Energy Savings and Interactions from Retrofit Measures in Small Commercial Buildings in Boston

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ABSTRACT

This paper presents simulation results that show some of the interactions that can occur within a building and between measures as a result of building energy retrofits. A baseline small commercial building is modeled to determine the impacts to building energy consumption from both shell and equipment retrofit measures using Boston weather data. Some interactions can be easily overlooked, and evaluating the economics of installing single and multiple measures in a building without considering interactive effects can lead to major discrepancies between savings projections and what really occurs.

INTRODUCTION

Existing buildings are being retrofitted daily by consumers, weatherization programs, demand-side management programs, and others seeking to reduce or control energy use. Numerous measures are available that will provide both energy consumption and demand reductions to benefit the consumer, business, and/or utility. Load calculations to determine benefits of a measure are often made without complete consideration of the interactions that can occur within a building or between measures (ASHRAE 1989; Treado 1989). In this study, five retrofit measures that offer substantial reductions in energy use are evaluated for their energy-savings potential and energy-savings interactions using a simulation program. Demand savings are not addressed here, but their inclusion could significantly improve the paybacks determined for some measures. Although a specific building is modeled, the results offer insight into the relative importance of these measures from an energy viewpoint that may apply to a variety of buildings.

APPROACH

The impacts on natural gas space heating and total electricity consumption in a small commercial building from ceiling insulation, lighting reduction, wall insulation, high-efficiency air conditioning, and thermostat setback/setup are evaluated. In addition, the interaction between various levels of ceiling insulation and other measures is examined along with the interactions that occur between measures targeted at specific end uses (lighting and cooling) and heating and cooling loads. Retrofit measures and their effect on building loads are evaluated using the DOE2.1D computer simulation code (LBL 1989). A baseline small commercial building is utilized for each simulation. The building's construction and systems are modified as needed to determine the resulting heating and cooling loads for each measure. Loads are calculated based on NOAA typical meteorological year weather data for Boston, Massachusetts (NOAA). Boston weather data are used because the original research on which this paper is based is targeted at buildings in the Boston area.

Reductions in natural gas and total electricity consumption are converted to cost savings for cases of low and high fuel costs. These cost savings are then related to measure costs to provide payback results. A range of low and high measure costs is also used so that results will likely bracket the wide range of fuel and measure costs that occur in practice.

BUILDING DESCRIPTION

The baseline building used in the simulations is a slightly modified version of a small office/bank building simulated in previous energy conservation standards and guidelines work (PNL 1983). The building is one story with 2642 ft^2 of floor area (concrete slab). Frame-and-brick facade walls have 1786 ft^2 of exterior wall area, and double-pane glass represents an additional 613 ft^2 (25% glass). The baseline building has no wall, ceiling, or roof insulation. A flat, built-up roof covers the attic (the open area between the ceiling and roof), which contains the return air ducts for the heating and cooling systems. The building is fully occupied during weekdays (average of 17 people) for nine hours per day. The occupied lighting level is set at 2.9 W/ft^2 in 80% of the building, 1.3 W/ft^2 in 14%, and 0 W/ft^2 in the remaining 6%. Unoccupied weekday, weekend, and holiday hours have lighting levels equal to 5% of that during normal business hours. The building is occupied for nine hours on Saturday with an average of two occupants and lighting levels equal to 15% of that during weekday business hours.

Ninety-three percent of the building floor area is heated and cooled. Building cooling is provided by two packaged single-zone systems, 3 and 4 tons each, with COPs of 2.43 and supply fan efficiencies of 60%. Heating is supplied by one 120 kBtu/h, natural gas fired, hot water boiler, which

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circulates hot water through coils in each air-handling unit. Distribution fans cycle on and off with the heating and cooling systems. Setpoints for heating and cooling are 72°F and 76°F, respectively. The baseline building does not have temperature setback/setup or timeclock controls. The building infiltration rate is set at 0.6 air changes per hour at a wind speed of 10 mph and is proportional to wind speed.

MEASURES

Five measures are evaluated for their impact on space heating and total electricity use: ceiling insulation, thermostat setback/setup, lighting reductions, wall insulation, and high-efficiency air conditioning. The modeled building is assumed to be capable of receiving each of these measures as a retrofit. In practice, some buildings will likely have obstructions or other factors that will prevent some of these measures from being installed or perhaps increase installation costs such that they are no longer cost-effective.

Ceiling insulation is evaluated at three different insulating ratings: R-7, R-19, and R-30. Ceiling insulation types are assumed to be either blown-in or batt. For practical purposes, different ceiling insulation types would simply change the installation cost for the measure. As a result, the energy savings of adding R-7 rigid roof insulation upon roof replacement could be approximated by the equivalent R-7 ceiling insulation evaluation. Thermostat setpoints for the setback/setup measure are 55°F for heating and 90°F for cooling. Setback/setup is active for 12 hours daily beginning at 6 p.m. except on Sundays and holidays when it is continuous. The lighting energy reduction measure is assumed to consist of the replacement of regular fluorescent tubes and standard ballasts with replacement high-efficiency units. The lighting energy reduction achieved is assumed to be 30% in all areas. The wall insulation retrofit is assumed to be blown-in to an R-11 insulating value. The replacement air-conditioning measure is assumed to represent the installation of high-efficiency air conditioners (COP=3.0) and distribution fans (fan efficiency of 65%).

RESULTS

Space Heating

Annual space-heating energy consumption for the baseline building in Boston is 230 MBtu, or 86.9 kBtu/ft^2. The impact of retrofit measures on baseline consumption can be determined by comparing the predicted building energy consumptions with the measures installed. The heating consumption by measure(s) is shown graphically in Figure 1. This figure shows that adding ceiling insulation to the baseline building is very effective in reducing space-heating energy consumption. Corresponding heating energy savings over the baseline building by measure(s) are summarized in Table 1. The addition of R-7 insulation saves 23.7 kBtu/ft^2 (27%) annually. Additional ceiling insulation increases this savings, although much less than the gain from adding the first R-7 level. The additional savings from adding ceiling insulation above R-19 are much smaller, less than 3 kBtu/ft^2 for all cases examined.

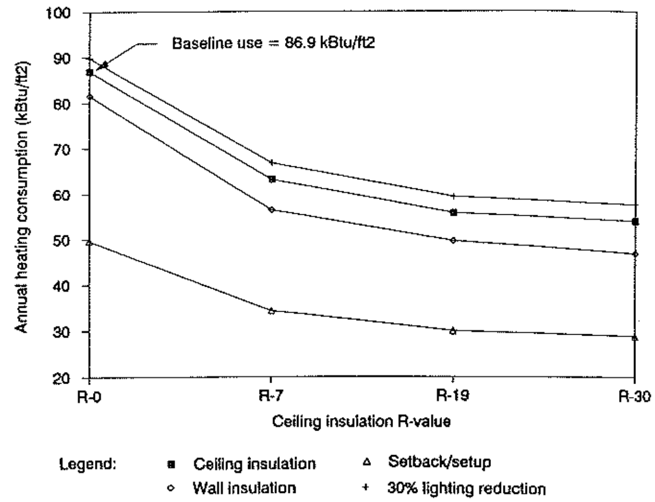

Figure 1 *Building annual heating energy consumption by measure(s) installed.*

Installing thermostat setback saves much more space-heating energy than any of the other measures examined. With no ceiling insulation present, this measure reduces consumption by 37.3 kBtu/ft^2 (43%). When R-30 ceiling insulation is present, this measure reduces consumption by an additional 25.2 kBtu/ft^2, resulting in an annual heating energy use 67% lower than that of the baseline building. As ceiling insulation levels increase above R-19, the slopes of the ceiling insulation line and the setback/setup line in Figure 1 are nearly identical. This indicates little dependency of setback savings on ceiling insulation levels above R-19; that dependency is most prevalent at low ceiling insulation levels (between R-0 and R-7).

A large interaction occurs between the thermostat setup/setback and ceiling insulation measures. When considered individually, their savings account for 37.3 kBtu/ft^2 and 23.7 kBtu/ft^2 (for R-7), respectively, which sum to 61.0 kBtu/ft^2. When evaluated together, their combined savings are 52.5 kBtu/ft^2, 16% less than this sum. This difference approaches 21% for R-30 ceiling insulation.

Wall insulation is also effective for reducing space-heating energy consumption. Unlike the setback\setup measure, wall insulation when combined with ceiling insulation actually performs slightly better (2-5%) than the sum of the savings from the individual measures. Adding R-11 wall insulation reduces space-heating energy use between 5 and 7 kBtu/ft^2, which corresponds to a 6% savings when no ceiling insulation is present and a 13% savings over the building with only R-30 ceiling insulation. These energy savings equate to between 14 and 19 MBtu annually for the building modeled (2642 ft^2).

TABLE 1
Annual Building Heating Energy Savings
Over the Baseline Building by Measure (kBtu/ft^2)

Measure(s)	Ceiling insulation level R-0	R-7	R-19	R-30
Ceiling insulation only	0.0*	23.7	31.1	32.9
Ceiling insulation with 30% lighting energy reduction	-2.9	20.1	27.5	29.3
Ceiling insulation with R-11 wall insulation	5.4	30.4	37.3	40.0
Ceiling insulation with high-efficiency air conditioner	-0.6	23.2	30.7	32.5
Ceiling insulation with thermostat setback/setup	37.3	52.5	56.9	58.1

*Baseline building: annual heating energy use is 86.9 kBtu/ft^2.

The 30% lighting reduction increases space-heating energy consumption. The increase is approximately fixed, depending on the amount of the lighting reduction, although there may be a slight dependency on ceiling insulation level (see Figure 1). The combined savings of the lighting reduction and ceiling insulation is around 3% less than the sum of the savings from the individual measures (refer to Table 1). The penalty for the 30% lighting reduction is an increase in space-heating energy use of around 3 to 4 kBtu/ft^2 (3% to 7% of the space-heating energy use without the lighting reduction).

The impact of installing a high-efficiency air conditioner and fan on annual heating energy consumption is very small and, therefore, not shown alongside the other measures in Figure 1. Installing this measure increases the annual space-heating energy consumption—but less than 1% in all cases. The increase occurs due to assuming a more efficient distribution fan, which results in less fan energy in the form of heat being provided to the interior space. Therefore, the primary heating system must provide slightly more heating to the space. For space heating, there is little if any interaction between this measure and ceiling insulation.

Electricity Use

Total electricity use for the baseline building is 12.34 kWh/ft^2 (42.0 MBtu/ft^2) annually. Consumption by measure(s) installed is shown graphically in Figure 2, and corresponding total electricity savings over the baseline building are summarized in Table 2.

Figure 2 shows that adding ceiling insulation to the baseline building is effective for reducing electricity consumption. The addition of R-7 ceiling insulation saves 0.91 kWh/ft^2 or 7% annually (see Table 2). Additional ceiling insulation increases this savings, although much less than the gain from adding the first R-7 level. The electricity savings from a ceiling insulation level above R-19 is insignificant for this building.

Lighting energy use represents 53% (17,258 kWh or 6.53 kWh/ft^2) of the total electricity consumption for the baseline building. Implementing a 30% lighting energy reduction saves much more electricity than any of the other measures examined. The electricity savings from this measure result from the direct lighting energy reduction and

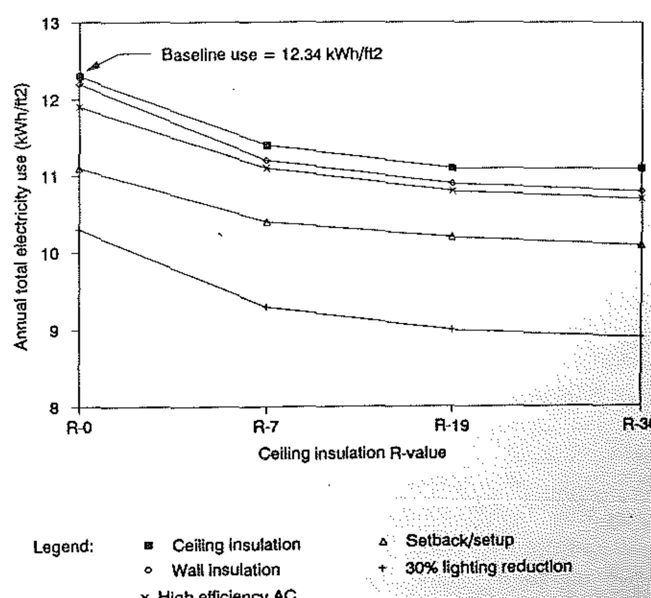

Figure 2 ***Building annual cooling energy consumption by measure(s) installed.***

TABLE 2
Annual Building Total Electricity Savings
Over the Baseline Building by Measure (kWh/ft^2)

Measure(s)	Ceiling insulation level			
	R-0	R-7	R-19	R-30
Ceiling insulation only	0.00*	0.91	1.21	1.29
Ceiling insulation with 30% lighting energy reduction	2.04	3.03	3.33	3.41
Ceiling insulation with R-11 wall insulation	0.15	1.14	1.40	1.51
Ceiling insulation with high-efficiency air conditioner	0.46	1.29	1.55	1.63
Ceiling insulation with thermostat setback/setup	1.25	1.97	2.16	2.23

*Baseline building: annual total electricity use is 12.34 kWh/ft^2.

from lower cooling energy requirements. Lower cooling energy use results because the lower lighting level adds less heat to the interior space during cooling periods. At all ceiling insulation levels, this measure reduces total electricity consumption by approximately 2.0 kWh/ft^2 annually. This corresponds to between 16% and 19% of the total electricity consumption of this building without lighting reduction. When combined, lighting reduction and ceiling insulation perform slightly better than the sum of their individual savings (around 2% to 3%).

Implementing thermostat setup is the second largest total electricity saver. This measure saves approximately half as much electricity as the lighting energy reduction measure. With no ceiling insulation present, this measure reduces total electricity consumption by 1.2 kWh/ft^2 annually (10% of the total electricity use of the baseline building). The presence of ceiling insulation reduces the benefit of this measure slightly. With R-30 ceiling insulation present, this measure reduces consumption by around 0.95 kWh/ft^2, or 8.6% of the consumption of this building without setup. Similar to heating energy savings, there is a large interaction between thermostat setup and ceiling insulation. Combined performance is between 10% and 14% less than the sum of their individual savings. Although not reflected in Table 2, other modeling results indicated no interaction between thermostat setup and the lighting energy reduction.

Adding R-11 wall insulation is the lowest total electricity saver of the measures evaluated. This measure saves around 0.2 kWh/ft^2 annually, representing less than 2% of the building's total electricity use. As in heating, the performance of this measure combined with ceiling insulation is also higher than the sum of the individual savings by 3% to 7%.

Installing a high-efficiency air conditioner saves slightly more electricity than the wall insulation measure. Total electricity savings from this measure ranges from 0.3 to 0.5 kWh/ft^2, corresponding to reductions of between 3% and 4%. This measure provides the higher percentage savings when the ceiling is uninsulated. Combined performance of a high-efficiency air conditioner and ceiling insulation is 6% to 8% less than the sum of their individual savings. Simulation results for fan energy savings exactly matched those from manual calculations based on the efficiencies of the original and replacement fans. Simulated cooling energy savings were around 70% of those calculated manually based on system COPs. This disagreement appears related to the low seasonal COPs indicated by DOE-2 modeling results.

Combined Heating and Cooling Fuel Cost Savings

Savings are evaluated for both low and high fuel costs. The low fuel costs are \$4/MBtu for natural gas and \$0.05/kWh for electricity. The corresponding high fuel costs are \$7/MBtu and \$0.10/kWh. A high and low installation cost for each measure is also evaluated. These ranges bracket reasonable middle ranges of fuel and measure costs found across the country. Ceiling insulation, wall insulation, and thermostat setup/setback provide both gas heating and electricity savings. The heating cost savings from these measures are approximately twice as large as the total electricity cost savings for the Boston climate.

In contrast, while lighting reduction and installing a high-efficiency air conditioner reduce total electricity consumption, they both result in an increase in heating energy consumption. The heating penalty (heating energy increase) from the high-efficiency air conditioner is very small (less than 1% for all cases). The heating energy penalty from reduced lighting, however, is significant, ranging from 3% to 7% of the heating energy use depending on the ceiling insulation level. In site energy terms, the heating penalty for reduced lighting in this building is equivalent to around 40% of the total electricity reduction. The heating penalty in terms of cost is around one-tenth of the electricity cost savings.

Total cost savings (combined heating and cooling savings) by measure are presented in Table 3 for low-cost fuels and Table 4 for high-cost fuels. The ceiling insulation and thermostat setup/setback measures provide the largest cost savings, ranging from $0.21/ft^2 (based on floor area) for low-cost fuels to $0.63/ft^2 for high-cost fuels. Lighting reduction also provides substantial cost savings of $0.09/ft^2 to $0.55/ft^2 using these fuel costs. The wall insulation and high-efficiency air-conditioner measures provide the least cost savings, ranging from a low of only $0.02/ft^2 to a high of $0.43/ft^2. The high fuel cost scenario approximately doubles the cost savings of the low-cost scenario.

TABLE 3
Combined Annual Heating/Total Electricity Cost Savings Over the Baseline Building for Low Fuel Costs ($/ft^2)

Measure(s)	Ceiling insulation level R-0	R-7	R-19	R-30
Ceiling insulation only	0.000*	0.140	0.185	0.196
Ceiling insulation with 30% lighting energy reduction	0.090	0.232	0.276	0.288
Ceiling insulation with R-11 wall insulation	0.029	0.179	0.219	0.236
Ceiling insulation with high-efficiency air conditioner	0.020	0.157	0.200	0.212
Ceiling insulation with thermostat setback/setup	0.212	0.309	0.336	0.344

*Baseline building: combined annual heating and total electricity costs are 0.963 $/ft^2 at low fuel costs. Low fuel costs are $4/MBtu for natural gas and $0.05/kWh for electricity.

TABLE 4
Combined Annual Heating/Total Electricity Cost Savings Over the Baseline Building for High Fuel Costs ($/ft^2)

Measure(s)	Ceiling insulation level R-0	R-7	R-19	R-30
Ceiling insulation only	0.000*	0.257	0.339	0.360
Ceiling insulation with 30% lighting energy reduction	0.184	0.443	0.525	0.546
Ceiling insulation with R-11 wall insulation	0.052	0.327	0.401	0.432
Ceiling insulation with high-efficiency air conditioner	0.041	0.291	0.370	0.391
Ceiling insulation with thermostat setback/setup	0.386	0.565	0.614	0.630

*Baseline building: combined annual heating and total electricity costs are 1.838 $/ft^2 at high fuel costs. High fuels costs are $7/MBtu for natural gas and $0.10/kWh for electricity.

Simple Payback

Simple payback is used as an economic indicator, dividing the first cost (installation cost) of each measure by its first year's fuel cost savings. High and low first costs are used for each measure to bracket a wide range of installation costs. The high and low first costs utilized are listed in Table 5. These costs are based on data from a repair and remodeling cost estimating handbook (Means 1992). Typically, the high and low costs used are about 30% above and below the values reported in this handbook (handbook values represent cost averages across major U.S. cities). Costs are presented on the basis of cost per square foot of floor area because measure savings are reported in this format. The ratio of exterior framed-wall area to total floor area is 0.68.

Measure installation cost data and fuel cost savings results are combined to generate the simple payback curves shown in Figures 3 through 6. The installation cost for a new, high-efficiency air conditioner is so high relative to its estimated energy cost savings that a curve for this measure is not shown. Except for high-efficiency air conditioning, all measures have at least one cost scenario (high fuel cost and low measure cost) where simple payback is less than ten years.

Thermostat setback/setup has the fastest payback at under one year for all cost scenarios (see Figure 6). The payback of this measure changed only slightly with ceiling insulation level.

The second fastest payback is from the addition of ceiling insulation to an uninsulated attic. The payback of this measure ranged between 1 and 8 years (see Figure 3). For low installation costs, ceiling insulation always has a payback of less than three years. The payback period for ceiling insulation increases as higher levels of ceiling insulation are installed. Although not shown in the figure, the payback period of adding insulation to an insulated ceiling can be determined from the data presented. Increasing ceiling insulation from R-7 to R-19 or R-30 provides paybacks of around 4 to 7 years for low measure costs and around 10 to 20 years when measure costs are high. The shorter paybacks (4 and 10 years) are associated with the lower fuel cost.

The payback from a 30% lighting energy reduction ranges from 8 to 27 years (see Figure 4). The high fuel/low measure cost scenario is the only one providing a simple payback of less than 10 years. All cases except the low fuel/high measure cost case have paybacks of less than 20 years. Simple payback for this measure is essentially independent of ceiling insulation level.

The simple payback of wall insulation is under 10 years only for the high fuel/low measure cost scenario (see Figure 5). Two of the three remaining cases have paybacks between 11 and 21 years. The payback period for wall insulation is slightly better when ceiling insulation is present.

The high-efficiency air-conditioning measure did not have a reasonable payback under any measure/fuel cost scenario. The lowest simple payback period is more than 50 years. The energy cost savings of this measure might justify the incremental expense of buying a more efficient unit when replacement becomes necessary, however. Based on

TABLE 5
High and Low Measure Costs Used for Payback Analysis

Measure(s)	Low cost ($/ft^2)	High cost ($/ft^2)
R-7 ceiling insulation	0.25	0.60
R-19 ceiling insulation	0.35	1.05
R-30 ceiling insulation	0.55	1.60
30% lighting reduction*	1.50	2.40
R-11 wall insulation**	0.60	1.60
High-efficiency air conditioner***	2.27	4.92
Thermostat setback / setup****	0.06	0.13

*Lighting based on 80 ft^2 per approximately 200-watt (four-lamp, two-ballast) fixture.
**Wall insulation cost based on ratio of framed-wall area to floor area of 0.68.
***Air conditioner low cost: $3000 per unit; high cost: $6500 per unit.
Low-cost example: ($3000 per unit x 2 units / 2642 ft^2 = 2.27 $/ft^2).
****Thermostat low cost: $75 per unit; high cost: $175 per unit.
Low-cost example: ($75 per unit x 2 units / 2642 ft^2 = 0.06 $/ft^2).

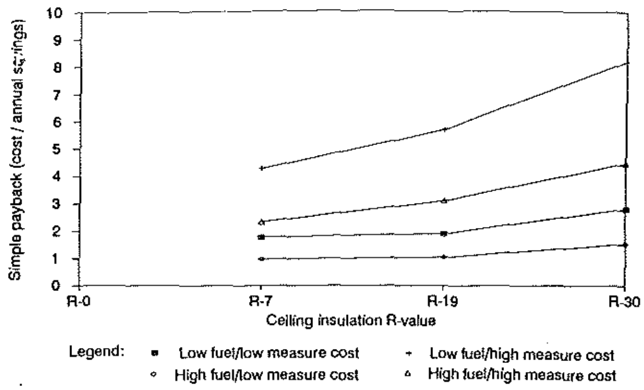

Figure 3 *Simple payback period of insulation added to an uninsulated attic.*

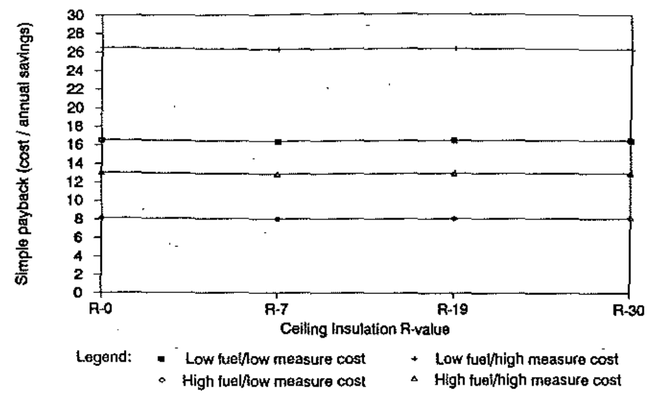

Figure 4 *Simple payback period of a 30% lighting energy reduction.*

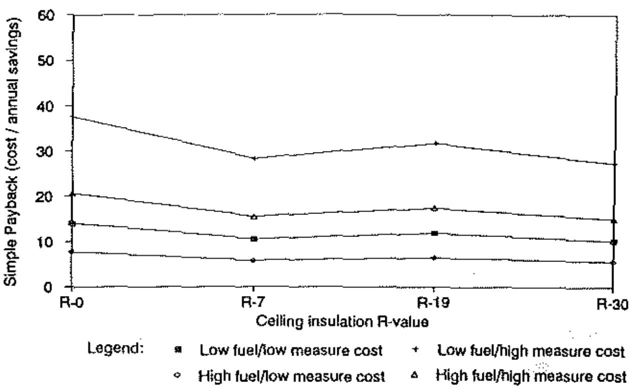

Figure 5 *Simple payback period of wall insulation.*

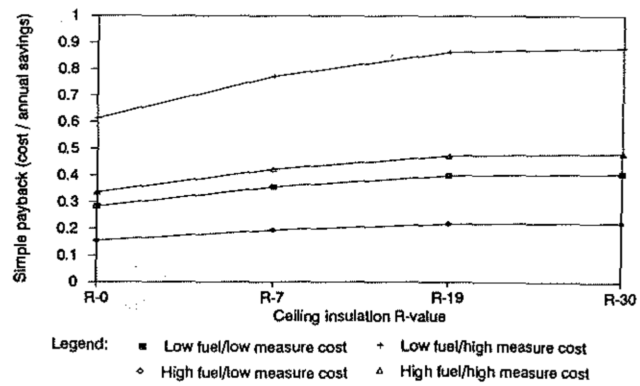

Figure 6 *Simple payback period of thermostat setback/setup.*

the equipment sizes in the building evaluated, additional expenditures of around $400 for the low-cost and $800 for the high-cost scenarios ($60 to $120 per ton) could be cost justified upon unit replacement for a simple payback within ten years.

CONCLUSIONS

In a climate similar to Boston, ceiling (or roof) insulation alone can reduce heating energy use by as much as 38% and total electricity use by as much as 10% (R-0 to R-30) for a single-story commercial building. Except where high installation costs occur, the simple payback of ceiling insulation levels up to R-30 should be less than three years in most cases. Because some rigid roof insulations (some phenolic foams and polystyrenes) have costs comparable to the higher ceiling insulation costs evaluated, the simple paybacks shown for the higher-cost ceiling insulations should be representative of those expected if these rigid insulations are added during the replacement of an existing roof (for equivalent R-values).

Thermostat setup/setback is the best overall energy saver and has the best payback of all measures evaluated. For a small commercial building, this measure can offer heating energy savings greater than 40% and total electricity savings greater than 9% even at high ceiling insulation levels. Because thermostat setup/setback changes indoor temperature substantially, there is a sizable interaction between this measure and ceiling insulation. Combined performance between 10% and 20% less than the sum of their individual performances can be expected for both energy and cost savings. The simple payback of thermostat setup/setback can be expected to be less than one year over a wide range of fuel and measures costs. Payback of this measure is highly dependent upon the occupancy schedule of the building. If there are few unoccupied hours, the savings of this measure could be reduced substantially.

Lighting reduction offers the best electricity use reduction of all measures examined. Unlike other measures, however, reduced lighting reduces electricity costs while it increases heating energy costs. The electricity use reduction can approach 16% to 20% for a small commercial building, but the associated heating penalty can be expected to be around half of this reduction (in energy terms). For natural gas heating, this penalty will reduce the payback of this measure by around 10%. This penalty will be much more significant when electric space heating is utilized. The small interaction between lighting reduction and ceiling insulation is negative (lower performance when combined) in heating and positive in cooling. Because of this, these interactions can counter one another in terms of cost savings.

The simple payback of lighting reduction is estimated to typically be 8 to 16 years, based on energy costs alone (no demand savings considered). High measure costs will increase this payback substantially. In a cooling-dominated climate, or in buildings with high internal gains, the heating penalty could be much less and, thus, the payback period for this measure could be substantially reduced as well.

For a small commercial building, wall insulation will provide heating energy savings of around 6% for an uninsulated ceiling (and roof) and savings of around 10% to 13% when the ceiling is insulated. Wall and ceiling insulation combined can be expected to perform around 5% better than the sum of their individual performances in terms of energy and cost savings. Wall insulation offers marginal cooling energy savings. Significant internal loads are present in the building evaluated, and its location in a heating-dominated climate affects potential wall insulation benefits. In most cases, the simple payback of wall insulation is estimated to be above 10 years.

Installing a high-efficiency air conditioner will provide only a small reduction in total electricity use. The less than 5% reduction achieved indicates small cost savings for small commercial buildings in the climate simulated. The cost savings could be much more significant if installed in a multi-story building where high internal gains often create a cooling-intensive building or in a cooling-dominated climate. The additional savings offered by a high-efficiency unit are much too small to justify air conditioner replacement but may be attractive when used to justify the incremental cost of a more efficient unit at replacement. The payback of this measure is strongly dependent on fuel and equipment costs. The interaction between high-efficiency air conditioning and ceiling insulation is significant only for electricity use and will result in total electricity savings of around 7% less than the sum of their performances as individual measures.

The shell, mechanical, and lighting measures evaluated can provide significant decreases in the annual space-heating fuel and the total electricity use of a building. When multiple measures are installed, however, positive and negative interactions between measures can occur. These measure interactions can be significant, particularly in the case of a lighting reduction measure, and should always be considered when evaluating measure energy and costs savings.

This paper summarizes a framework for examining measure savings and interactions in small commercial buildings. Future related work could involve additional measures, evaluation in cooling-dominated buildings, and/or evaluation in other climates.

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