TO-98-12-5

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 temperature 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 $\hat{E}_{Pre}$. The procedure to calculate actual savings is summarized by:

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

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* 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:

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

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 effect 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 gain 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:

$$Q_f = [UA\,(T_i - T_o) - Qi]^+ \quad (3)$$

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.

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

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 versus outside air 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.

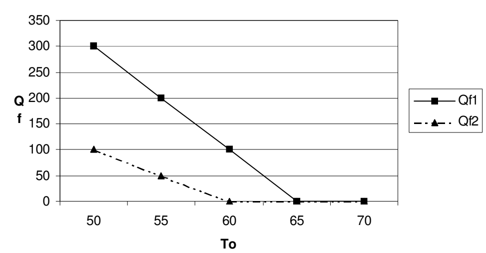

Figure 1. Expected traces of baseline (1) and post-retrofit (2) furnace heat into a building versus outdoor air temperature when UA decreases as a result of a weatherization retrofit and T_i and Q_i remain constant.

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.

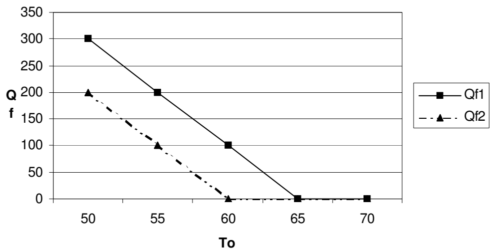

Figure 2. Traces of baseline (1) and post-retrofit (2) furnace heat into a building versus outdoor air temperature when the building UA remains unchanged, but either Ti decreases from 70 F (21.1 C) to 65 F (18.3 C) or Qi increases from 100 to 200. The decreased energy consumption during the post-retrofit period is caused by changing Ti and Qi.

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

$$Q_1 = UA_1 \ (T_{i,1} - T_{o,1}) \quad (5)$$

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:

$$\hat{Q}_1 = UA_1 \ (T_{i,1} - T_{o,2}) \quad (6)$$

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 ΔT_i degrees less than during the pre-retrofit period.

$$UA_2 = f \ UA_1 \quad (7)$$

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

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

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

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

$$S_{To} = \hat{Q}_1 - Q_2 = UA_1 \ (T_{i,1} - T_{o,2}) - f \ UA_1 \ (T_{i,1} - T_{o,2} - \Delta T_i) \quad (10)$$

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:

$$\hat{Q}_1 = UA_1 \ (T_{i,2} - T_{o,2}) \quad (11)$$

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* $S_{(Ti-To)}$ would be:

$$S_{(Ti-To)} = \hat{Q}_1 - Q_2 = UA_1 \ (T_{i,2} - T_{o,2}) - f \ UA_1 \ (T_{i,1} - T_{o,2} - \Delta T_i) \quad (12)$$

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

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

It can be readily seen that if the inside temperature remains the same in the pre and post-retrofit periods, then ΔT_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 periods (ΔT_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 that 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 which explicitly include a measure of internal heat gain and those based only on T_o is:

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

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-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, the Bonneville Power Administration 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 (New Horizon Technologies, Inc. 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-$RMSE_{pre}$ = 20.8%; R^2_{post} = 0.83, CV-$RMSE_{post}$ = 40.1%. The estimated actual savings derived using on a baseline model with outdoor air temperature as the independent variable S_{To} is 16.1 kWh/day. This estimate implicitly assumes that the indoor air temperature remains constant during the pre and post-retrofit periods.

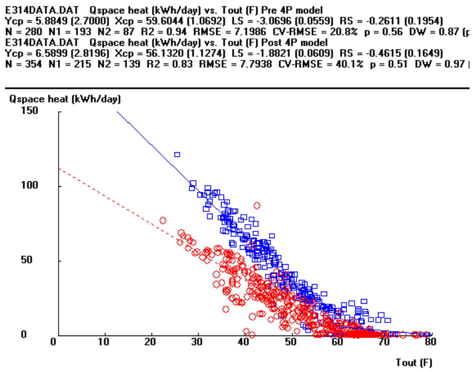

Figure 3. Pre (square) and post-retrofit (circle), daily space-heating energy consumption plotted against outside temperature for mobile home 314 in Shelton Washington and fit with four-parameter regression models.

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: $R^2_{pre} = 0.96$, $\text{CV-RMSE}_{pre} = 16.3\%$; $R^2_{post} = 0.91$, $\text{CV-RMSE}_{post} = 29.6\%$. In addition, the slope of the energy consumption versus 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 $S_{(Ti-To)}$ is only 10.1 kWh/day. The percentage difference between the two methods of estimating savings is:

$$\frac{S_{To} - S_{(Ti\text{-}To)}}{S_{(Ti\text{-}To)}} = \frac{16.1 - 10.1}{10.1} = 59\%$$

The difference in savings estimates is clearly significant and could dramatically influence the economic feasibility of retrofit measures. It imply 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.

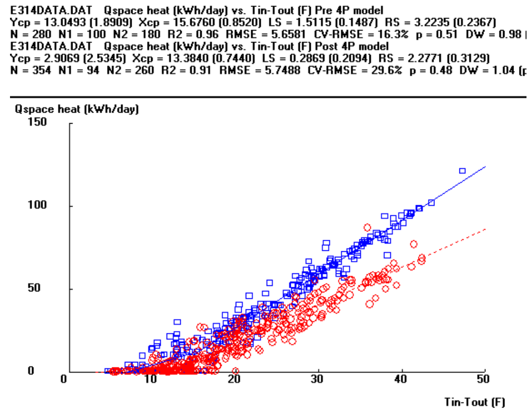

Figure 4. Pre (square) and post-retrofit (circle), daily space-heating energy consumption plotted against the inside-outside temperature difference for mobile home 314 in Shelton, Washington and fit with four-parameter regression models.

It is instructive to compare the actual difference between 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 ΔT_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, let's consider the periods 12/1/1993 - 4/30/1994 and 12/1/1994 - 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:

$$f = UA_{post} / UA_{pre} = Slope_{post} / Slope_{pre} = 2.28\ (\text{kWh/dayF}) / 3.22\ (\text{kWh/dayF}) = 0.71 \quad (14)$$

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:

$$\frac{S_{To} - S_{(Ti\text{-}To)}}{S_{(Ti\text{-}To)}} = \frac{4.55\,F}{(1 - 0.71)\,(24.5\,F)} = 64\,\%$$

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, 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 $S_{(Ti-To)}$. 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.

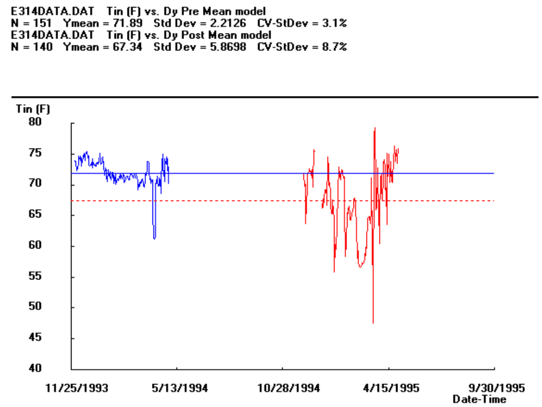

Figure 5. Inside air temperatures from December through April of the baseline and post-retrofit period

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

Table 1. Space-heating savings for seven mobile homes that underwent weatherization retrofits (New Horizon Technologies, Inc., 1996). 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 excluded data from September, 1994, when the retrofit took place, from our analysis.

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_{To}, 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 $S_{(Ti-To)}$, 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_{To} 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 $S_{(Ti-To)}$ 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 temperature 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.

Acknowledgments

The research was supported in part by the Texas LoanSTAR Program.

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