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ABSTRACT

An energy analysis computer program, DOE-2, was used to compute annual energy use for a typical office building as originally designed and with several energy conserving design modifications. The largest energy use reductions were obtained with the incorporation of daylighting techniques, the use of double pane windows, night temperature setback, and the reduction of artificial lighting levels.

A life-cycle cost model was developed to assess the cost-effectiveness of the design modifications discussed above. The model incorporates such features as inclusion of taxes, depreciation, and financing of conservation investments. The energy conserving strategies are ranked according to economic criteria such as net present benefit, discounted payback period and benefit to cost ratio.

KEYWORDS

Cost-benefit analysis, energy conservation, energy analysis, life-cycle cost model, office building.

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INTRODUCTION

An energy and life cycle cost analysis was carried out for a six-story, 100,000 square foot office building. The building energy analysis computer program, DOE-2.1 (Lokmanhekim, 1979), was utilized to obtain annual energy consumption by end use. Annual energy use for the base case building and for several energy-conserving designs, plus initial added cost of the energy-conserving measures, served as input to a life-cycle cost model (LCCM). The LCCM is utilized to assess the economic costs and benefits (with reference to a base case building) to the commercial building owner who constructs a new building of varying initial cost and energy efficiency. The conservation measures that were evaluated include:

(1) building orientation

(2) added insulation

(3) single and double glazing with varying solar transmission

(4) use of daylighting

(5) use of night setback thermostats

(6) use of thermostat deadbands

BASE CASE BUILDING ENERGY ANALYSIS

Many assumptions must be made concerning the base case building's operating conditions and characteristics before its operation can be simulated with DOE-2.1. Our main source of information about appropriate assumptions is included in a report prepared for the Department of Energy (DOE) by Fleming and Associates (Fleming, 1981). This report contains occupancy, lighting and hot water use schedules, thermostat set points, etc., intended for use in obtaining the design energy consumption for various commercial building types.

The annual energy use profile for a six-story office building located in Denver (using a 1971 NOAA weather tape) is shown in Figure 1. This building is one of those studied during Phase II of the DOE Building Energy Performance Standards (BEPS) project (AIA, 1979). The lighting load in the DOE-2.1 simulation is 2.6 W/ft^2 and the ratio of window to wall area is 25%. Cooling and space heating are provided by a zoned, water to air unitary heat pump system with a circulating water loop. A 300kW electric boiler provides off-peak heat generation. Also shown in Figure 1 is the peak demand for each month in kW. For this building type in Denver's climate zone, energy consumption and peak demand are greatest in the winter months. The total annual energy use is approximately 50,000 Btu/ft^2.

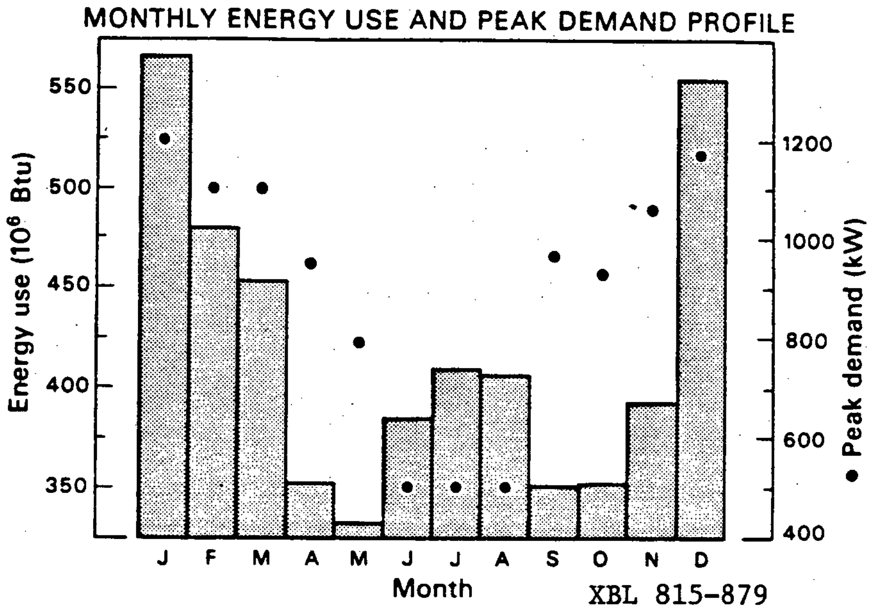

Fig. 1 Total building site energy use and peak demand are shown for each month, in a six story office building located in Denver.

We have studied the effect of moving the office building from Denver to other cities by calculating the annual heating and cooling loads for the entire building in four climate zones. In future work we will alter the heating, ventilation, and air conditioning system as appropriate for different climate zones and compute annual energy use. Table 1 summarizes the results of the present study. Both the heating and cooling loads are seen to vary significantly with the number of heating degree days and cooling load hours respectively. The cooling load is less sensi-

Table 1: Heating and Cooling Loads as a Function of Climate Zone, Six Story Office Building

City	Base 65°F Heating Degree Days	Number of Hours > 80°F	(10^6 Btu) Heating Load	(10^6 Btu) Cooling Load	(10^6 Btu) Total Heating Plus Cooling Load
Miami, Florida	206	2408	87	3740	3827
Birmingham, Alabama	2844	1380	937	2504	3441
Denver, Colorado	6016	667	2325	1725	4050
Portland, Maine	7498	206	2856	1367	4223

tive than the heating load to climatic changes since the load from the occupants and lights dominate the building cooling load. The sum of the heating and cooling loads shows a maximum change of 15% from one city to another. Therefore, if the efficiencies of the heating and cooling systems employed in the various cities are similar, then the energy used for space conditioning will vary by no more than approximately 15%. This corresponds to a 7.5% change in total energy use for a very wide range of climatic conditions.

ENERGY ANALYSIS OF REDESIGNED BUILDINGS

Glazing Choice and use of Daylighting

Figure 2 shows the results of a parametric energy analysis, performed for the office building located in Denver, designed to determine the dependence of space conditioning energy use on the solar transmission of both single and double glazing. Changes in heating and cooling energy consumption tend to cancel each other when the transmission of the windows is varied. Fig. 2 also shows that space conditioning energy use is approximately 25% lower for

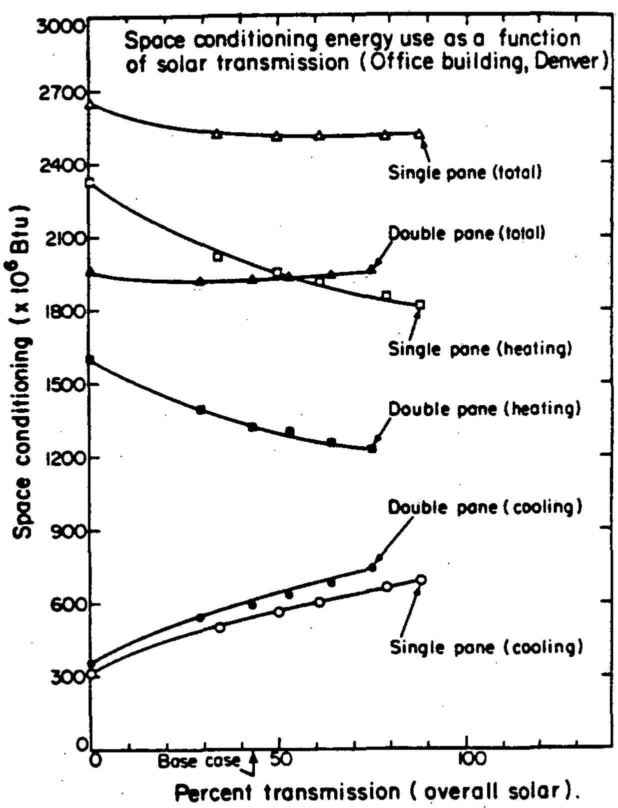

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Fig. 2 Space conditioning energy use is shown as a function of overall solar transmission for single and double pane windows.

double pane as compared to single pane windows of the same solar transmittance.

The weak dependence of the total space conditioning energy use on the solar transmittance of the glazing is a very important finding; it implies that in a climate zone similar to Denver's, the maximum benefit from the use of daylight to offset electric lighting consumption will occur when the glazing with the maximum visible light transmission is utilized. In the daylighting analysis we assumed that lighting existed throughout the building perimeter at a level of 50 footcandles and that the maximum lighting power reduction was 70% for the base case building power use when the daylight availability reached 50 footcandles. We also assumed that only diffuse sky light is used as a substitute for electrical lighting in order to minimize glare which would otherwise result from direct sunlight. The reduction in power use is achieved through a dimmable lighting control system actuated by photoelectric sensors. The lighting schedules were modified in the perimeter zones (40% of building floor space) for each orientation and for each of the four seasons of the year. Details of the method of analysis are discussed in a report prepared by Selkowitz (1980), of LBL's Windows and Lighting Group.

Tables 2 and 3 show energy consumption by end use for double and single pane windows respectively--with and without daylighting.

Table 2. Energy Use as a Function of Glazing Type and Daylighting Utilization In a Six-Story Office Building in Denver

SITE ENERGY USE 10^6 Btu	***Double-Pane***					
	(Bronzed Glass) BASE CASE	BASE CASE Daylighting	CLEAR GLASS No Daylighting	CLEAR GLASS Daylighting	BLUE-GREEN GLASS No Daylighting	BLUE-GREEN GLASS Daylighting
SPACE HEATING	1332	1423	1253	1357	1332	1445
SPACE COOLING	586	509	685	586	586	498
HVAC AUXILIARY	50	48	55	53	50	48
DOMESTIC HOT WATER	409	409	409	409	409	409
LIGHTS	2568	2167	2568	2095	2568	2108
VERTICAL TRANSPORT	93	93	93	93	93	93
TOTAL	5038	4649	5062	4594	5038	4601
% HOURS ANY ZONE OUTSIDE THROTTLING RANGE	7.9%	8.1%	8.9%	8.6%	7.9%	8.1%

It can be seen that daylighting utilization allows a reduction in energy used for cooling, lighting and fans. At the same time it increases the energy required for space heating. The net result is a reduction in total building energy use; the maximum reduction is approximately 10% for double pane windows in the Denver climate zone.

Table 3. Energy Use as a Function of Glazing Type and Daylighting Utilization In a Six-Story Office Building in Denver

SITE ENERGY USE 10^6 Btu	***************************Single-Pane***************************					
	GREY GLASS No Daylighting	GREY GLASS Daylighting	BLUE-GREEN GLASS No Daylighting	BLUE-GREEN GLASS Daylighting	CLEAR GLASS No Daylighting	CLEAR GLASS Daylighting
SPACE HEATING	1952	2053	1952	2072	1852	1977
SPACE COOLING	560	490	560	477	659	567
HVAC AUXILIARY	63	60	63	60	67	65
DOMESTIC HOT WATER	409	409	409	409	409	409
LIGHTS	2568	2167	2568	2095	2568	2070
VERTICAL TRANSPORT	93	93	93	93	93	93
TOTAL	5644	5273	5644	5206	5648	5182
% HOURS ANY ZONE OUTSIDE THROTTLING RANGE	7.5%	7.5%	7.5%	7.8%	8.3%	8.1%

A parametric energy analysis was also carried out for varying amounts of roof and wall insulation. Tables 4 and 5 show the results of the energy and cost-benefit analysis for roof and wall insulation respectively. The maximum reduction in total energy use is quite small, between 2 and 3% for 12 inches of fiberglass insulation as compared to 3 inches of fiberglass insulation in both cases. The cost benefit analysis is discussed in a later section.

Table 4. Summary of Results From Economic Analysis** of Varying Roof Insulation (Three-Inch Wall Insulation), Office Building, Denver

Option	Annual Energy Use (10^6 Btu)	Added Initial Cost (1981 $)	Sum of Monthly Peak Demand (kw)	Net Present Benefit (1981 $)	Benefit* To Cost Ratio	Discounted Payback Period
R11 3" insulation Base Case	4923	0	10,539	-	-	-
R19 6" insulation	4847	2000	10,386	19,855	10.9	3.1
9" insulation	4817	6200	10,233	32,252	4.0	5.5
12" insulation	4801	8200	10,167	37,948	3.9	5.8

* This is a marginal benefit to cost ratio, relative to previous measure. Other economic parameters are calculated relative to the base case.

** Discount rate and fuel escalation rates are 3% and 2.5% real respectively. Building assumed to have 25 year economic lifetime and tax rate assumed to be 50%.

Table 5. Summary of Results From Economic Analysis** of Varying Wall Insulation (Six-Inch Roof Insulation), Office Building, Denver

Option	Annual Energy Use (10^6 Btu)	Added Initial Cost (1981 $)	Sum of Monthly Peak Demand (kw)	Net Present Benefit (1981 $)	Benefit* To Cost Ratio	Discounted Payback Period
R11 3" insulation Base Case	4847	0	10,386	-	-	-
R19 6" insulation	4760	3900	10,007	39,652	11.2	2.0
9" insulation	4728	12,100	9837	51,079	2.4	7.1
12" insulation	4711	16,000	9815	51,002	.98	8.0

* This is a marginal benefit to cost ratio, relative to previous measure. Other economic parameters are calculated relative to the base case.

** Discount rate and fuel escalation rates are 3% and 2.5% real respectively. Building assumed to have 25 year economic lifetime and tax rate assumed to be 50%.

Other Energy Conserving Measures

Table 6 summarizes energy consumption by end use for a number of conservation measures carried out in the six-story office building located in a Denver climate zone. The first measure, changes in orientation, produces less than a 1% change in total energy use. The original orientation of the building (dimensions of 70 ft by 220 ft) is with the long axis oriented northeast to southwest at an angle of 60° East of North. The other two orientations that were simulated (Table 6) are a due north and a due east orientation for the long axis.

Table 6. Energy Use as a Function of Various Design Measures

SITE ENERGY USE 10^6 Btu	BASE* CASE	ORIENTATION AZIMUTH=0	ORIENTATION AZIMUTH=90	THERMOSTAT DEADBAND INCREASED T_H=69 T_C=81	NIGHT SETBACK REMOVED	NIGHT SETBACK EQUALS 55°F	ELECTRICAL LIGHTING DECREASED TO 1.5 w/f^2
SPACE HEATING	1338	1368	1356	1025	1698	1298	1678
SPACE COOLING	595	608	580	547	623	594	400
HVAC AUXILIARY	50	53	51	57	57	48	51
DOMESTIC HOT WATER	409	409	409	409	409	409	409
LIGHTS	2568	2568	2568	2568	2568	2568	1465
VERTICAL TRANSPORT	93	93	93	93	93	93	93
TOTAL	5053	5098	5036	4700	5447	5009	4098
% HOURS ANY ZONE OUTSIDE THROTTLING RANGE	7.2%	8.8%	7.1%	3.8%	1.8%	8.9%	7.3%

* Azimuth = 60°F
Night Setback = 60°F
Heating Set Temperature = 72°F = T_H
Cooling Set Temperature = 77°F = T_C
Insulation = Roof 3", Walls 1" of Polystyrene

Altering the thermostat setpoints produces a significant change in energy use. The base case building utilized heating and cooling thermostat setpoints of 72° F and 77° F respectively. Widening the deadband (temperature range where neither heating or cooling takes place) so that the setpoints are 69° F and 81° F respectively, results in a 6% decrease in total annual energy use. This is not a very large change in total annual energy use considering the large increase in deadband width from 3° F to 10° F . The heating energy use however, decreased by 23% and the cooling energy use by 7%. Energy used for space heating is approximately one quarter of the total energy use, so a relatively large change in that end use resulted in only a 6% change in total energy use. We have not calculated the net present benefit derived from expansion of the deadband as this conservation measure may adversely affect the comfort of the building occupants.

We have also studied the effect of varying the night setback temperature on total building energy use. The base case building was modelled with a 60° F night setback temperature from 6 P.M. to 6 A.M. Monday through Friday and all day weekends and holidays. Reducing the night setback temperature to 55° F causes less than a 1% reduction in annual energy use and increases the percentage of hours that any zone is outside the throttling range from 7.2 to 8.9%. Removing the night setback entirely increases energy use by 8% and decreases the number of hours that any zone is outside the throttling range to 1.8%. Most of the hours that the indoor temperature falls outside the throttling range occur before 8 A.M. during the equipment start up time in the winter months. Therefore, we consider a 60° F night setback temperature to be reasonable as regards comfort of building occupants.

A reduction of the electric lighting power density to 1.5 w/ft^2 from 2.6 w/ft^2 reduces annual energy use to 4100 x 10^6 Btu. Further investigation is necessary before we can determine if the comfort or productivity of building occupants would be affected by this energy-conserving measure.

COST BENEFIT ANALYSIS

Methodology

We applied the methodology of life-cycle cost analysis to the evaluation of the economic costs and benefits (with reference to a base case building) to the commercial building owner who constructs a new building of varying initial costs and energy efficiency. There are a number of economic parameters that may be evaluated to rank a series of potential capital investments. These include: rate of return, net present benefit or life-cycle cost reduction, payback period and benefit to cost ratio. All of these, except payback period, yield the same rank ordering when a list of potential investments is prioritized.

The life-cycle cost of owning and operating a building is equal to the purchase price plus the operating and maintenance costs over the lifetime of the building. In our analysis, we assumed that the purchase price is financed by a loan. The major inputs required for performance of a life-cycle cost analysis are: initial cost, annual energy use, and an assortment of energy cost and financial factors. Energy cost factors include initial fuel costs, fuel cost escalation rates, and peak power charges. In order to rank a number of potential capital investments (energy-conserving measures or otherwise) a profit making organization should consider the effects of taxes, depreciation, and the cost of capital. The LCCM developed at LBL takes account of these factors and computes all the economic parameters mentioned above. In developing this model we assumed that all expenses and revenues would not be known, and therefore calculated differences in LCC between redesigned and base case buildings. We assumed that unknown costs and revenues, such as insurance, property taxes, and rental income remained constant as energy use varied.

It is important to consider the effect of taxes in the cost-benefit analysis, since a reduction in energy use causes a decrease in expenses and corresponding increase in taxable income and therefore taxes. Hence, the benefit derived from an energy-conserving investment is lessened when it is appropriate to consider taxes. In order to compute taxes owed (one of the costs in total LCC) it is necessary to determine the annual cash flow before taxes. We make the conservative assumption (i.e., it lowers benefits) that revenues in the form of rental income are unchanged when the building is constructed in a more energy efficient manner.

One of the objectives of the life-cycle costing process is the minimization of total cost or maximization of net benefit to the building owner. The net present benefit is essentially the difference between after tax energy cost savings and initial investment--with proper discounting and energy cost escalation. If the more efficient building design results in greater net benefit to the owner-builder over the lifetime of the building, the owner-builder benefits although a higher initial capital outlay may cause an adverse impact in the short run. This potential problem of higher first costs associated with greater net benefit of more energy-efficient buildings will be assessed in terms of a payback period, that is, the time required for the investor to recoup his or her additional investment in a more energy efficient building.

Assumptions

The results of the economic analysis depend on estimates of several factors. These include discount rate, fuel-price escalation rate, initial fuel price and additional cost of the conservation measure. There is almost always some uncertainty in projecting values for these parameters. Thus a sensitivity study was performed. The base case parameters are described below.

We chose an economic life time for the building and a loan amortization period of 25 years for our basic economic studies. The loan interest rate, discount rate, and fuel escalation rate were chosen to be 3%, 3%, and 2.5% real, respectively.* The initial electricity price ($.023/kWh) and peak demand charge ($8.18/kw) were obtained from the Public Service Company of Colorado.

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*At a 10% annual inflation rate, these rates are 13%, 13%, and 12.5% respectively.

We assumed no change in maintenance costs and a 50% tax rate for all of our economic studies. Although we calculated all economic parameters for three depreciation methods (straight line, sum of years, double declining balance) we have only included results obtained from the first method since there was little difference in the final results among the three methods. However, the pattern of cash flows is altered by varying the method of depreciation. The cost of the various conservation measures was obtained through telephone calls to equipment suppliers and from two other sources of construction costs (Saylor, 1981., Winkelmann, 1981.).

Results

Tables 4 and 5 summarize the results of the cost benefit analysis for varying amounts of roof and wall insulation respectively. The added initial cost of the conservation measures shown in Tables 4 and 5 include only the added cost of insulation material and labor but not any other potential costs of additional framing. It appears to be cost-effective to use 12 inches of roof insulation in the Denver climate zone. The payback period for 12 inches of insulation (relative to the base case of 3 inches) is 5.8 years. Many builders of commercial buildings may choose option 2 (6 inches of insulation) of this conservation measure because of its much shorter payback period (3.1 years). For energy-conserving measures in existing commercial buildings, the desired payback period is usually 2-3 years or less (Turiel, 1981). When wall insulation thickness is varied and roof insulation thickness remains constant at 6 inches, we find 9 inches to be the greatest thickness of insulation that is cost effective. However, the payback period of 7 years will probably discourage most builders from going beyond 6 inches of wall insulation (R-19). As stated earlier, the energy savings derived from increasing insulation are very small and the cost of the conservation invesment may be somewhat underestimated.

The cost benefit analysis just described was also carried out for a building being designed by a non-profit making organization such as a government agency. In this case, there are no tax considerations. As expected, the benefit to cost ratios of all measures increase (~ a factor of two) and all the payback periods decrease (~ a factor of two). Therefore, all conservation measures are more cost-effective when taxes are not one of the costs.

We have performed a cost-benefit analysis of different glazing types with and without daylighting. Table 7 summarizes the results of this analysis. Figure 3 illustrates the relationship between the net present benefit, relative to the base case, derived from each conservation measure and the annual energy use. The maximum net present benefit occurs at a site energy use of approximately 47,000 Btu/ft^2 although there is less than a 10% difference in the net present benefit for double pane glass with reflective coating (31% reflectance for overall solar spectrum) and blue-green tinted double-pane glass with daylighting. There is however, a large increase in the discounted payback period from 1.7 to 5.5 years which may discourage profit making organizations from making the added initial investment of approximately $27,000.

Table 7. Summary of Results From Economic Analysis, Office Building, Denver

Option	Annual Energy Use (10^6 Btu)	Added Initial Cost (1981 $)	Sum of Monthly Peak Demands(kw)	Net Present Benefit 10^3 (1981 $)	Benefit* To Cost Ratio	Discounted Payback Period (Years)
Single-Pane, Clear Glass (BASE CASE)	5648	0	12,283	0	-	-
Double-Pane, Bronzed Glass	5038	15,000	10,675	188.9	13.6	1.65
Double-Pane, Reflective	4774	23,600	9814	284.7	12.1	1.7
Double-Pane, Blue-Green-w/Daylighting	4600	50,000	9921	262.1	.14	5.5

* This is a marginal benefit to cost ratio relative to the previous measure. Other economic parameters are calculated relative to the BASE CASE.

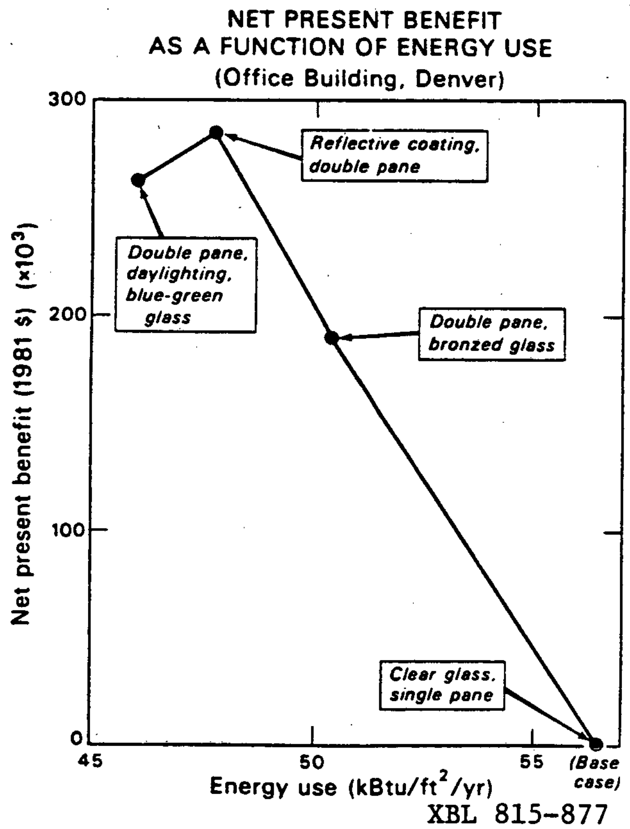

Fig. 3 The relationship between net present benefit and energy use is shown for several measures in a six-story office building located in Denver.

Sensitivity Studies

The sensitivity of the results shown in Table 7 to variations in a number of parameters was studied. The position of the maximum in net present benefit was unchanged by all of the following variations carried out one at a time. We assessed variations in the fuel price escalation rate of zero to 5% real, discount rate of 1% to 6%, economic lifetime of 10 to 25 years, tax rate of zero to 50%, depreciation period of 5 to 15 years, and initial cost of ±50% of original values. The marginal benefit to cost ratios are sensitive to values of the above parameters, particularly for the case of the fourth option relative to the third option.

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