# The Effects of Varying Indoor Air Temperature and Heat Gain on the Measurement of Retrofit Savings

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## ABSTRACT

*Many methods of estimating energy savings from measured weather-dependent energy consumption data attempt to compensate for varying weather conditions between the pre- and post-retrofit periods by identifying an empirical model of pre-retrofit energy consumption and outdoor air temperature. Even though the pre-retrofit model may include a balance-point or change-point temperature, savings determined using this method implicitly assume that the indoor air set-point temperature and internal heat gains are the same during the pre- and post-retrofit periods. In this paper, we develop simplified expressions that suggest that estimates of retrofit savings are highly sensitive to minor changes in indoor air temperature and internal heat gains between the pre- and post-retrofit periods. This observation is confirmed in a mobile-home weatherization study where savings estimated with and without considering changing indoor air temperature varied by as much as 89%. These findings suggest that in simple buildings, the accuracy of estimated savings can be significantly improved by routinely measuring both indoor and outside air temperatures and explicitly including them in the baseline model for estimating savings.*

## INTRODUCTION

Changing weather conditions can have a large effect on building energy consumption and savings determined from measured data. For example, in a study of simulated energy consumption in commercial buildings in five U.S. cites, Eto (1988) found that gas consumption during abnormally cold or warm years was as much as 28.6% higher or 26.4% lower than usual. Because these deviations are, in many cases, equal to the magnitude of the retrofit savings, the need to account for changing weather when determining savings in buildings is clear, even when a full year of pre- and post-retrofit energy consumption data is available. The importance of weather adjustment increases as the difference between the average pre- and post-retrofit temperatures increases; thus, weather adjustment is essential when the baseline model of pre-retrofit energy consumption is based on less than a full year of energy consumption data.

In response to the need for weather adjustment, many methods of measuring savings first develop an empirical, weather-dependent model of baseline (and sometimes the post-retrofit) energy consumption (Fels 1986; Greely et al. 1990; Kissock et al. 1992; Ruch and Claridge 1992; Fels and Reynolds 1993; Kissock 1997; Sonderegger 1997). Two types of weather-adjusted savings, actual and normalized, can then be estimated. Actual savings estimate how much energy was saved during the weather conditions that actually occurred. Actual savings are calculated as the difference between an estimate of how much energy the building would have consumed had it not undergone a retrofit and the measured energy consumption during the post-retrofit period $E_{Post}$. The estimate of baseline energy consumption is usually derived from an empirical model describing the correlation of pre-retrofit energy consumption and outdoor air temperature $E_{pre}$. The procedure to calculate actual savings is summarized by

$$E_{Save} = \sum_{j=1}^{m} (\hat{E}_{Pre,j} - E_{Post,j}) \tag{1}$$

where *m* is the number of periods in the post-retrofit period.

Normalized savings estimate the savings that would have occurred during normal, or average, weather conditions. The typical procedure to determine normalized savings is to identify weather-dependent regression models of both the pre- and

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post-retrofit energy consumption. An estimate of annual energy consumption in a normal weather year, sometimes called the "normalized annual consumption," is then developed for each period using long-term average weather data, such as the TMY2 weather data (NREL 1995), as the input to each model. The procedure to calculate normalized savings is summarized by

$$E_{Save} = \sum_{j=1}^{m} (\hat{E}_{Pre,j} - \hat{E}_{Post,j}) \qquad (2)$$

Although outside air temperature, humidity, solar radiation, and wind speed all influence building energy consumption, many baseline energy consumption models use only outside air temperature as an indicator of weather conditions because of the relative magnitudes of the conduction and sensible air-conditioning loads and because of the high correlation between outside air temperature and the other environmental variables (Reddy and Claridge 1994; Ruch et al. 1993). These methods have been shown to adequately adjust for changing weather conditions so that savings can be measured with standard errors on the order of 10% assuming that internal air temperature and heat gains do not change between the pre- and post-retrofit periods (Fels 1986; Kissock 1993). In this paper, we discuss the magnitude of additional error if internal air temperature and heat gain change between the pre- and post-retrofit periods and are not accounted for in the baseline model.

## GRAPHICAL TECHNIQUES FOR DIFFERENTIATING BETWEEN REAL AND APPARENT SAVINGS

To illustrate how changing internal air temperature and heat gains can affect measurements of retrofit savings, consider a simple building in winter in which the major energy flows into and out of the building can be summarized by three vectors: heat from the furnace into the building, $Q_f$; internal heat gains from people, electricity consumption, and surfaces warmed by solar radiation, $Q_i$; and heat loss through the building shell via conduction and infiltration, $Q''_{ua}$. An energy balance gives

$$Q_f = [UA(T_i - T_o) - Q_i]^+ \qquad (3)$$

where $Q_{ua}$ is the product of the overall building load coefficient $UA$ and the indoor/outdoor temperature difference $(T_i - T_o)$, and the superscript + indicates that the parenthetic term is zero when negative. The outside air temperature at which no heating is needed is called the balance-point temperature, $T_b$.

$$T_b = T_i - Q_i / UA \qquad (4)$$

Consider the case in which $Q_i = 100$ (arbitrary units), $T_i = 70°F$ (21.1°C) and the building $UA$ decreases from 20 to 10 (arbitrary units) as a result of a weatherization retrofit. The plot of furnace heating energy consumption, $Q_f$, vs. outside air
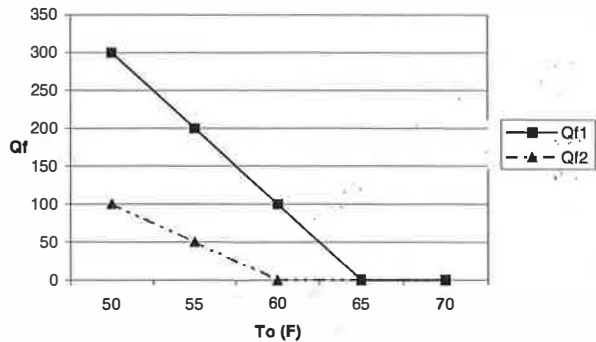


*Figure 1*　*Expected traces of baseline (1) and post-retrofit (2) furnace heat into a building vs. outdoor air temperature when UA decreases as a result of a weatherization retrofit and T_i and Q_i remain constant.*

temperature, $T_o$, is shown in Figure 1. Actual savings are represented graphically by the distances between the baseline (1) and post-retrofit energy consumption (2) traces. For the data points shown, actual savings would total 450 units. Note that the retrofit had the effect of decreasing both the slope of the post-retrofit energy consumption trace and the balance-point temperature. Thus, it is expected that the balance-point temperature will drop as a result of decreasing $UA$ even when the indoor air temperature and heat gains remain the same.

Next, consider the cases in which the $T_i$ decreases from 70°F (21.1°C) to 65°F (18.3°C) and $Q_i$ increases from 100 to 200 while the building $UA$ remains the same. In both cases, the traces of post-retrofit energy consumption are identical and give the appearance that energy consumption was reduced as the result of a weatherization retrofit (Figure 2). Only close inspection of the pre- and post-retrofit traces would indicate that the building $UA$ (slope) is unchanged and the decreased energy consumption during the post-retrofit period is due to a lower indoor air temperature or increased internal heat gains.

Actual savings estimated using baseline models of $T_o$ alone would indicate savings of 300 units, when, in fact, the building $UA$ remained the same and there are no savings due to weatherization. This potential source of error in savings estimates is not accounted for by traditional methods of estimating the uncertainty of savings, even though it can be much larger than the error caused by random variations in energy consumption. In the next section, we develop a method for estimating the magnitude of the error in savings measurement due to changing internal temperatures or heat gains if they are not explicitly accounted for in the baseline model.

## HOW VARYING INSIDE AIR TEMPERATURE AND INTERNAL HEAT GAIN AFFECT ESTIMATES OF SAVINGS

To quantify the difference in the estimates of savings from baseline models that explicitly include and exclude indoor air temperature, consider the simplified case when the
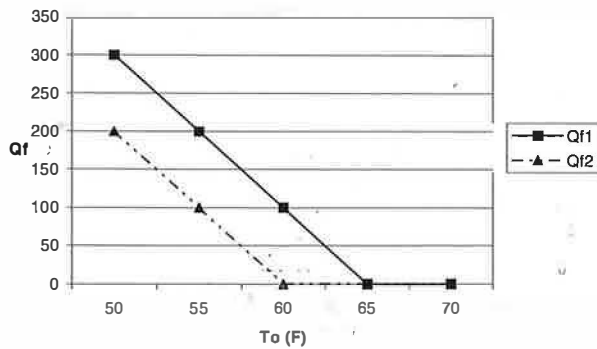
*Figure 2* Traces of baseline (1) and post-retrofit (2) furnace heat into a building vs. outdoor air temperature when the building UA remains unchanged but either $T_i$ decreases from 70°F (21.1°C) to 65°F (18.3°C) or $Q_i$ increases from 100 to 200. The decreased energy consumption during the post-retrofit period is caused by changing $T_i$ and $Q_i$.

outdoor air temperature is below the balance point. The actual energy consumption during the pre-retrofit period would be

$$Q_i = UA_1(T_{i,1} - T_{o,1}).  \qquad (5)$$

If indoor air temperature was not measured, most traditional methods for measuring savings assume that it remains unchanged between the pre- and post-retrofit periods. If so, the simple two-parameter regression model for estimating baseline energy consumption under post-retrofit weather conditions would be

$$\hat{Q}_i = UA_1(T_{i,1} - T_{o,2}),  \qquad (6)$$

in which outdoor air temperature $T_{o,2}$ is the only independent variable.

Next, assume that the retrofit decreases the building load coefficient by a factor $f$, and the inside temperature during the post-retrofit period is $\Delta T_i$ degrees less than during the pre-retrofit period.

$$UA_2 = f\,UA_1  \qquad (7)$$

$$T_{i,2} = T_{i,1} - \Delta T_i  \qquad (8)$$

Under these circumstances, the post-retrofit energy consumption would be

$$Q_2 = UA_2(T_{i,2} - T_{o,2}) = f\,UA_1(T_{i,1} - T_{o,2} - \Delta T_i).  \qquad (9)$$

The *actual* savings, based on outside air temperature $S_{To}$ alone, would be

$$S_{To} = \hat{Q}_i - Q_2$$
$$= UA_1(T_{i,1} - T_{o,2}) - f\,UA_1(T_{i,1} - T_{o,2} - \Delta T_i)  \qquad (10)$$

In contrast, if the indoor air temperature $T_i$ were measured in addition to $T_o$, then the estimate of baseline energy could be based on the inside-outside temperature difference and written as

$$\hat{Q}_i = UA_1(T_{i,2} - T_{o,2}).  \qquad (11)$$

In this case, the independent variable in the baseline model is the difference between the indoor and outdoor temperatures. The estimated actual savings, based on this temperature difference $S_{(T_i - T_o)}$, would be

$$S_{(T_i - T_o)} = \hat{Q}_i - Q_2$$
$$= UA_1(T_{i,2} - T_{o,2}) - f\,UA_1(T_{i,1} - T_{o,2} - \Delta T_i)  \qquad (12)$$

The percentage difference between the two methods of estimating savings relative to $S_{(T_i - T_o)}$ would be

$$\frac{S_{To} - S_{(T_i - T_o)}}{S_{(T_i - T_o)}} = \frac{\Delta T_i}{(1 - f)(T_{i,2} - T_{o,2})}.  \qquad (13)$$

It can readily be seen that if the inside temperature remains the same in the pre- and post-retrofit periods, then $\Delta T_i$ is zero, and the two estimates of savings are identical. Consider, however, the plausible case in which the average indoor air temperature varies by 5°F (2.8°C) between the pre- and post-retrofit periods ($\Delta T_i = 5°F [2.8°C]$), the retrofit reduces the building UA by 20% ($f = 0.8$), and the average difference between the indoor and outdoor temperatures during the post-retrofit winter is 40°F (22.2°C). The percentage difference between the two methods of estimating savings would be 62.5%! This error would be unaccounted for by traditional methods of estimating the uncertainty of savings, even though it is likely to dwarf the inherent statistical errors involved. Thus, it appears that the accuracy of savings measurements is highly sensitive to the assumption of constant indoor air temperature, and if that assumption is in any way suspect, it is important to measure indoor air temperature and include it in the baseline model.

A similar relation can be derived for cases in which internal heat gains vary between the pre- and post-retrofit periods. If the internal heat gain during the post-retrofit period is $m$ times as much as during the baseline period ($Q_{i2} = m\,Q_{i1}$), the percentage difference in actual savings estimated by methods with baseline models that explicitly include a measure of internal heat gain and those based only on $T_o$ is

$$\frac{S_{To} - S_{(T_o, Q_i)}}{S_{(T_o, Q_i)}} = \frac{Q_{i1}(m - 1)}{UA_1(T_{i,2} - T_{o,2})(1 - f)}  \qquad (14)$$

Thus, if internal heat gains increased by 20% during the post-retrofit period ($m = 1.2$) and the ratio $Q_{i1} / UA_1$ was 7°F (3.9°C) (which is the difference between a 72°F [22.2°C] set NS-point temperature and a standard 65°F [18.3°C] balance-point temperature) and $f$ and the indoor/outdoor temperature difference remained 0.8 and 40°F (22.2°C) as before, the percentage difference in savings given by the two baseline

models would be about 18%. This appears to indicate that estimates of savings are less sensitive to reasonable variations of internal heat gains than indoor air temperatures.

Equations 13 and 14 also indicate that the potential error is greater when the change in building $UA$ is small and in temperate climates when the average indoor-outdoor air temperature is small.

## CASE STUDY EXAMPLE

In 1992, a public utility began developing refined mobile-home weatherization specifications. As part of this project, space-heating energy consumption in seven mobile homes was measured for several months before and after comprehensive weatherization retrofits (NHT 1996). Several other types of energy consumption, moisture and relative humidity levels, and indoor and outdoor air temperatures were also recorded. The data were collected continuously, remotely polled, and integrated to the daily time scale. The total electricity supplied to the electric furnace was measured by redundant current transducers. The indoor air temperature was measured in the kitchen/living room. The outdoor air temperature sensor was shielded from radiation. The retrofits took place during September 1994.

Figure 3 shows four-parameter change-point models (Kissock et al. 1994) of pre- and post-retrofit daily space-heating electricity consumption plotted against outside air temperature for a mobile home in Shelton, Washington. Data from September 1994, when the retrofit took place, were deleted. The energy consumption signature of an effective retrofit is clearly evident. The effective balance-point temperature and slope of the energy consumption trace decrease in the post-retrofit period. Thus, it is apparent that the retrofit effectively reduced the building load coefficient $UA$. Savings are evident as the difference between the pre- and

post-retrofit energy consumption traces. The models fit the data reasonably well: $R^2_{pre} = 0.94$, CV-RMSET$_{pre} = 20.8\%$; $R^2_{post} = 0.83$, CV-RMSE$_{post} = 40.1\%$. The estimated actual savings derived using a baseline model with outdoor air temperature as the independent variable $S_{T_o}$ is 16.1 kWh/day. This estimate implicitly assumes that the indoor air temperature remains constant during the pre- and post-retrofit periods.

Figure 4 shows four-parameter change-point models of the same pre- and post-retrofit daily space-heating electricity consumption, this time plotted against the difference between indoor and outdoor temperatures. As expected, these models fit the data slightly better: $R^2_{pre} = 0.96$, CV-RMSE$_{pre} = 16.3\%$, $R^2_{post} = 0.91$, CV-RMSE$_{post} = 29.6\%$. In addition, the slope of the energy consumption vs. temperature difference traces decrease in the post-retrofit period, again validating that the retrofit successfully decreased the building $UA$. However, the estimate of actual savings derived using a baseline model with the indoor/outdoor temperature difference as the independent variable $S_{(T_i - T_o)}$ is only 10.1 kWh/day. The percentage difference between the two methods of estimating savings is

$$\frac{S_{T_o} - S_{(T_i - T_o)}}{S_{(T_i - T_o)}} = \frac{16.1 - 10.1}{10.1} = 59\%$$

The difference in savings estimates is clearly significant and could dramatically influence the economic feasibility of retrofit measures. It implies that of the total 16.1 kWh/day reduction in energy consumption, 6.0 kWh/day of the reduction is attributable to reduced indoor air temperature and 10.1 kWh/day is attributable to the reduction in the building load coefficient.

It is instructive to compare the actual difference between

E314DATA.DAT  Qspace heat (kWh/day) vs. Tout (F) Pre 4P model
Ycp = 5.0049 (2.7000) Xcp = 59.5044 (1.0592) LS = -3.0696 (0.0553) RS = -0.2611 (0.1954)
N = 280  N1 = 193  N2 = 87  R2 = 0.94  RMSE = 7.1986  CV-RMSE = 20.8%  p = 0.56  DW = 0.97 (p
E314DATA.DAT  Qspace heat (kWh/day) vs. Tout (F) Post 4P model
Ycp = 6.5899 (2.6196) Xcp = 56.1320 (1.1274) LS = -1.8821 (0.0609) RS = -0.4615 (0.1649)
N = 354  N1 = 215  N2 = 139  R2 = 0.83  RMSE = 7.7938  CV-RMSE = 40.1%  p = 0.51  DW = 0.97 (
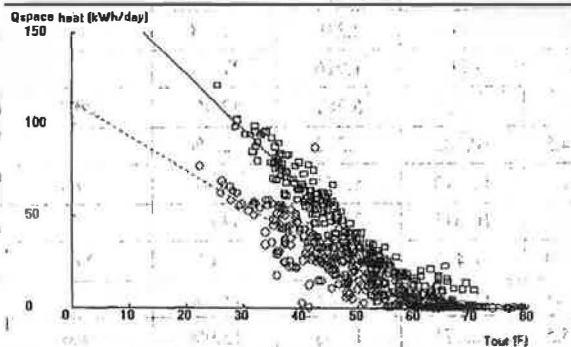
Qspace heat (kWh/day)



*Figure 3*  *Pre- (square) and post-retrofit (circle) daily space-heating energy consumption plotted against outside temperature for mobile home 314 in Shelton, Washington, and fit with four-parameter regression models.*

E314DATA.DAT  Qspace heat (kWh/day) vs. Tin-Tout (F) Pre 4P model
Ycp = 13.0493 (1.8909) Xcp = 15.6760 (0.8520) LS = 1.5115 (0.1487) RS = 3.2235 (0.2367)
N = 280  N1 = 100  N2 = 180  R2 = 0.96  RMSE = 5.6581  CV-RMSE = 16.3%  p = 0.51  DW = 0.98 (
E314DATA.DAT  Qspace heat (kWh/day) vs. Tin-Tout (F) Post 4P model
Ycp = 2.9069 (2.5345) Xcp = 13.3840 (0.7440) LS = 0.2863 (0.2094) RS = 2.2771 (0.3129)
N = 354  N1 = 94  N2 = 260  R2 = 0.91  RMSE = 5.7488  CV-RMSE = 29.6%  p = 0.48  DW = 1.04 (
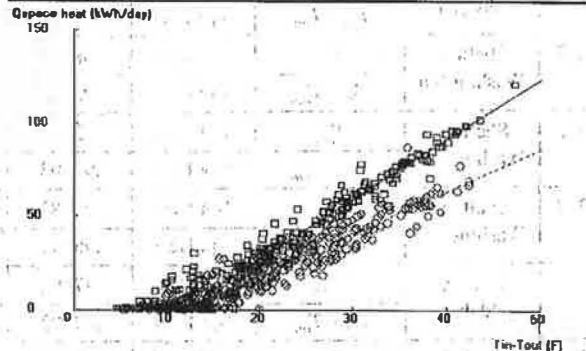
Qspace heat (kWh/day)



*Figure 4*  *Pre- (square) and post-retrofit (circle) daily space-heating energy consumption plotted against the inside-outside temperature difference for mobile home 314 in Shelton, Washington, and fit with four-parameter regression models.*

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the two methods of estimating savings (59%) with the estimate of the difference given by Equation 13. Equation 13 is derived for a two-parameter baseline model. In the previous example, a four-parameter baseline model was used to estimate savings. Four-parameter models have two linear sections over different temperature ranges. To apply Equation 13 to this example, we should select $\Delta T_i$, $(T_i - T_o)_2$, and $f$ from the temperature range where most of the savings take place. This is clearly during the colder temperatures in the winter months. Thus, consider the periods 12/1/1993 to 4/30/1994 and 12/1/1994 to 4/30/1995. The inside air temperature was 4.55°F (2.5°C) colder in the post-retrofit winter than the pre-retrofit winter (Figure 5). The fraction reduction in the building load coefficient can be estimated from the slopes of the pre- and post-retrofit models in winter:

$$f = UA_{post}/UA_{pre} = Slope_{post}/Slope_{pre}$$
$$= 2.28(\text{kWh/day°F})/3.22(\text{kWh/day°F}) = 0.71 \quad (15)$$

The average indoor/outdoor temperature difference during the post-retrofit winter was 24.5°F (13.6°C). The difference in savings, as estimated by Equation 13, is

$$\frac{S_{To} - S_{(T_i - T_o)}}{S_{(T_i - T_o)}} = \frac{4.55°F}{(1 - 0.71)(24.5°F)} = 64\%$$

Given the approximations to accommodate the use of four-parameter baseline models, this agrees reasonably well with the actual difference in savings of 59%.

In the Bonneville mobile-home weatherization project,

E314DATA.DAT Tin (F) vs. Dy Pre Mean model
N = 151  Ymean = 71.89  Std Dev = 2.2126  CV-StDev = 3.1%
E314DATA.DAT Tin (F) vs. Dy Post Mean model
N = 140  Ymean = 67.34  Std Dev = 5.0598  CV-StDev = 0.7%
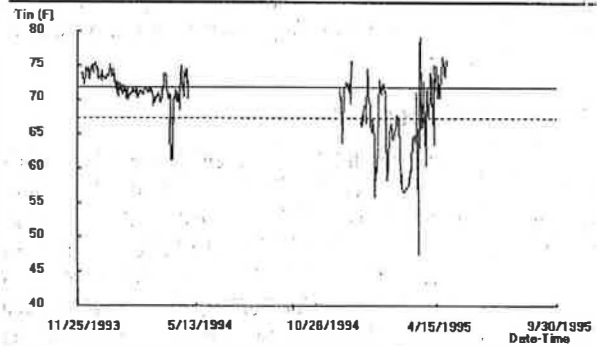


**Figure 5** *Inside air temperatures from December through April of the baseline and post-retrofit periods.*

savings were estimated using baseline models with outside temperature as the independent variable $S_{To}$ and using baseline models with the indoor-outdoor temperature difference as the independent variable $S_{(T_i - T_o)}$. Table 1 summarizes the savings calculated using the different methods. It draws attention to the sensitivity of estimated savings to changing indoor air temperature; the estimates of savings vary by up to 89% depending on the method used to calculate savings.

## TABLE 1
### Space-Heating Savings for Seven Mobile Homes That Underwent Weatherization Retrofits (NHT 1996)*

| Site | Location | Independent Variable | Model Type | $R^2$ | CV-RMSE | Base (kWh) | Savings (kWh) | Savings (%) | $\frac{S_{To} - S_{(T_i - T_o)}}{S_{(T_i - T_o)}}$ |
|---|---|---|---|---|---|---|---|---|---|
| 304 | Redmond, Oregon | $T_{out}$ | 4-pt Heat | .92/.84 | 23.7/26.0 | 10,109 | 4,443 | 44.0% | −17% |
| | | $T_{in} - T_{out}$ | 4-pt Heat | .87/.81 | 30.3/28.6 | 11,034 | 5,368 | 48.6% | |
| 307 | Shelton, Washington | $T_{out}$ | 4-pt Heat | .88/.87 | 36.0/37.7 | 7,312 | 2,319 | 31.7% | 20% |
| | | $T_{in} - T_{out}$ | 4-pt Heat | .93/.89 | 27.4/35.0 | 6,919 | 1,926 | 27.8% | |
| 313 | Shelton, Washington | $T_{out}$ | 4-pt Heat | .93/.83 | 28.3/53.2 | 13,137 | 6,287 | 47.9% | 89% |
| | | $T_{in} - T_{out}$ | 4-pt Heat | .96/.93 | 20.5/34.5 | 10,182 | 3,332 | 32.7% | |
| 314 | Shelton, Washington | $T_{out}$ | 4-pt Heat | .94/.83 | 21.2/41.2 | 12,712 | 5,771 | 45.4% | 57% |
| | | $T_{in} - T_{out}$ | 4-pt Heat | .96/.91 | 16.7/30.5 | 10,612 | 3,671 | 34.6% | |
| 309 | Shelly, Idaho | $T_{out}$ | 4-pt Heat | .87/.90 | 34.5/32.0 | 11,435 | 1,555 | 13.6% | 24% |
| | | $T_{in} - T_{out}$ | 4-pt Heat | .89/.92 | 31.5/28.7 | 11,135 | 1,255 | 11.3% | |
| 310 | Shelly, Idaho | $T_{out}$ | 4-pt Heat | .86/.83 | 42.2/35.5 | 12,121 | 1,683 | 13.9% | 4% |
| | | $T_{in} - T_{out}$ | 4-pt Heat | .85/.84 | 43.2/34.3 | 12,062 | 1,623 | 13.5% | |
| 311 | Shelly, Idaho | $T_{out}$ | 4-pt Heat | .91/.90 | 40.8/26.4 | 12,541 | 2,190 | 17.5% | −8% |
| | | $T_{in} - T_{out}$ | 4-pt Heat | .91/.89 | 41.4/27.8 | 12,727 | 2,377 | 18.7% | |

*Savings were calculated with and without consideration of changing indoor air temperatures. The numbers reported for site 314 in the example in this paper are slightly different from the numbers in Table 1 because we exclude from our analysis data from September 1994 when the retrofit took place.

## SUMMARY AND CONCLUSIONS

This analysis highlighted the sensitivity of estimated savings to variations in indoor air temperatures and internal heat gains between the pre- and post-retrofit periods. It illustrated that decreasing indoor air temperatures or increasing internal heat gains can cause energy consumption that mimics retrofit savings and that failure to account for these changes can produce unreliable estimates of savings.

Savings calculated using a baseline model with outside temperature as the only independent variable $S_{T_o}$, estimate the "savings" after the influence of changing outdoor air temperature has been removed. Savings calculated using a baseline model with the inside/outside temperature difference as the independent variable $S_{(T_i - T_o)}$ estimate energy savings after the influences of both changing outdoor and indoor air temperatures have been removed. The difference between the two is the "savings" due to changing inside air temperatures. If the inside air temperature changes as an intended result of the retrofit, then it would be appropriate to report $S_{T_o}$ as the best estimate of savings. If, on the other hand, the change in inside air temperature is unrelated to the retrofit, then it would be appropriate to report $S_{(T_i - T_o)}$ as the best estimate of savings.

In principle, the effect of changing internal heat gains between the pre- and post-retrofit periods could also be removed; however, this would require a measurement of internal heat gains, such as the building electrical plug load, or more extensive data analysis. Further research may suggest appropriate methods for adjusting for changing internal heat gain.

In light of the sensitivity of estimated savings to changing indoor air temperature identified here, we recommend routinely measuring both indoor and outside air temperatures and explicitly including them in the baseline model for estimating savings. In fully occupied commercial buildings, it is probable that the indoor air temperature is controlled within fairly narrow limits and that the effect of changing indoor air temperature on savings would be smaller than observed in this study of mobile homes. However, this appears to be an important area for further research.

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