. Petersen,[11] based on a technical economics report prepared for analysts.[12] The handbook provides the homeowner with a method of determining how much to buy of any single technique for retrofitting buildings for energy conservation, and what combination of techniques to buy.

The approach and findings of *Making the Most of Your Energy Dollars* serve well as a case illustration of LCC analysis. The illustration is intended to show how the LCC application provides useful information, rather than to present the model in any detail.

To find the most economically efficient investments in energy conservation, a model was developed to compare the value of energy savings over time with costs for each selected alternative type of conservation. An LCC model was written in BASIC programing language to enable an analyst to calculate, at a time-sharing terminal, the optimal package for retrofitting a house. The LCC model is sensitive to the house location (i.e., the climate as measured in heating degree days and cooling hours)[13] and the price of fuel. Both heating and cooling loads are taken into account.

Tables 2, 3, and 4 illustrate the format used in *Making the Most of Your Energy Dollars,* to provide data for making an efficient decision on insulating attic floors and ducts in a heated and air-conditioned residence. The information that would be needed to plan the retrofitting of a given house is the heating and cooling zones (readily available in map form), the fuel type and price, and the level of insulation currently in the house. Tables of index values which combine the climate and fuel information are provided to simplify the computation. For example, Tables 2 and 3 show that a house in heating zone III and cooling zone B, with heating oil at \$.34/gal and electricity for air conditioning at \$.04/kWh, has an index of 20 for heating and 5 for cooling. These add up to a combined index of 25. For a range of combined heating and cooling index values, Table 4 gives the economically efficient level of resistance to heat flow in the attic and duct insulation of the building, as well as the corresponding thickness of different

11. National Bureau of Standards, CIS-8, June 1975 (hereafter cited as *Energy Dollars*).

12. S. R. Petersen: *Retrofitting Existing Housing for Energy Conservation: An Economic Analysis,* National Bureau of Standards, Building Science Series 64, December 1974 (hereafter cited as *Retrofitting*).

13. "Heating degree days" is a measure of the temperature differences (design conditions) between the interior and exterior of a building that are used to establish the heating load of a building. Annual heating degree days are computed by adding the number of degrees that the daily mean temperature is below 65F, for all days of the year. "Cooling hours" are the number of hours annually in which air conditioning is required. (*ASHRAE Handbook of Fundamentals,* ASHRAE, New York, 1972.)

TABLE 2

Heating Index to Relate Climate and Fuel Price to Cost Savings in Heating Energy

Type of fuel	Cost per unit[a]									
Gas (therm)	9¢	12¢	15¢	18¢	24¢	30¢	36¢	54¢	72¢	90¢
Oil (gal)	13¢	17¢	21¢	25¢	34¢	42¢	50¢	75¢	$1.00	$1.25
Electric (kWh)				1¢	1.3¢	1.6¢	2¢	3¢	4¢	5¢
Heat pump (kWh)	0.9¢	1.1¢	1.5¢	1.8¢	2.3¢	2.9¢	3.5¢	5.3¢	7.0¢	8.8¢
HEATING ZONE I	2	2	3	3	4	5	6	9	12	15
HEATING ZONE II	5	6	8	9	12	15	18	27	36	45
HEATING ZONE III	8	10	13	15	20	25	30	45	60	75
HEATING ZONE IV	11	14	18	21	28	35	42	63	84	105
HEATING ZONE V	14	18	23	27	36	45	54	81	108	135
HEATING ZONE VI	22	28	36	42	56	70	84	126	168	210

[a] Cost of last unit for heating and cooling purposes, including all taxes, surcharges, and fuel adjustments.

TABLE 3

Cooling Index to Relate Climate and Fuel Price to Cost Savings in Cooling Energy

Type of air conditioner	Cost per unit[a]						
Gas (therm)	9¢	12¢	15¢	18¢	24¢	30¢	36¢
Electric (kWh)	1.5¢	2¢	2.5¢	3¢	4¢	5¢	6¢
COOLING ZONE A	0	0	0	0	0	0	0
COOLING ZONE B	2	2	3	4	5	6	7
COOLING ZONE C	3	5	6	7	9	11	13
COOLING ZONE D	5	6	8	9	12	15	18
COOLING ZONE E	7	9	11	14	18	23	27

[a] Cost of last unit for heating and cooling purposes, including all taxes, surcharges, and fuel adjustments.

TABLE 4

Attic Floor Insulation and Attic Duct Insulation

INDEX	Attic insulation				Duct insulation[a]	
		Approximate thickness				
Heating index plus cooling index for attics	R-Value	Mineral-fiber blanket	Mineral-fiber loose-fill[b]	Cellulose loose-fill[b]	R-Value	Approximate thickness
1–3	R-0	0"	0"	0"	R-8	2"
4–9	R-11	4"	4–6"	2–4"	R-8	2"
10–15	R-19	6"	8–10"	4–6"	R-8	2"
16–27	R-30	10"	13–15"	7–9"	R-16	4"
28–35	R-33	11"	14–16"	8–10"	R-16	4"
36–45	R-38	12"	17–19"	9–11"	R-24	6"
46–50	R-44	14"	19–21"	11–13"	R-24	6"
61–85	R-49	16"	22–24"	12–14"	R-32	8"
86–105	R-57	18"	25–27"	14–16"	R-32	8"
106–130	R-60	19"	27–29"	15–17"	R-32	8"
131–	R-66	21"	29–31"	17–19"	R-40	10"

[a] Use Heating Index only if ducts are not used for air conditioning.
[b] High levels of loose-fill insulation may not be feasible in many attics.

TABLE 5

Costs and Savings for a Range of Attic Insulation Levels Given an Index Value of 25[a]

	Dollar cost			
Insulation resistance (1)	Insulation (acquisition & installation costs) (2)	Energy consumption (present value of future costs) (3)	Total life-cycle costs (4) = (3) + (2)	Marginal life-cycle savings (5)
R-11	300	1878	2178	N.A.[b]
R-19	500	1126	1626	552
R-22	580	986	1566	60
R-30	780	739	1519	47
R-33	860	676	1536	−17
R-38	990	592	1582	−46
R-44	1140	514	1654	−72
R-49	1280	483	1763	−109

[a]Assumptions are the following:
Degree days = 5,000; cooling hours = 750 (New York City)
Oil = 34¢/gal; efficiency = .6
Electricity = 4¢/kWh; COP = 2.0
Insulation prices are based on typical 1976 installed costs.
Present Worth Factor = 20 (based on the assumption of a 20-year life and a rate of fuel price escalation equal to the discount rate).
[b]N.A. means not applicable. The value of energy consumed when no insulation is installed was not computed.

types of insulation which would be required to achieve the indicated resistance, or "R" value. For example, the combined index of 25 calls for R-30 insulation in the attic and R-16 around attic ducts. The recommended resistance value, R-30, is shown to be provided alternatively by 10 in. of mineral-fiber batt blanket, 13–15 in. of mineral-fiber loose-fill, or 7–9 in. of cellulose loose-fill insulation. The retrofit requirements for the attic and ducts are then calculated as the difference between the amount indicated by the tables and the amount of insulation already in place in the house.

The economic significance of failing to install R-30 insulation in the attic under the described conditions is illustrated in *Table 5*. For each "R" value of insulation (column 1), the table shows the total life-cycle costs (column 4), as well as the marginal life-cycle savings (column 5). Note that the minimum total life-cycle cost (column 4) is $1,519, and that the corresponding resistance level is R-30. That is, the sum of insulation costs (column 2) and energy consumption costs (column 3) are at a minimum for R-30 insulation. Another way of establishing R-30 as the optimal level is to examine marginal life-cycle savings. Note that marginal savings (column 5) from each additional amount of insulation is positive as "R" increases up to R-30, but beyond that point marginal savings become increasingly negative (i.e., life-cycle costs begin to increase). The increment from R-22 to R-30 brings a marginal savings of $47 ($1,566 − $1,519), but the next increment, R-30 to R-33, brings a loss of $17 ($1,519 − $1,536). Thus, a quantity of insulation that provides a resistance value of R-30 is the economically efficient level of insulation among those shown in Table 5; it is the level for which the building owner will maximize net savings from energy conservation. Installing more insulation would not raise savings sufficiently to offset the additional cost of the insulation; installing less would mean foregoing fuel savings in excess of the required cost.[14]

Selecting Windows for Energy Conservation and Economic Efficiency Another recent application of life-cycle cost analysis to energy conservation in buildings pertains to window selection and use. Although it is estimated that about one-fourth of the total energy used for heating and cooling buildings in the United States each year is lost through windows, a recent study at the National Bureau of Standards has shown that it is possible to alter considerably the impact of windows on energy consumption and total lifetime building costs. Depending upon critical design and use decisions, it was shown that windows can increase, decrease, or have little impact on energy and building costs.[15]

The NBS research first identified specific window systems with potential for saving energy. A computer model was developed for estimating the impact of selected window systems on energy conservation. Life-cycle costing techniques were then used to combine the costs of acquisition, maintenance, repair, and energy, in order to determine the over-all impact of alternative window systems on the cost of the building.[16]

NBS conducted 18 case studies of window use—nine for residential buildings and nine for commercial buildings. The following nine geographical locations, covering five major heating zones and four major cooling zones in the United States, were treated: Washington, DC; Miami, Florida; Atlanta, Georgia; Portland, Maine; Indianapolis, Indiana; San Antonio, Texas; Los Angeles, California; Bismark, North Dakota; and Seattle, Washington.

Life-cycle costs were estimated for (1) a range of window sizes, (2) alternative orientations, (3) choices of single, double, and triple glazing, (4) the use of two interior accessories—venetian blinds and insulating shutters; and (5) the use of windows for daylighting. Costs were estimated for gas heating and electric cooling, and for electric heating and cooling, as well as for a range of energy escalation values.

The study is relevant to the design of new buildings in that it identifies the least-cost window system from among alternatives, and to the retrofit of existing buildings in that it indicates how existing windows may be accessorized and used more efficiently.

Following is an example of results taken from the Washington, DC case study for windows in a detached, single-family residence. *Figures 1* and *2* show graphically the behavior of net life-cycle costs associated with single- and double-glazed windows as the area of the window is increased relative to the wall area. The costs are based on using varying sizes of double-hung wooden windows in a "typical" family-room–kitchen of a brick rambler.

14. In *Footnotes 12* and *13* (Jacobs and Petersen: *Energy Dollars;* Petersen: *Retrofitting*), additional alternatives for retrofitting, such as weatherstripping, storm doors and windows, and caulking are evaluated, and alternative measures of economic desirability, such as the years required for an investment to pay back its costs, are also evaluated.

15. R. T. Ruegg and R. E. Chapman: *Economic Evaluation of Windows in Buildings*, vols. 1 and 3, National Bureau of Standards Building Science Series, in press.

16. R. Hastings and R. W. Crenshaw: *Window Design Strategies to Conserve Energy*, National Bureau of Standards Building Science Series, June 1977; T. Kusuda and B. L. Collins: *Simplified Analysis of Thermal and Lighting Characteristics of Windows: Two Case Studies*, National Bureau of Standards Building Science Series, November 1977. Only those costs and benefits which could be measured in dollars with a relatively high degree of confidence were included in the analysis; the benefits of natural ventilation and psychological, safety, and aesthetic effects were not included.

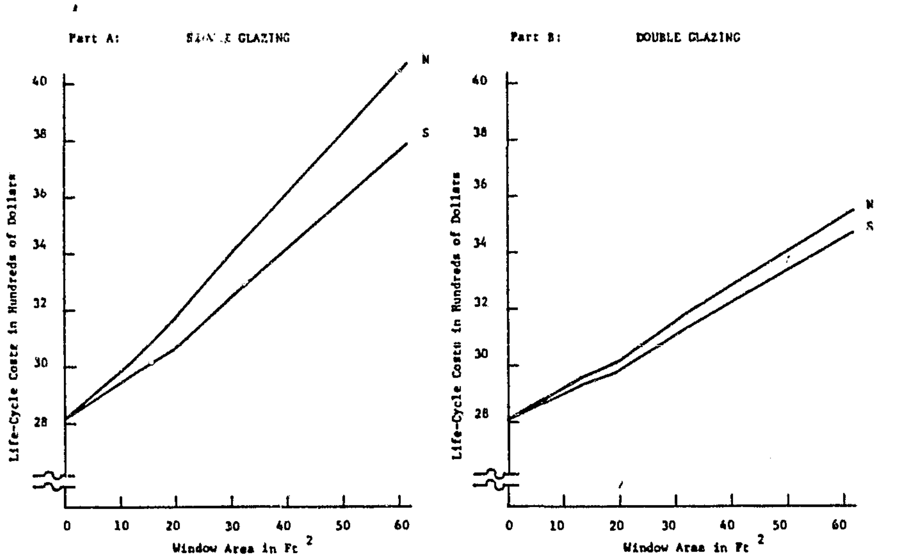


Fig. 1 Washington, DC Case Study: Life-cycle costs for a room with a north (N) or south (S) window area without energy conservation accessories and without daylight utilization.

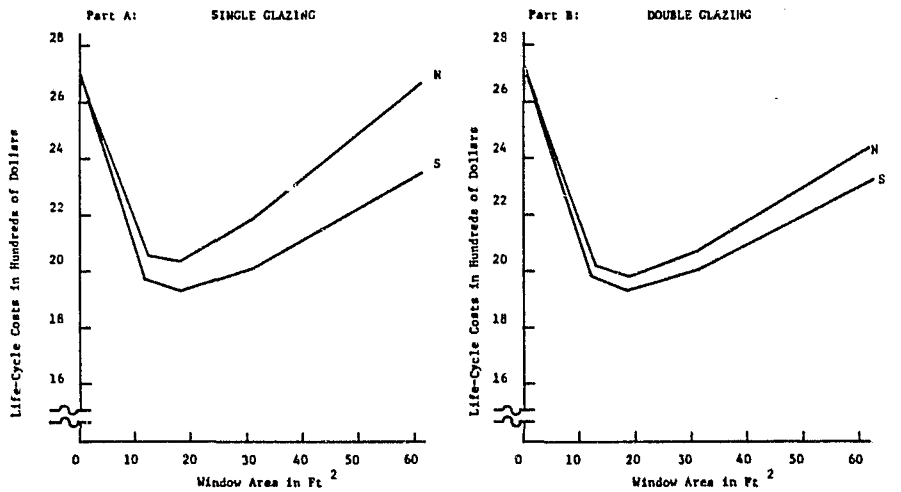


Fig. 2 Washington, DC Case Study: Life-cycle costs for a room with a north (N) or south (S) window area with energy conservation accessories and daylighting utilization.

In each figure, Part A is for single glazing, and Part B is for double glazing. Two situations of window use are described by these figures. Figure 1 shows the costs based on the assumption that the window is bare and is not used for daylighting. Figure 2, in contrast, shows the costs based on the assumption that the window is accessorized with insulating shutters which are closed at night during the winter, and venetian blinds which reduce undesirable solar radiation in summer. It is further assumed in Figure 2 that the window is used for daylighting, thereby reducing the reliance on electric lighting. It is also assumed that the thermostat is adjusted at night for energy conservation.

For simplicity, only two orientations, north and south, are shown. Costs are shown for gas heating at $.30/therm and electric cooling at $.03/kWh. A 12% annual rate of escalation in energy prices is assumed, and future cash flows are discounted to present value with a discount rate of 8%. The vertical axis of each figure measures the life-cycle costs in present value dollars. The horizontal axis measures the window area in square feet, beginning with zero (no window) at the origin and going to 60 ft^2. When the room is windowless, the figures show only the costs for heating and cooling the room. When a window area is added to the room, the figures show the combination of the room's energy costs and costs of purchasing, installing, maintaining, and repairing the window area over and above the costs which would be incurred for an equal area of opaque wall.

From Figure 1 we can draw the following conclusions about a bare window area, unutilized for daylighting, in a house in a moderate climate like Washington, DC: (1) the larger the window, the larger the life-cycle costs of the building; (2) the life-cycle costs of windows are lower on the south side than on the north side of the building; and (3) if there is a relatively high rate of escalation in energy prices, double glazing is economical for all window sizes examined, both on the north and south sides of the building.

From Figure 2, we can draw the following conclusions about windows that are equipped with energy-conserving accessories and used for daylighting in a house in a moderate climate like Washington, DC: (1) over-all cost of the building can be lowered by adding a window area, provided steps are taken to reduce its undesirable heat gains and losses, and if it is used during the day to eliminate electric lighting; (2) the greatest savings result from adding a small-to-medium, single-glazed window area on the south side; and (3) with rapid escalation in energy prices, double glazing tends to be cost effective for all window sizes examined, except for small-to-medium windows on the south side.

Apart from the consideration of psychological or other factors, these conclusions suggest that a homeowner, builder, or designer of a house in the Washington, DC area could reduce the house's life-cycle costs by keeping window areas as small as possible in those rooms which are not used much during the day or which, for some other reason, cannot be used effectively to reduce electric lighting requirements. Where daylighting can be used effectively, it appears better from a life-cycle cost standpoint to have a window area—even a relatively large one—than to have a windowless exterior wall. In either case, however, small- to medium-sized window areas tend to be more economical than large areas. With rapidly rising energy prices, it will generally pay to use either insulating and shading accessories like those described, or double glazing, or in most cases both accessories and double glazing. The use of accessories and double glazing is particularly important for large window areas and north-facing areas.

LCC Evaluation of Solar Energy Systems Another application of LCC to energy conservation investments in buildings is in the evaluation of solar energy systems. This investment is similar to many other approaches to energy conservation in that it requires a relatively large initial expenditure to achieve fuel cost savings over time. It works, however, by replacing nonrenewable energy sources with renewable energy, rather than by reducing the building's energy requirements.

LCC analysis may be applied both to the evaluation of the cost effectiveness of a given solar energy system in a specific application, and to the optimal sizing and design of a solar energy system for a specific application. The primary difference is in the complexity of the number of analyses to be performed.[17]

In the case of evaluating the cost effectiveness of a particular system for a given building, the analysis consists of using a model like that described in the first section of this chapter to compare life-cycle investment costs against life-cycle fuel cost savings. In the case of optimally designing and sizing a solar energy system, the approach is to evaluate the costs and cost savings associated with marginal changes in the various design and size alternatives. One tries to identify that design and size which maximizes net savings, or, when said another way, minimizes the life-cycle costs of providing a given comfort level in a building.[18]

To calculate the life-cycle costs to the owner for a heating and/or cooling system, the following items are relevant: (1) acquisition costs, which consist of the costs of "identifying" and/or designing the system, as well as purchasing, delivering, installing, and modifying the building to receive it; (2) system repair and replacement costs, including damage losses and insurance premiums, net of reimbursements; (3) routine maintenance costs; (4) operating costs, comprised mainly of fuel costs; and (5) salvage values in excess of removal and disposal costs, or alternatively, resale value if the building is to be sold during the time frame of the analysis. In assessing costs, it is also important to take into account the impact of property and income tax effects, as well as the impact of any available incentive programs provided by the state or federal government.

A computerized model to assess the life-cycle costs of solar heating systems has been developed at the National Bureau of Standards, and is referred to in *Footnote 19*. The following example is based on this report.

The solar energy LCC model allows the user to specify the values of key parameters, such as the cost per unit of the collector, the present price of fuel, its anticipated rate of escalation, and the discount rate. It was developed to assess the impact on owner costs of seven different types of financial incentives which could be provided to homeowners and to businesses. The inclusion of

17. For a description of the major steps in LCC analysis as applied to solar energy systems, see R. T. Ruegg: "Life-Cycle Costs and Solar Energy," *ASHRAE Journal*, November 1976.

18. For a more comprehensive discussion of the necessary conditions for the economic optimization of solar HVAC systems and the building envelope, see R. T. Ruegg: *Solar Heating and Cooling in Buildings: Methods of Economic Analysis*, National Bureau of Standards Interagency Report 75-712, July 1975, pp. 35–40.

19. R. T. Ruegg: *Evaluating Incentives for Solar Heating*, National Bureau of Standards Interagency Report 76-1127, September 1976.

incentives in the model was in recognition of the considerable legislative activity at both the state and federal levels to enact financial programs to encourage the widespread use of solar energy systems.[20]

Table 6 presents the results of eight hypothetical case studies described in the National Bureau of Standards publication. The case studies are for climate regions typical of Madison, Wisconsin, and of Albuquerque, New Mexico. They assume solar equipment costs, fuel prices, and tax rates typical of those found in many parts of the country, but not necessarily specific to Madison and Albuquerque. Costs are based on 500 ft^2 of a "standard" liquid collector at \$10.50/ft^2 installed, plus \$1,700 of non-collector components, or a total of \$6,950. The solar heating system is assumed to supply 75% of the 65 $\times$ 10^6 Btu heating load of a

TABLE 6

Annual Savings to the Owner of a Solar-Equipped Building with and without Incentives: Case Studies[a]

Building type	Selected locations	Fuel cost/ therm output
Residential	Albuquerque, NM	$.45
		$.90
	Madison, WI	$.45
		$.90
Commercial	Madison, WI	$.45
		$.90

20. National Conference of State Legislatures Energy Task Force, *Turning Towards the Sun*, vol. 1 (Abstracts of State Legislative Enactments of 1974 and 1975 Regarding Solar Energy), n.d.; Robert M. Eisenhard: *A Survey of State Legislation Relating to Solar Energy*, National Bureau of Standards Interagency Report 76-1082, April 1976; and J. Glen Moore, "Solar Energy Legislation in the 94th Congress: A Compilation of Bills through June 30, 1976," the Library of Congress, Congressional Research Service, unpublished abstracts of bills.

1,500 ft² house in Albuquerque, and 47% of the 118 × 10^6 Btu heating load of a 1,500 ft² house in Madison, Wisconsin. The assumed system life is 25 years. Tax effects are computed with a composite state and federal rate of 32% for systems used on owner-occupied residences, and 50% for systems used on commercial buildings. Future cash flows are discounted with a real rate of 3% for residential systems, and 10% for commercial systems. For each location and building type, life-cycle costs are evaluated first for a fuel cost of $.45/therm of heat output, and second for a cost of $.90/therm of heat output. The $.45/therm fuel cost is equivalent to a price of $.015/kWh of electricity, $.38/gal of fuel oil, and $.27/therm for natural gas. The $.90/therm fuel cost is equivalent to a price of $.03/kWh, $.76/gal, and $.54/therm. The fuel costs per therm of heat output are based on the

Annual net savings in dollars

(1) Before taxes No incentives	(2) With taxes No incentives	(3) Grant or tax credit $1,000	(4) 3% prop. tax exempt.	(5) 5-yr. depr. allow.	(6) 4% sales tax exempt.	(7) Interest subsidy 2%	(8) Fuel tax 20%
−110	−190	−110	−50	−80	−180	−160	−140
300	230	310	370	350	240	260	340
−60	−140	−60	10	−20	−130	−100	−70
			130[c]				
410	340	420	480	460	350	370	470
			600[c]				
−200	−350[b]	−300	−250	−190	−330	−300	−310
			−90[c]				
180	−150	−70	−40	10	−130	−100	−70
			110[c]				

[a]Note that this compilation of annual savings is based on a specific set of assumptions regarding input variables such as cost and performance of the system, the heating load of the building, the future escalation of energy prices, and discount rates and tax rates. A different set of assumptions would produce different results.

[b]Use of a double-declining balance method of depreciation and a 10-year life instead of a straight-line method and a 25-year life would reduce annual losses with existing taxes from $350 to $204.

[c]The annual savings or losses are based on a combination of the two incentives bracketed.

following system efficiencies: electric resistance system, 100%; oil furnace, 60%; natural gas system, 60%. Energy prices are assumed to escalate at a rate 5% faster than general price inflation.

The results of the case studies are given for a homeowner and a business in terms of the annual net savings (or annual net losses where a minus sign precedes the number) to be realized by the building owner under eight different conditions: (1) before any taxes and without incentives; (2) with existing "typical" taxes and without incentives; (3) with taxes and a grant or a tax credit of $1,000; (4) with taxes and an exemption of the assumed 3% property tax; (5) with taxes and a five-year depreciation tax write-off of the investment cost of the solar energy system; (6) with taxes and an exemption of the assumed 4% sales tax on purchase of the solar equipment; (7) with taxes and an interest subsidy of 2% on the loan for the purchase of the solar energy system; and (8) with taxes and a special tax on fuel of 20%. From Table 6, we can see that the cost effectiveness of this particular solar heating system is quite sensitive to the cost of fuel, as well as to the applicable tax rules and special governmental incentive programs. With a fuel cost of $.45/therm of heat output, for example, this particular system appears not to be cost effective, except for a residential structure in Madison under conditions (4) and (5) combined. However, with a fuel cost of $.90/therm of heat output, this particular system appears generally cost effective to homeowners under all eight conditions described. For the same system installed in a commercial building with an equal heating load (i.e., only the tax provisions are different), the outcome appears less favorable to the use of the solar heating system. That is, it is cost effective on an after-tax basis only under condition (5).

It should be stressed that the results presented in Table 6 are based on specific conditions and are not measures of the cost effectiveness of solar energy systems in general. The point is that it is possible to apply an LCC model for the particular circumstances of an individual building owner and thereby gain a clearer idea of the economic desirability of fitting the building with a solar energy system.

Energy Conservation Standards for New Buildings A promising new application of LCC analysis in energy conservation is in the development of energy conservation performance standards for new residential and commercial buildings. Title III of Public Law 94-385, The Energy Conservation Standards for New Buildings Act of 1976, requires the Secretary of Housing and Urban Development (HUD) to develop and promulgate building performance standards that achieve the "maximum practicable improvement in energy efficiency" while meeting minimum habitability criteria.

Several questions have to be answered about these standards. First, should one standard be used for all types of buildings in the United States, regardless of building type and fuel price? Second,

TABLE 7

Present Value of Life-Cycle Costs of Alternative Energy Budget Standards for a Small Office Building[a]

Annual energy budget (1,000 Btu)	Present value of energy costs	Mild climate		Cold climate	
		First cost	Total life-cycle cost	First cost	Total life-cycle cost
(1)	(2)	(3)	(4) = (2) + (3)	(5)	(6) = (2) + (5)
40	$18,000	$25,000	$43,000	$50,000	$68,000
50	22,500	20,000	42,500	40,000	62,500
60	27,000	16,667	43,667	33,333	60,333
70	31,500	14,286	45,786	28,572	60,072
80	36,000	12,500	48,500	25,000	61,000
90	40,500	11,111	51,611	22,222	62,722

[a]Assumptions are the following:
Heating and Cooling Only: cold climate has twice the kWh requirements of the mild climate for the same design.
Life = 30 years
Discount Rate = 10%
Fuel Price Escalation Rate = 6%
kWh used annually for HVAC = 40,000
Present Cost per kWh = $.025
Energy requirements are inversely proportional to conservation investment.

on what factors should the development of a standard depend? Should we base it on potential LCC savings of energy and investment costs, or on a selected percentage reduction in building energy consumption?

The National Bureau of Standards is conducting research on the development of building standards for energy conservation. An LCC approach is being studied which bases the standard for a given climate/fuel price/building type on the expected savings in energy over the life cycle of that building and the costs of the energy-conserving technique. The economically efficient standard will require that level of energy conservation beyond which an additional investment would not be covered by extra dollar energy savings, and below which potential net dollar savings would be lost.

An example of the dollar losses that could result from a standard that does not take into account life-cycle costs and savings is illustrated in *Table 7*. Assume that a performance standard in the form of a maximum "energy budget" (i.e., a maximum allowable energy consumption for specific uses, such as heating and cooling) is to be assigned to an office building. A set figure, such as GSA's budget of 55,000 Btu/gross ft²/year for new buildings, could be established, or a variable budget could be selected as a function of climate and fuel price.

Table 7 shows, in dollar terms, how the same annual energy budget required of two identical office buildings, one located in a mild climate (e.g., Atlanta) and the other in a cold climate (e.g., Chicago), could result in economic losses to building owners in both regions. (Although building type and fuel price are fixed in

Table 7, these variables too affect the optimum energy budget.) Looking at columns 4 and 6 in comparison with column 1, we see that the annual energy budget that minimizes total life-cycle costs for the building in a mild climate is 50,000 Btu, for a cost of $42,500. In a cold climate, it is 70,000 Btu, for a cost of $60,072. Picking an energy budget that is efficient for either one of the climate regions would be inefficient for the building in the other region. For example, establishing 50,000 Btu as the budget would result in a loss of $2,428 (i.e., $62,500 − $60,072) for the building in the cold climate, for which the efficient budget is 70,000 Btu. Picking a budget below or above the range bounded by the efficient levels (50,000 to 70,000 Btu) would also result in losses. For example, establishing a budget of 80,000 Btu would result in a loss of $6,000 to the building owner in the mild climate and $928 in the cold climate. An efficiency loss occurs even when a budget between the optimal levels is chosen. Taking 60,000 Btu in this case, for example, will result in a loss to the building owner in the mild climate of $1,167, and in the cold climate of $261.

The examples of dollar losses described above show clearly the life-cycle savings to be gained by having an economically efficient energy budget for each climate. What is less obvious, however, is that building owners as a group may gain not only in energy cost savings, but in savings of initial investment costs as well. For example, looking again at Table 7, and taking 60,000 Btu as the standard for both climates, the combined first cost will be $50,000. But if we take the efficient budgets of 50,000 Btu for the mild climate and 70,000 Btu for the cold climate, the combined first cost is $48,572. In this case, a combined first-cost savings of $1,428 results from selecting efficient budgets for each climatic region. Note further that these energy and first-cost savings are achieved at the same level of 120,000 Btu of energy consumption (i.e., 60,000 Btu + 60,000 Btu = 50,000 + 70,000 Btu).

Promulgators of a single uniform standard might defend it on the basis that it is easier to determine, explain, and enforce. However, tables like Table 7 can be provided to local code authorities with the energy budgets appropriate for their region, not only in terms of climate factors, but in terms of fuel prices and building types as well. The potential national resource savings from setting energy budgets which are sensitive to climate and life-cycle costs may outweigh considerably the inconvenience and cost of administering a variable standard.

Where Do We Go From Here?

This chapter has described state-of-the-art techniques for measuring life-cycle savings of energy-conserving approaches to building design.

One might conclude from this chapter that architects and engineers have only to apply LCC analysis to all design decisions to determine the most cost-efficient allocation of resources for energy conservation in buildings. Theoretically this is true; certainly a broader awareness of LCC techniques in the design professions will, in fact, lead to greater economic efficiency in the use of energy conservation designs for buildings. Impediments to widespread application of these techniques do exist, however, and it will be helpful to know what they are.

One impediment is that the calculation of life-cycle costs and savings require life-cycle data on performance, durability, dependability, present and future operation and maintenance costs, and knowledge of the appropriate discount rate. Thus, although LCC analysis is relatively straightforward, the results are generally sensitive to a number of data assumptions, some of which may be quite uncertain. A second deterrent to the application of LCC analysis is that the analyses of complex systems may be expensive. At present, it is generally advisable to undertake an LCC analysis for individual projects only when large expenditures are involved and the economic feasibility of various design alternatives is not apparent. Advances in computer technology and access to better data may change this in the future. Third, and probably most significant, the building owner or developer may have objectives that are in conflict with the selection of the energy conservation techniques that are the most economically efficient. For example, speculative builders producing units for quick turn-over generally have a very short time horizon and are interested in minimizing total building costs for only that short possession period prior to the first sale. Thus, many builders are likely to aim at minimizing only those costs they themselves incur and may not take into account the life-cycle costs that accrue to subsequent building owners. Hopefully, building purchasers will become more informed about the potential savings from energy conservation design and consequently will be willing to pay more for energy-conserving buildings, which in turn will make it profitable for builders and developers to extend their investment time horizon beyond their actual period of ownership and to seek the architect's assistance in choosing building designs with cost-effective, energy-conserving features.

In conclusion, we envision wider use of LCC analysis in evaluating energy-conserving designs and a better understanding and use of the LCC analysis at all levels in the building community, including builders, owners, architect/designers, mechanical engineers, and mortgage lenders. A wider use of LCC analysis will thus enable more efficient allocation of energy resources for use in buildings, lower total life-cycle costs for buildings than would otherwise result, and more energy conserved per dollar invested in conservation techniques.

END