Monetization of Thermal Comfort in Residential Buildings

Xia Fang, Marcus V. Bianchi, Craig Christensen, National Renewable Energy Laboratory

ABSTRACT

Building energy simulations can help us determine the energy savings benefits that can accrue when energy efficiency measures are implemented in a home. Researchers and industry have been using the National Renewable Energy Laboratory's BEopt, a building energy optimization tool, to determine optimal packages that deliver given energy savings levels at least cost for new construction and home energy upgrades. These are certainly important factors, but a major driver for improving energy efficiency is to increase comfort, which is often called a *soft benefit*. The home energy upgrade industry does not have straightforward ways to evaluate the value of comfort and other intangibles; however, other industries (the insurance industry, for example) routinely monetize soft benefits. This paper proposes a method that considers pre- and post-retrofit comfort levels to evaluate prospective energy savings that result from residential energy upgrades and seeks to monetize the value of comfort. This paper study presents a thermal comfort index and uses BEopt/EnergyPlus to optimize the retrofit building designs to increase energy savings levels under the same thermal comfort index.

Introduction

The U.S. residential sector has almost 130 million homes, and accounts for 22% of the energy consumed in the United States (EIA 2009). Cost-effective improvements to the energy efficiency of this stock would save energy and lower utility bills. The U.S. Department of Energy set a goal to retrofit 1.3 million homes by 2013 (Lee 2010), so accelerating the pace at which retrofits take place is urgent.

A growing body of anecdotal evidence suggests that many consumers purchase whole-house retrofit services for the associated non-energy benefits, including improved comfort, aesthetic enhancements, and better indoor air quality (Amann 2006). For example, we found that of 100 retrofit jobs sold by a local retrofit company, the homeowners cited comfort reasons in 70 cases, energy efficiency in 55 cases, and reduced energy bills in 30 cases (multiple reasons were given in each case).

Home performance contractors[1] and builders face a dilemma when trying to sell a retrofit: they have detailed calculations that show in the cost and energy savings the retrofit could provide, but cannot monetize non-energy benefits. Energy simulation models today calculate benefits only in the form of reduced energy bills. Improved thermal comfort, however, is often cited as an intangible or soft benefit that comes with the retrofit program. The home energy upgrade industry does not have straightforward ways to evaluate the value of comfort and other intangibles; however, other industries (the insurance industry, for example) routinely monetize soft benefits.

In post-retrofit homes, the energy efficiency upgrades to windows, walls, and attics have reduced the conduction heat transfer energy flows through the envelope assembly and brought

[1] It is telling that the primary technical organization of home performance contractors in the United States is called Affordable Comfort, Inc.

the interior surface temperatures much closer to the room air temperature. This in effect raised the whole-house mean radiant temperature so that at the same air temperature the homeowners will feel warmer. (See the Comfort Model Description section for details.) A similar—but more dramatic—illustration of the radiant temperature effect is infrared radiant heaters that are mounted outdoors near movie ticket boxes. On winter nights, people waiting in lines can stay relatively comfortable near these heaters when the ambient air is drafty and chilly. In a pre-retrofit home, to achieve equivalent comfort, the homeowner will have to dial up the thermostat so the air temperature is elevated high enough to combat the cold wall and window radiant effects. Energy efficiency upgrades can increase thermal comfort and save money.

Many studies about residential thermal comfort and economic benefits are characterized by the take-back effect instead. For example, Clinch and Healy (2003) have shown that homes with sub-optimal pre-retrofit comfort will have reduced post-retrofit energy savings as occupants tend to forego some savings in exchange for increased temperature. The take-back effect depicts this scenario theoretically: the homeowners choose to live with sub-optimal thermal comfort in the pre-retrofit condition to avoid skyrocketing utility bills; after the retrofit, the increased thermal comfort that naturally comes with the energy efficiency upgrades at the same temperature setting alone is not adequate; rather, the homeowners choose to dial up the thermostat set point even further to achieve superior comfort, because now they pay much less for utilities and probably are not worried about recouping the investment on home energy upgrades. This paper does not include detailed discussions and analyses of take-back; however, monetization of thermal comfort will help us examine this effect in depth. Our objectives in this paper are to:

- Propose a method to evaluate prospective energy savings achieved by residential retrofits considering the pre- and post-retrofit comfort levels.
- Monetize the value of comfort as energy efficiency measures (EEMs) are considered.

Comfort Model Description

Six primary factors affect thermal comfort: metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity. According to ASHRAE Standard 55 (ASHRAE 2004), predicted mean vote (PMV) is used as a thermal sensation scale to relate these factors to the average response of people as listed in Table 1.

Table 1. PMV Index

+3	**+2**	**+1**	**0**	**–1**	**–2**	**–3**
(hot)	(warm)	(slightly warm)	(neutral)	(slightly cool)	(cool)	(cold)

Figure 1 is the ASHRAE Standard 55 thermal comfort chart that colors the range of acceptable thermal comfort for 80% occupant acceptability. This is equivalent to 10% dissatisfaction for whole-body thermal comfort, plus an additional 10% dissatisfaction that may occur on average from local (partial body) thermal discomfort. The two overlapping shaded zones are the acceptable comfort zones for the summer clothing level of 0.5 and winter clothing level of 1.0 separately, which correspond to –0.5< PMV< +0.5. Figure 2 plots the correlation of PMV vs. PPD (predicted percentage of dissatisfied) (ASHRAE 2004). The green part of the curve is the range for 10% PPD, and is equivalent to a PMV range of –0.5 to 0.5.

Figure 1. ASHRAE Standard 55 Comfort Region

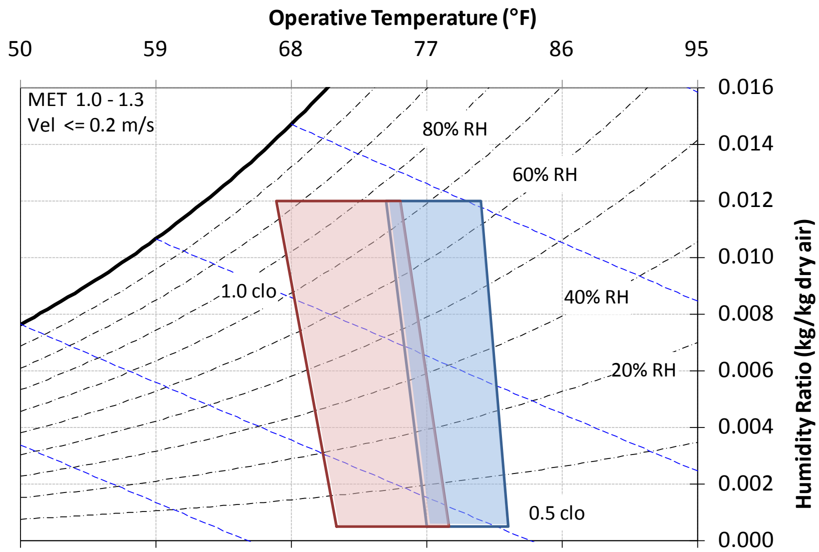
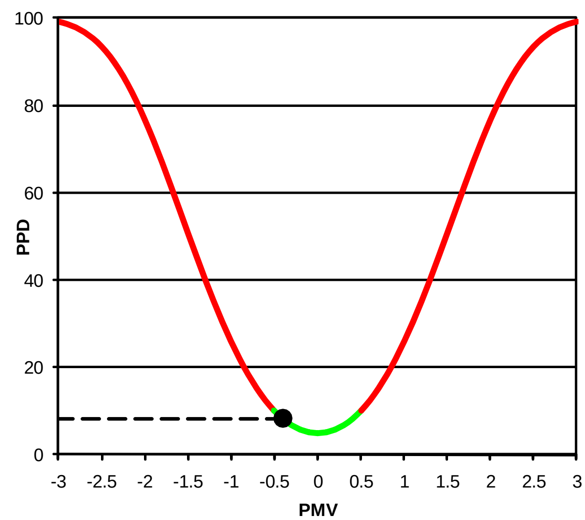


Figure 2. PPD-PMV Chart



Generally speaking, the PPD-PMV scale is more applicable to a commercial building setting, where a group of workers work 8 hours per day in their assigned seating areas, or sit at long meetings in conference rooms. PPD or PMV captures the mean response of the large group. In a residential setting, clothing levels and metabolic rates change with daily activities, and an individual homeowner may prefer a comfort index that significantly deviates from the mean response. This means that each individual home retrofit project requires a pre-retrofit survey of homeowner comfort before a comfort monetization analysis can be conducted. However, using PPD-PMV on a large community scale, regional scale, or climate zone scale to analyze retrofit thermal comfort may be adequate. This large-scale characterization is applicable in Building America House Simulation Protocol (Hendron and Engebrecht, 2010) for home appliance, miscellaneous electric loads, lighting, domestic hot water, etc.

Of the six primary factors, thermal comfort is highly sensitive to clothing levels and metabolic rates. A heavily dressed active person can feel hot when a lightly dressed sitting person in the same environment can feel cool. This study used a constant metabolic rate / occupant activity or a constant occupant sensible and latent heat gain as prescribed by the Building America House Simulation Protocol. This in turn leads to a simplified constant daily clothing level assumption. Because the overall comfort effect of night sleeping (lower metabolic rates) at higher clothing level vs. daytime sitting (higher metabolic rates) at normal clothing level is very much the same.

We adjusted the occupant clothing level with some seasonal variations based on monthly average temperatures (see Table 2).

Table 2. Clothing Level (clo) Assumption

Average Outside Monthly Temperature	**< 35°F**	**≤80°F & ≥35°F**	**> 80°F**
Clothing Level	1.0	0.75	0.5

The study assumes a well-mixed steady-state condition; any cyclic variations caused by PMV controls, local draft, and radiant asymmetry are not great concerns in a home; thus, contributed to a PPD < 10%.

Thermal Comfort Models in EnergyPlus Version 7.0

The thermal comfort model points out that the equivalent air temperature settings, though measurable, do not indicate equivalent thermal comfort. To predict and control comfort, EnergyPlus offers control algorithms that are based either on zone operative temperature or on thermal comfort PMV index. In this paper, Fanger PMV (1970) index is used. Operative temperature, though often quoted and used, is a partial—and not entirely accurate—indicator with human objects treated as blackbody with their clothing surface temperatures ignored. The thermal comfort PMV model is a comprehensive metric that incorporates clothing levels and daily activities/metabolic rates.

To implement the thermal comfort control, EnergyPlus offers a zone comfort control mechanism that dials the thermostat set point either up or down within user-defined temperature bounds to meet the specified comfort PMV criterion. For the PMV comfort stat to gain full control, the user defined temperature bounds need to have a wide enough range to prevent temperature limits from overriding the PMV control. In this study, the minimum and maximum dry-bulb temperature limits are set to 50°F and 90°F to enable full PMV control.

BEopt Comfort Monetization Analysis

The National Renewable Energy Laboratory developed the software tool BEopt (Building Energy Optimization) to find optimal building designs that increase energy savings. A user specifies options from various categories in a predefined options library. BEopt selects the most cost-effective option or options that yield the greatest energy saving at the lowest cost. BEopt also assumes that in every case the house is operated under the same thermostat temperature setting. The optimization and the least-cost curve generated by this approach, i.e. same thermostat temperature setting, lead to houses that will have very different comfort levels. We have been unable, using this method, to identify the cost premium a homeowner needs to pay to operate an uncomfortable house at the same comfort level as that of a house with a superior comfort level.

With the PMV comfort stat defined, we can use the following two operational settings in BEopt/EnergyPlus to analyze a typical retrofit project:

- Conventional way of thermostat control: 68°F heating and 78°F cooling with a dead band of 10°F;
- Comfort-stat: Using pre- and post-retrofit equivalent comfort PMV index control.

The study house is located in Chicago, Illinois. All cases studied in this paper have the same house configuration (Figure 3): 2-story, east-facing 1,800 square feet with unfinished basement, 3 bedrooms, and 2 bathrooms. Table 3 lists the features of the pre-retrofit house, assuming the original homeowners have made certain lighting and appliance upgrades. In addition to interior floors, a dividing wall is added along the north-south direction to mimic the real house configuration, so the east and west windows do not face each other.

Figure 3. Study House (Rendered by BEopt)

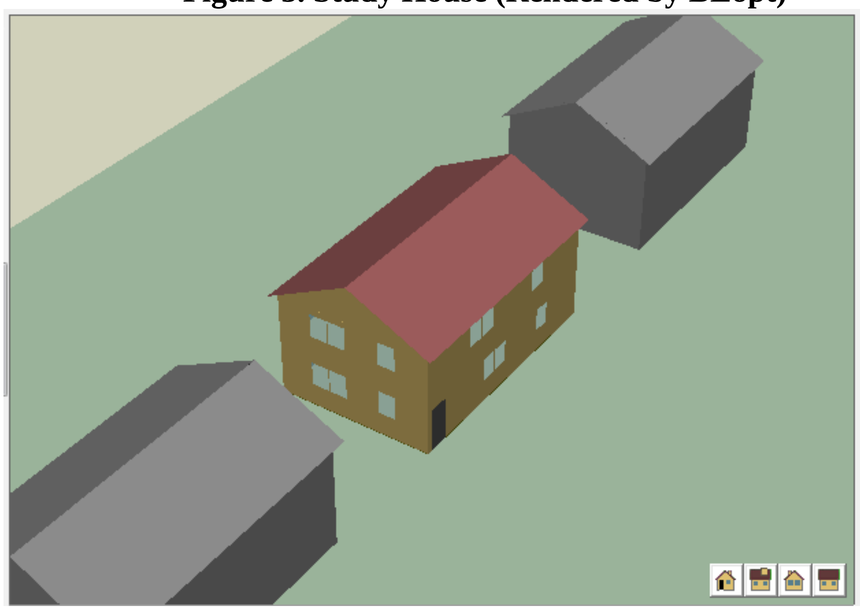


Table 3. Pre-Retrofit House Reference

Description	Pre-Retrofit Reference
Window Type	Single-Pane Clear
Wall Assembly	2 × 4, 16” on center R-7 Cavity Grade 3
Basement	Unfinished 8 feet R-10 Rigid
Attic	Unfinished R-11 Blown-in Cellulose
Specific Leakage Area	Very Leaky 0.0009 (ACH50 = 18.6)
Duct Location	Basement, Typical (Leakage Fraction = 0.15)
Duct Insulation	R-6
Lighting	40% Fluorescent, Hardwired
Appliance	ENERGY STAR®
A/C and Furnace Rating	SEER 10, 78% Furnace
Water Heater	0.67 Energy Factor, Gas
Mechanical Ventilation	Spot Vent

This house is poorly insulated and leaky, which is typical for homes constructed in the 1950s and 1960s. For a cost-neutral retrofit target, the following envelope upgrade EEM (Energy Efficiency Measures) options were considered for optimization:

Table 4. EEM List

EEM No.	EEM Description
1	Replace existing window with 2 pane low-e argon low SHGC window (U=0.259, SHGC = 0.310)
2	Increase ceiling insulation to R-60 (U=0.016)
3	Upgrade existing wall envelope to R-13 cavity with 1.5inch rigid foam (U=0.047)
4	Seal the building envelope to specific leakage area = 0.00018 (ACH50 = 1.9)

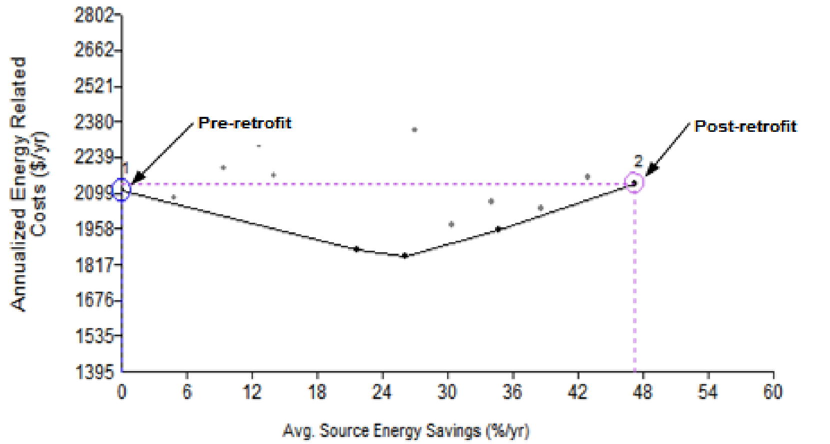
To simplify the analysis, we only proposed EEM 1-4 as a reduced set of options. The proposed EEMs all exceed 2009 International Energy Conservation Code (ICC 2009) prescriptive envelope requirements. There is room for improvement in space lighting, water heating, and HVAC; however, we consider only EEMs 1–4, as they directly affect thermal comfort conditions. Throughout the study, the gas furnace with direct expansion air conditioner is not upgraded and has a fixed capacity of 100 kBtu/h of heating and 5 tons of cooling. This eliminated system upgrading or auto sizing related first cost differences caused by thermostat or comfort-stat settings. The retrofit project has a loan period of 5 years, 7% interest rate, 3% inflation, and 3% real discount rate. The analysis period is 30 years.

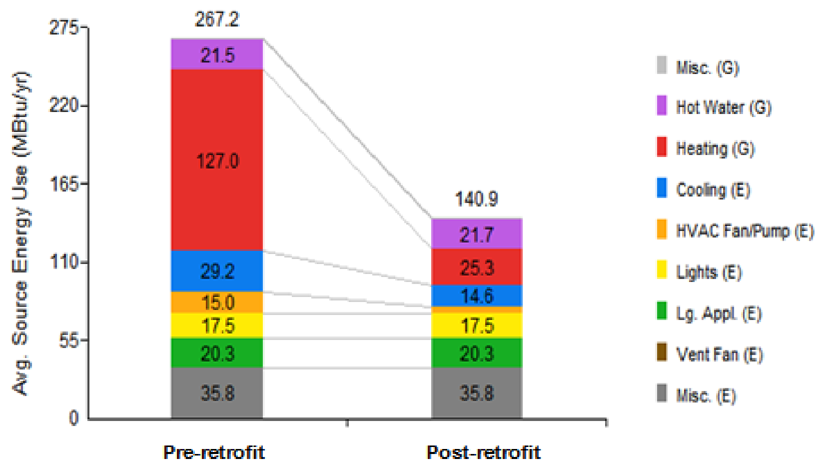
Conventional Thermostat

Figure 4 shows the optimization (least-cost) curve and utility cost by end uses using the default thermostat of 68°F heating and 78°F cooling on the retrofit path. Annualized energy-related cost (AERC, $/year) is the annualized energy-related cash flows over the 30-year analysis period, and is converted from the present value calculated from loan payments, replacement costs, utility bill payments, and residual values (BEoptE+ 1.2). Figure 4 shows EEM 2 & 4 result in the lowest AERC and EEM 1-4 combined result in an almost neutral AERC and are thus all selected.

Figure 4 shows that EEMs 1, 2, 3, 4 combined result in 47% whole-house source energy (Deru and Torcellini, 2007) savings, and 74% heating, cooling and fan source energy savings. EEMs 1, 2, 3, 4 combined also result in a slightly positive AERC ($30). The pre-retrofit house AERC includes only the house utility bill ($2,107). The post-retrofit house AERC is $2,137 with the annual utility bill portion of $1,191.

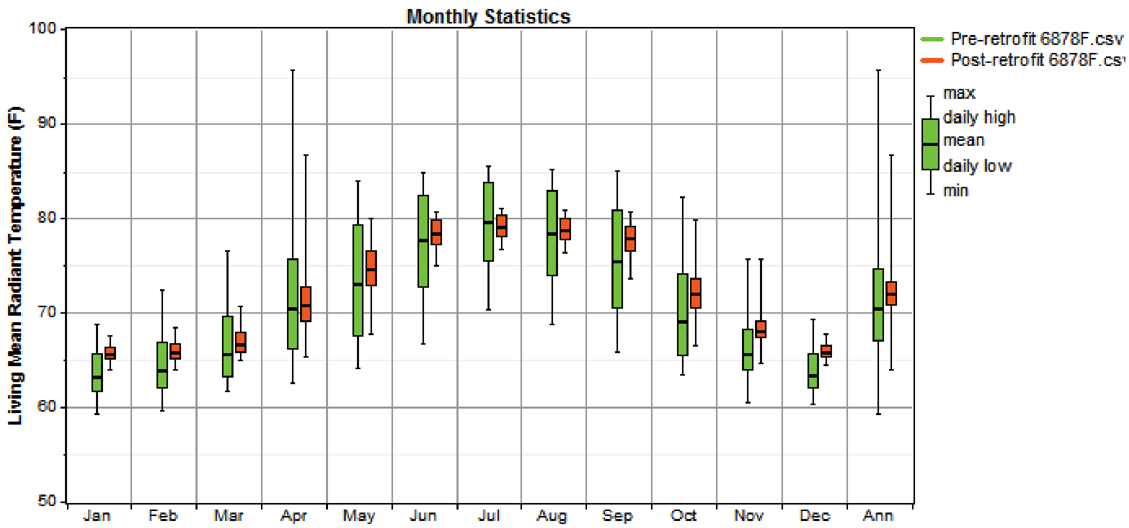
Figure 4. 68/78°F Optimization Curve & Source Energy Use Plot





The optimization curve generated by this approach leads to very different comfort levels. Figure 5 shows the monthly statistical average of the living space mean radiant temperatures (MRTs): green denotes the pre-retrofit condition; orange denotes the post-retrofit condition. The post-retrofit MRT shows a much smaller monthly variation. In addition, the monthly average post-retrofit MRTs are higher than the pre-retrofit MRTs during the winter months.

Figure 5. Monthly MRT Statics Pre-Retrofit and Post-Retrofit



In order to achieve the post-retrofit home winter comfort or MRT level, the pre-retrofit home will have to increase its air temperature (thermostat heating set point) a few degrees to compensate for lower MRT, given that all other comfort factors remain the same. This adjustment will result in thermal comfort-related energy and cost premiums.

Figure 6. Pre- and Post- Retrofit House Daytime PPD Bin Data

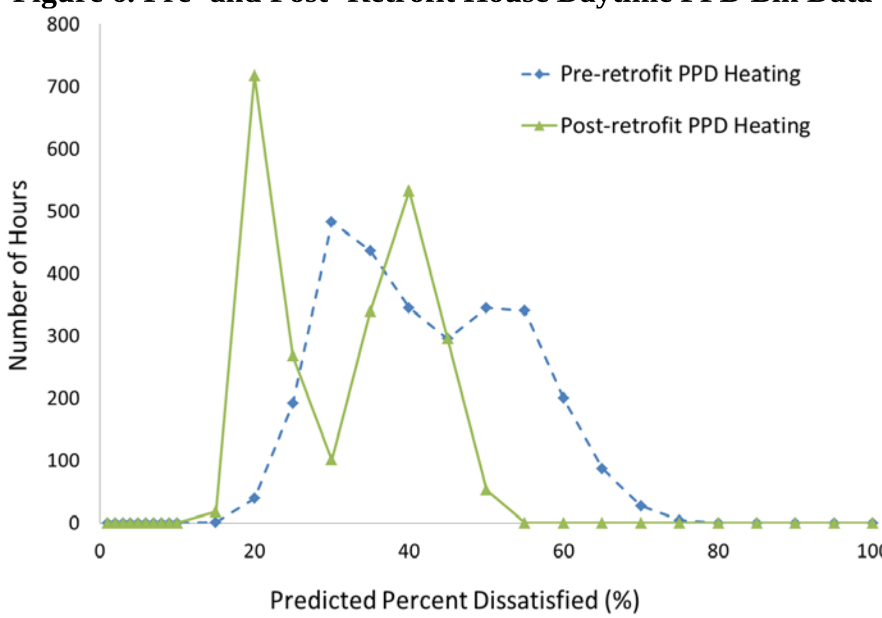


Figure 6 uses PPD bins during daytime heating hours to examine various comfort levels. Both the pre- and post-retrofit daytime (7:00am to 11:00pm) heating PPD bin hours are displayed, assuming that maintaining comfort levels at night is less critical, since most people adjust their bedding levels to stay comfortable. The pre-retrofit home shows a wider PPD distribution with more than 658 daytime heating hours of PPD > 50%. This means that there are more than 658 daytime heating hours during which more than 50% of homeowners will be dissatisfied or uncomfortable. The post-retrofit home, on the other hand, reduces the number of daytime heating hours during which PPD > 50% down to 0.

PMV Comfort-Stat

There are two ways to examine the retrofit project using PMV comfort-stat: a) maintaining pre-retrofit equivalent comfort and b) maintaining post-retrofit equivalent comfort. First, using pre-retrofit comfort settings depicts a scenario where in the post-retrofit home homeowners dial down the thermostat setting and live with the same comfort condition as before. Second, using post-retrofit comfort settings depicts a scenario where in the pre-retrofit home homeowners choose to live with the post-retrofit equivalent (better) comfort conditions, and dial up the thermostat setting accordingly.

To find the pre-retrofit PMV control settings, heating and cooling binned average PPD values (daytime) were calculated and converted to PMV indices (ASHRAE 2004) for the pre-retrofit home. The comfort-stat setting equivalent to the pre-retrofit comfort level is +0.7 PMV (cooling) and –1.3 PMV (heating). The comfort-stat PMV settings also account for control set point hysteresis, ±0.05PMV.

Figure 7 shows optimization results with thermostat settings at 68/78°F vs. comfort-stat at pre-retrofit PMV levels. With conventional thermostat settings at 68/78°F, the post-retrofit home has better comfort (lower PPD) than the pre-retrofit home. With comfort-stat set at pre-retrofit PMV levels, the post-retrofit home shown in Figure 7 maintains the same comfort level (same PPD) as the pre-retrofit home. The post-retrofit home (with conventional thermostat settings at 68/78°F) has an AERC or utility bills $39 higher than the post-retrofit home with a comfort-stat (set to maintain pre-retrofit PMV levels).

Figure 7. Retrofit Optimization Curves with Thermostat (68/78°F) Vs. Comfort-stat (at Pre-Retrofit PMV Levels)

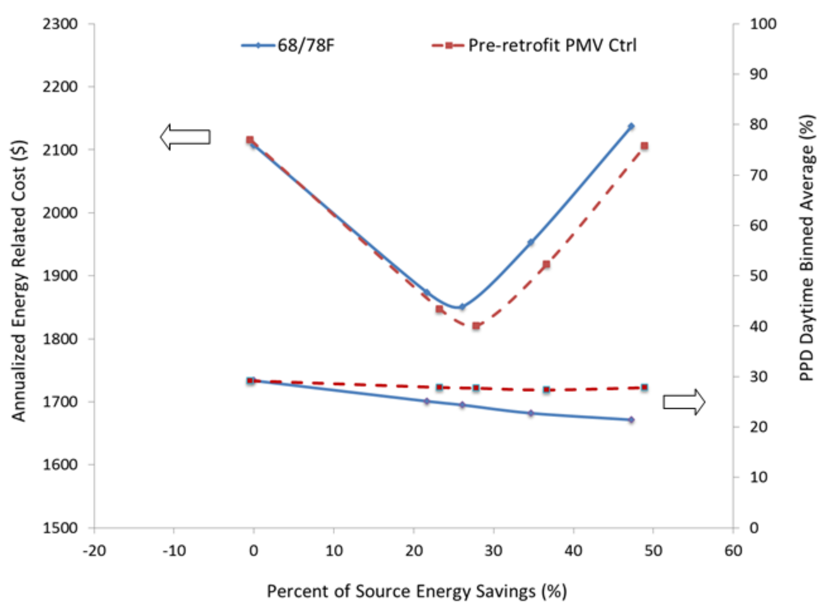


Figure 8 shows optimization results with thermostat settings at 68/78°F vs. comfort-stat at post-retrofit PMV levels. The comfort-stat setting equivalent to the post-retrofit comfort level is found to be +0.55 PMV (cooling) and –1.05 PMV (heating). The comfort-stat PMV settings also account for control set point hysteresis, ±0.1PMV.

In this case, with thermostat settings at 68/78°F the pre-retrofit home has worse thermal comfort (higher PPD) than the post-retrofit home. To achieve thermal comfort levels equal to the post-retrofit home, the pre-retrofit home with a comfort-stat (set to maintain post-retrofit comfort levels) has an AERC approximately $133 higher than the pre-retrofit home with a conventional thermostat (68/78°F).

Figure 8. Retrofit Optimization Curves with Thermostat (68/78°F) Vs. Comfort-Stat (at Post-Retrofit PMV Levels)

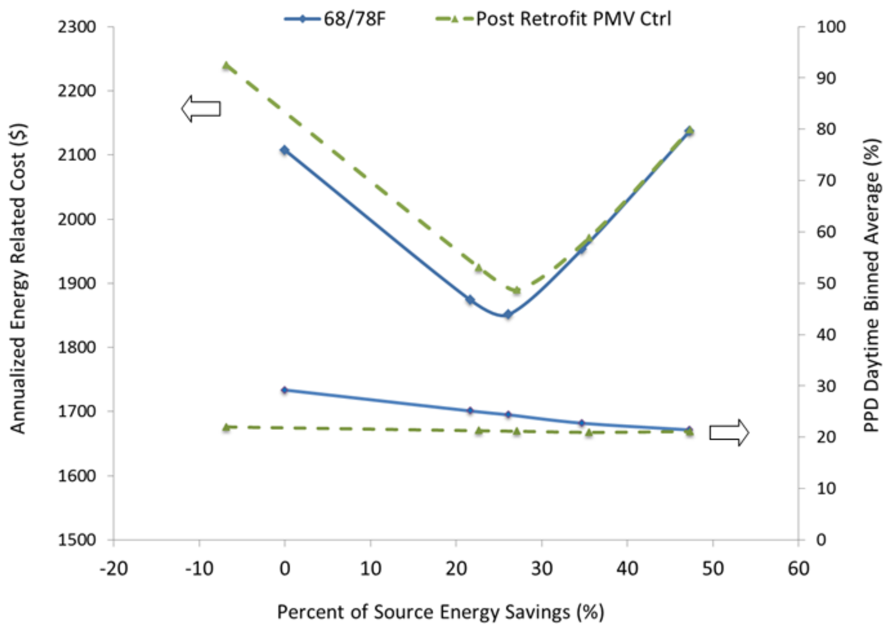
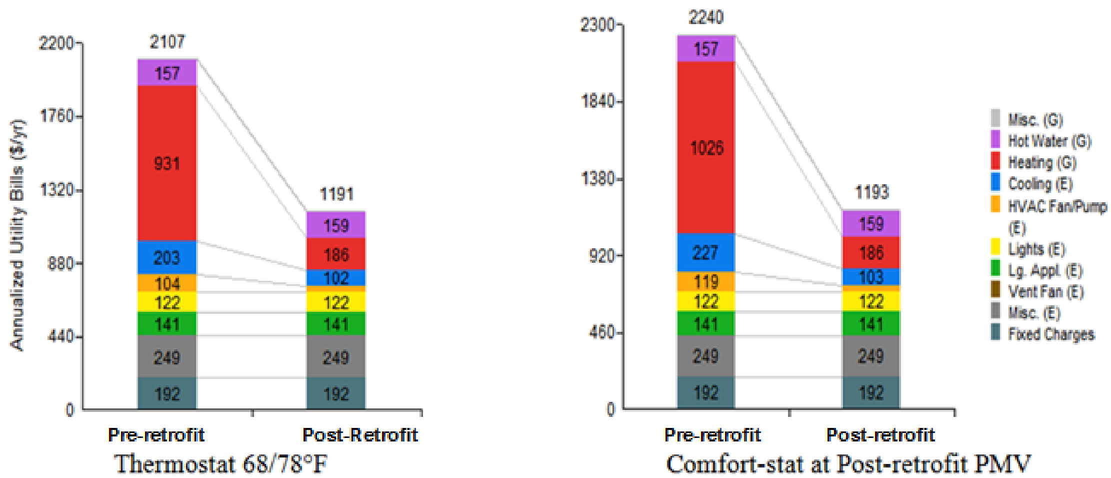


Figure 7 and Figure 8 illustrate the energy and cost benefits or premiums associated with thermal comfort. We recommend using the comfort-stat settings at post-retrofit PMV levels. The comfort-stat set at pre-retrofit PMV levels may not give enough credit for the retrofit project, because even when neither the pre- nor the post-retrofit home calls for heating or cooling system operation, the post-retrofit home can naturally stay at better comfort levels than what the relaxed comfort-stat can indicate.

Figure 9 compares the utility bill differences for the pre- and post-retrofit home with conventional thermostat setting at 68/78°F vs. comfort-stat setting at post-retrofit PMV level (+0.55 PMV [cooling] and –1.05 PMV [heating]).

Figure 9. Thermostat vs. Post-retrofit Comfort-Stat



After reconciling the slight difference on the post-retrofit home utility bills between the two controls ($2), we see that to achieve the post-retrofit equivalent thermal comfort, the pre-retrofit homeowner will need to pay $131/year extra for utilities. This is equivalent to 6.2% increase on the pre-retrofit home overall utility bills ($2,107), and 10.6% increase on the pre-retrofit home heating and cooling cost ($1,238).

Using the post-retrofit equivalent comfort-stat as a constant operational setting to evaluate the retrofit, this retrofit project also becomes more attractive by bringing 51% of source energy savings as opposed to 47% and generating a negative cash flow (ΔAERC) of –$101 per year instead of a positive cash flow of $30.

Conclusion

The thermal comfort benefits from retrofit projects are no longer soft benefits. In lieu of conventional temperature based thermostat, this study proposes using PMV comfort-stat and monetizes the value of comfort when considering home retrofit projects. In the case study of an existing home in Chicago, Illinois, 10.6% heating and cooling cost premiums are required to operate the pre-retrofit home at equivalent comfort conditions as the post-retrofit home. In addition, using post-retrofit equivalent comfort-stat vs. conventional thermostat as a fixed operational setting, the retrofit project becomes more cash flow attractive and achieves higher source energy savings levels (51% vs. 47%).

References

Amann, J.T. 2006. *Valuation of Non-Energy Benefits to Determine Cost-Effectiveness of Whole-House Retrofit Programs: A Literature Review*. ACEEE Report No. A061, May 2006.

[ASHRAE] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 2004. ANSI/ASHRAE Standard 55-2004, Thermal Environmental Conditions for Human Occupancy.

BEoptE+ 1.2, 2012, http://beopt.nrel.gov.

Clinch, J.P. & J.D. Healy. 2003. "Valuing Improvements in Comfort From Domestic Energy-Efficiency Retrofits Using a Trade-Off Simulation Model," *Energy Economics* 25 (5): 565–583.

Deru, M. & P. Torcellini. 2007. *Source Energy and Emission Factors for Energy Use in Buildings*. NREL/TP-550-38617. Golden, Colo.: National Renewable Energy Laboratory.

[EIA] U.S. Energy Information Agency. 2009. Residential Energy Consumption Survey. Washington, DC: US Department of Energy, 2005.2.

Fanger, P.O. 1970. *Thermal Comfort: Analysis and Applications in Environmental Engineering*. Danish Technical Press, Copenhagen, Denmark.

Hendron, R. & C. Engebrecht. 2010. *Building America Research Definition: December 2009*. NREL/TP-550-47246. Golden, Colo.: National Renewable Energy Laboratory.

[ICC] International Code Council, 2009. *2009 International Energy Conservation Code.*

Lee, D. 2010. "Delivering Whole House Solutions – Federal Efforts." presented at the CEE meeting. http://www.cee1.org/cee/mtg/09-10mtg/Presentations/ThuGen_Delivering_Lee.pdf.