

Why occupancy-responsive adaptive thermostats do not always save - and the limits for when they should

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ABSTRACT

So-called ‘smart thermostats’ are beginning to fill the gap left in efficiency programs after researchers and policy makers discovered that in practice, simple programmable thermostats do not guarantee energy savings. As a result, EPA ended EnergyStar certification of programmable thermostats in 2010. Many recent pilots for communicating thermostats, occupancy-responsive thermostats, and adaptive control schemes have shown significant annual HVAC savings on the order of 10-20%. However, the form and function for technologies in this space vary widely. Some controls merely allow for remote management (e.g., web-based set-point scheduling or smart-phone interface and control), while other devices monitor occupancy and automatically adjust set-points when a space is vacant. Still other technologies automatically adapt to user behaviors and preferences in order to anticipate changes and adjust HVAC operation. These differences have different savings implications. Further, the application into which any of these technologies is installed also impacts savings potential.

The study focuses particularly on a series of pilot evaluations conducted with one occupancy-responsive adaptive thermostat system that resulted in very little energy savings during normal operation in university residence halls. These results came as a great surprise to the research team, especially since the HVAC system run-time for vacant zones was reduced to nearly zero in the buildings. The detailed evaluation of this case forms a conceptual basis for explanation of the limitations for smart thermostat devices. The research shows that considerable savings can be had in certain instances, but that the impact is sensitive to technology and application. The study also reviews previous research on the technology and recommends methodological improvements for future studies.

Introduction & Technology Overview

‘Smart thermostats’ are characterized generally by their communicating capabilities, including web and mobile user interface options, as well as networked control that allows for instantaneous management of multiple thermostats in a facility. Smart thermostats may include occupancy responsive control, adaptive or learning functionality, demand response capability, fault detection and diagnostics, and runtime optimization features. This promises general improvement to programmed setpoint scheduling, as well as automated schedule and setpoint optimization. However, amidst the range of new and emerging opportunities in this space, it is not clear which technology features actually provide energy savings, which improve level of

service, which enhance usability, or which are actually of little technical value¹ (Lopes et al. 2010, Meier et al. 2010, Peffer et al. 2011, Pistochini et al. 2008, Woolley et al. 2012).

Building from programmable ‘setback’ thermostats and modern lighting controls, occupancy-responsive thermostats adjust operation for heating, cooling, and ventilation when a space is vacant (Gupta, Intille, and Larson 2009, Lu et al, 2010). Most occupancy responsive thermostats do this by shifting the occupied temperature set point to a setback, which allows the room temperature to drift and should result in reduced runtime for heating² and cooling equipment. In certain applications it may also reduce energy use related to ventilation. Generally, this adjustment is intended to capture energy savings when no occupants are detected while also maintaining level of service (thermal comfort, indoor air quality, sense of control) during occupied periods. However, understanding the transition from the unoccupied to occupied state is critical for predicting energy savings. When the set-point is restored, additional energy must be expended for a period of time to recover from the setback. For example, if the setback and temperature drift occur during a hot afternoon, and recovery is in the evening, the energy saved during the setback will be greater than energy needed for recovery. There are also conditions for which the energy for recovery exceeds the energy saved during the setback period. Setback may also create periods of unsatisfactory thermal comfort for occupants (Manning et al, 2007).

Adaptive controls automatically change operating parameters according to learned and predicted factors. These systems adapt over time according to measured responses. They can learn about system physical characteristics (cooling capacity, temperature response time, etc) and user schedules and preferences (e.g., Nest, EcoFactor) in order to predict appropriate setback periods and ranges. These features can save energy, improve thermal comfort and/or improve convenience and user experience. For example, EcoFactor will automate schedule programming. These learning algorithms can be integrated with features that respond to occupant proximity (eg: Allure Energy), or that predict occupant comfort according to user feedback and measured and forecast outdoor temperature (eg: as per ASHRAE 55 - Adaptive Thermal Comfort).

This study focuses on one occupancy-responsive adaptive thermostat technology that learns about system response capabilities and automatically programs a setback for vacant periods to ensure a timely recovery to the comfort setpoint when a room is again occupied.

Field Study Methodology

The authors collaborated with Student Housing and the Energy Management Office at the University of California, Davis to monitor and analyze field performance of an occupancy-responsive adaptive thermostat technology by Telkonet. A previous paper outlines a preliminary study (Woolley et al, 2012).

The SS6000 Energy Management Thermostat is the center of the Telkonet EcoInsight system, which includes a ZigBEE mesh network, gateway, and centralized web-based user interface. Each thermostat has an on-board (or remote wireless) infrared motion detector. Additionally, the system incorporates an on-board light sensor and logic to distinguish between vacancy and a nighttime condition where occupants are sleeping.

¹ Another factor in success of any technology is the appropriate match of application; in previous work, we suggested that occupancy responsive thermostats should be cost-effective in dormitory settings because of high occupancy and low predictability (Woolley et al 2012).

² Studies performed in the 1970s, based on models of energy flows through a house, suggested that on average a daily eight-hour nighttime setback could bring approximately 1% reduction in natural gas consumption for each degree Fahrenheit offset (Nelson et al 1978).

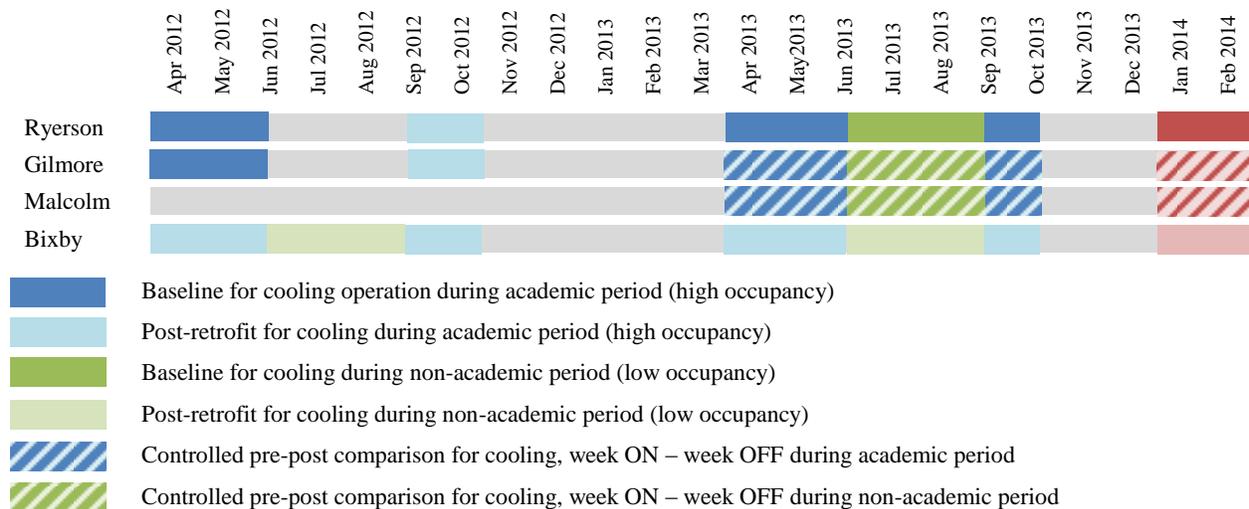
Telkonet applies a learning algorithm called Recovery Time™ that continually adapts the setback temperature for unoccupied periods so that a room can recover within an acceptable period upon the occupant’s return. The thermostat learns how quickly the associated mechanical system is able to respond, allowing the room temperature to drift only so far that it can still return to the occupied set-point within the allotted time. During occupied periods, users are allowed temperature control, although facility managers may limit the selectable set-point bandwidth to avoid excessive heating or cooling by residents.

In this study, the Telkonet system was installed in four dormitory buildings, each a 5-story concrete and steel structure originally constructed in 1965. The residence halls each have 110 rooms and various common spaces, such as corridors, meeting rooms, laundry rooms and bathrooms (about 4,000 m²). Rooms occupy about 50% of the total floor area. These buildings are equipped with two-pipe, three-speed fan coil systems for heating and cooling, so all rooms are restricted to either cooling or heating during any given period. Chilled water and steam supplied from the campus central plant are generally switched only once per season. Each room has a fan coil that is controlled by a thermostat in the room. Fresh air ventilation is provided to each room by infiltration and through operable windows. Corridor spaces have separate controls.

Telkonet occupancy-responsive thermostats were installed throughout Bixby Hall in September 2011. Installation in Malcolm, Gilmore and Ryerson followed in May, June and July 2012 respectively. In all cases, Telkonet thermostats replaced unrestricted manual thermostats.

We collected data in cooling seasons and during periods of high and low occupancy corresponding to the academic quarter, and summer conference housing periods. Data included whole building chilled water energy consumption, outside air temperature, occupancy, thermostat state, active set-point temperature (or set-back temperature), room temperature, and fan coil run time in every room. Since historical whole-building chilled water energy consumption data was only available for Ryerson and Gilmore, data from cooling season performance in September – October 2012 (post-installation) were compared against chilled water energy consumption data from April – May 2012 (pre-installation). Further, from April 2012 to February 2013, the thermostats in Gilmore and Malcolm were switched between an occupancy-responsive mode and a conventional operating mode in alternating weeks (ON-OFF). This allowed for comparison both in academic and non-academic periods (Table 1).

Table 1: Data periods utilized for study



	Baseline for heating operation during academic period
	Post-retrofit for heating operation during academic period
	Controlled pre-post comparison for heating, week ON – week OFF during academic period
	Data not available

In order to assess energy savings, the evaluation applies a hybrid of the Whole Building and Retrofit Isolation methods described by ASHRAE Guideline 14 (ASHRAE 2002, Haberl, Culp et al 2005). First, whole building chilled water energy use from before the thermostat installation in Ryerson and Gilmore was compared to the chilled water energy use during a similar climate period following the installation. Second, whole building chilled water consumption was combined with room-by-room data (available from the thermostats) to assess the effect of the occupancy-responsive adaptive set-back algorithm during periods where the feature was enabled (ON) and disabled (OFF) in week long intervals.

Data analysis used a multiple change-point regression to model the baseline chilled water energy consumption as a function of several independent variables (outdoor temperature, 24 hour temperature history, and average building occupancy rate). Measured chilled water consumption from each post-retrofit dataset was compared to a projected baseline that uses the regression model to predict baseline consumption for the post installation conditions. For the experiment that involved alternating weeks with the occupancy-responsive feature enabled and disabled, the combination of all weeks with the feature disabled were used as baseline.

For brevity, only some of the results from this study are presented here, the complete methodology and additional results are presented in a parallel paper (Pritoni et al., 2014).

Results of Field Study

Initial analysis of energy savings for the thermostat installation in these buildings was challenging because there was a lack of reliable data from before installation. The four buildings were included in major renovations and retro-commissioning in the months preceding thermostat retrofit; therefore, energy data from previous years was not representative of a baseline to test impact of the thermostats. The only two buildings that had a reliable pre-retrofit baseline were Ryerson and Gilmore because thermostats were installed several months later and the gap in time allowed data collection for a baseline. This baseline was tested against the fall academic quarter 2012, after the summer installation. Only the cooling operation was compared. Baseline performance for these buildings was collected in Spring 2012, and compared to data from Fall 2012 following the thermostat installation. The two different seasons were characterized by a very similar distribution of meteorological conditions. Chilled water energy savings were calculated at 3.4% for Ryerson and 0% for Gilmore.

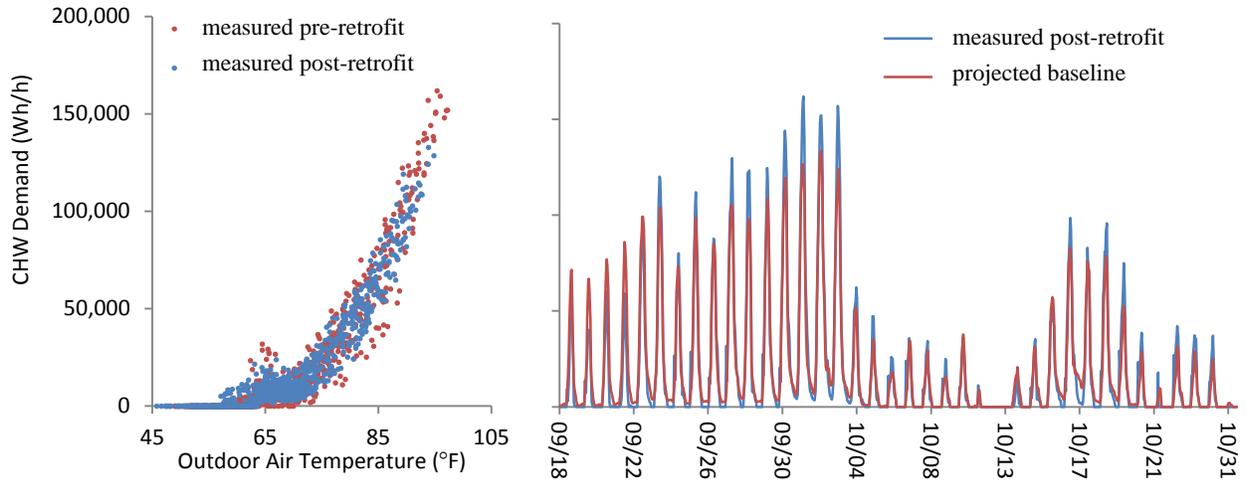


Figure 1: Cooling demand for baseline and post retrofit in Gilmore (spring 2012 and fall 2013) in a controlled pre-post comparison. The analysis indicates 0% savings (0 kWh/day).

Note: each point represents hour average energy consumption (Wh/h)

To confirm these results, Gilmore and Malcom were subjected to an experiment that involved alternating weeks with the occupancy-responsive feature enabled and disabled. Analysis from this experiment supports the conclusion that chilled water energy savings are negligible during the academic period. Results are summarized in Table 2.

A previous study in Bixby indicated that energy use during the summer period (July – August 2012) was much lower than during academic periods with more regular occupancy. However that analysis was not able to separate the portion of chilled water use reduction that was as result of reduced internal gains (due to reduced occupancy) from the savings that could rightfully be attributed to the occupancy responsive feature. The alternating weeks experiment allowed for better isolation of the effect of the occupancy-responsive feature, and shows cooling energy savings between 20%-30% during the non-academic period.

Table 2: Summary of results from all study periods analyzed

Building	Study Period	Absolute Savings (kWh/day)	Savings (%)
Ryerson	Pre-post Comparison Cooling Spring 2012 vs Fall 2012 Academic Period	39.2	3.4%
Gilmore	Pre-Post Comparison Cooling Spring 2012 vs Fall 2012 Academic Period	-	0.0%
Gilmore	Week ON - Week OFF Control Cooling Summer 2013 Non-Academic	158.0	29.0%
Malcolm	Week ON - Week OFF Control Cooling Spring 2013 Academic Period	25.5	2.8%
Malcolm	Week ON - Week OFF Control Cooling Summer 2013 Non-Academic	338.4	24.9%
Malcolm	Week ON - Week OFF Control Cooling Fall 2013 Academic Period	35.3	6.4%

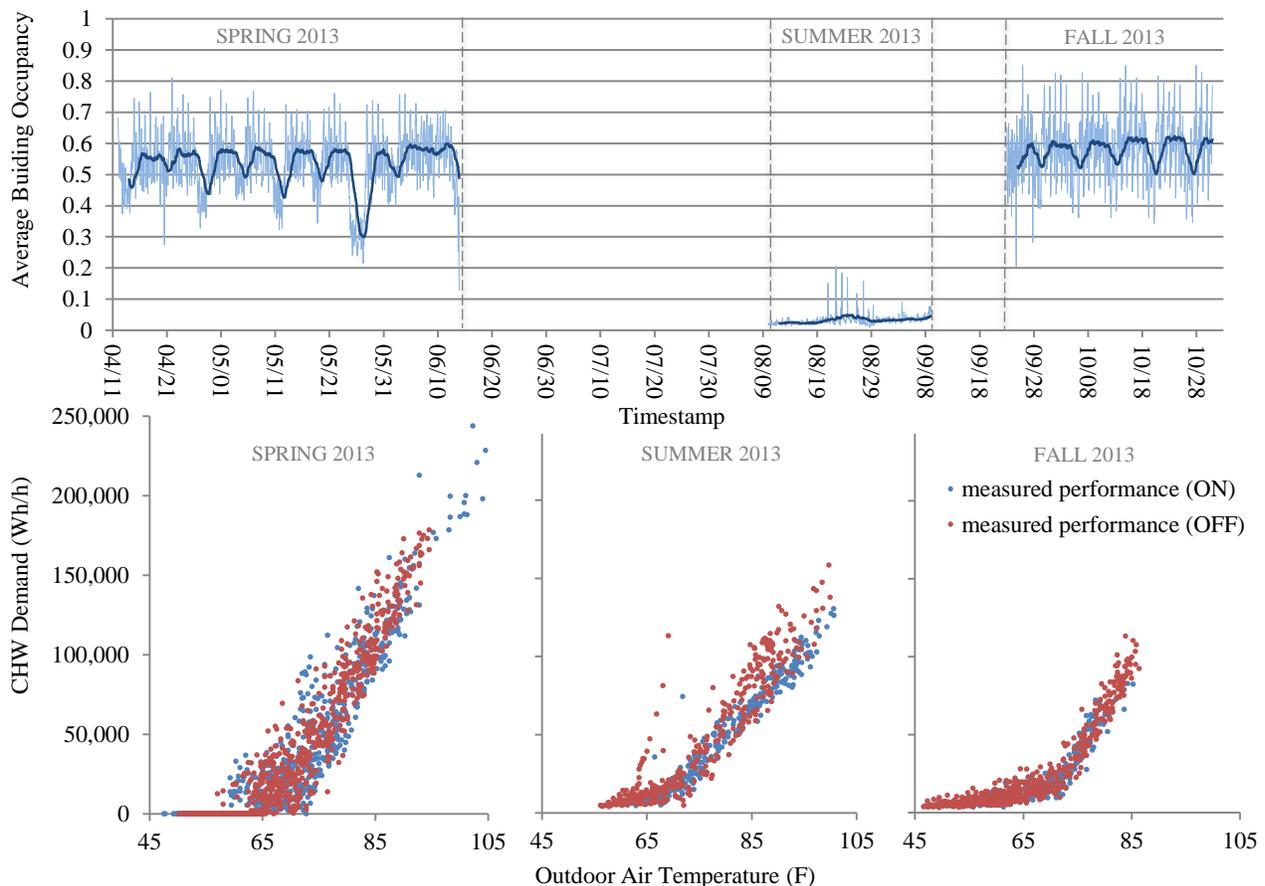


Figure 2a) Average building occupancy (fraction of bedrooms with at least one occupant) in Malcolm during spring, summer and fall 2013. 2b) Cooling demand for Malcolm with occupancy responsive functions

It appears that the major difference between savings potential in the academic and non-academic periods is a result of the fact that occurrences of vacancy in each room during the non-academic period are more temporally and physically coincident with vacancy throughout the building. Although whole building occupancy during the academic period is only 60-70% on average, the occurrences of vacancy in each room are more disaggregate and sporadic. For example in the academic period, some students leave for class for a few hours, but adjacent rooms tend to remain occupied. The building may only be 50% occupied, but the distribution of vacant rooms veritably occurs as a checkerboard spread across the building, and the periods of vacancy in each room is often too short to allow temperature to drift all the way to the setback. To the contrary, occupancy patterns over the summer period are more regular, and vacancy in one room is more likely to correspond to vacancy throughout the building. During this time, residence halls are used as conference housing with no permanent residents.

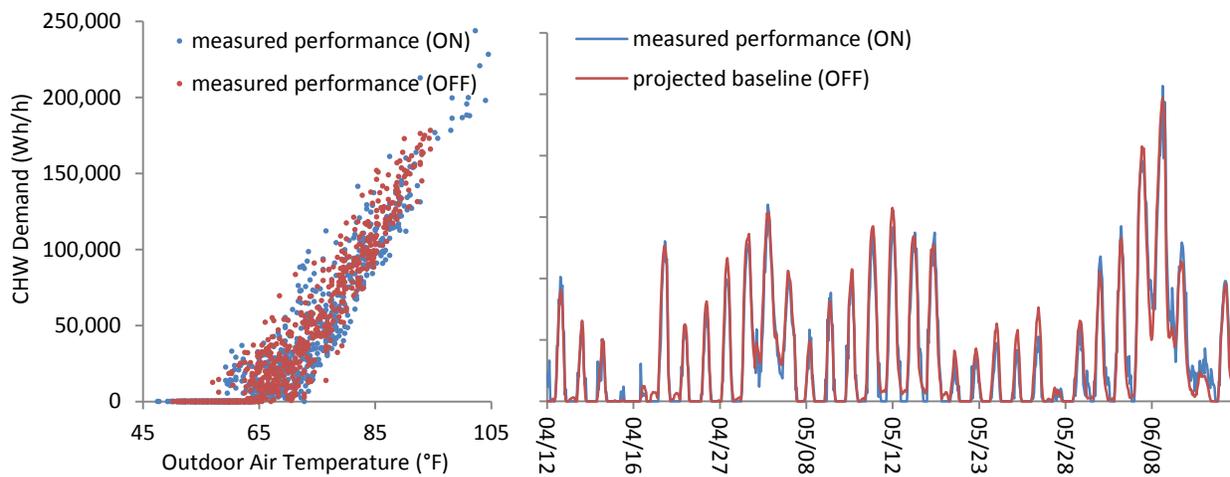


Figure 3: Cooling demand for ON-OFF periods during academic period (spring) in Malcolm. The analysis indicates 2.8% savings. (25.5 kWh/day)

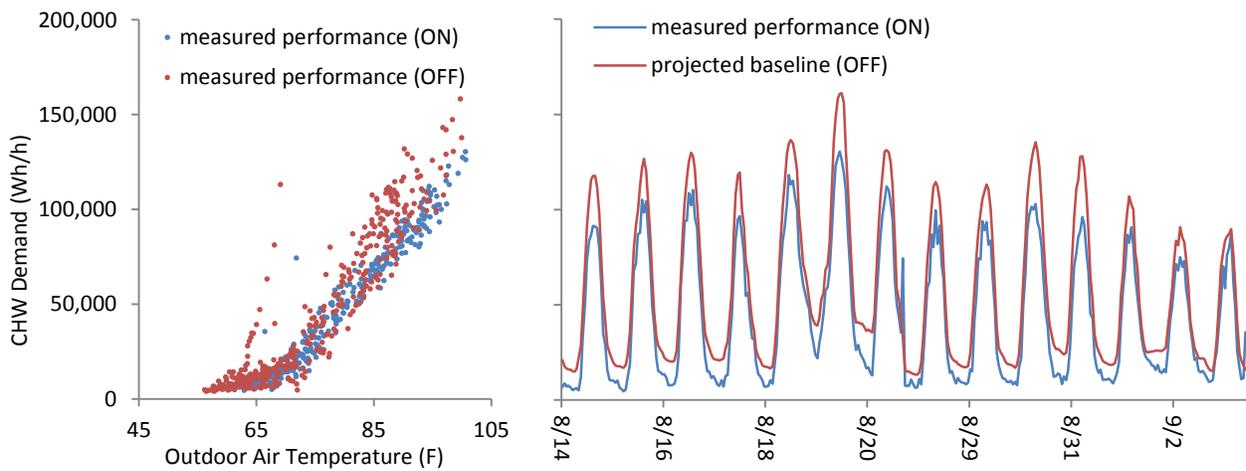


Figure 4: Cooling demand for ON-OFF periods during non-academic period (summer) in Malcolm. This analysis indicates 24.9% savings (338.3 kWh/day)

Periods of vacancy tend to be much longer, indoor-outdoor temperature difference is generally larger, and indoor temperature tends to drift all the way to the setback temperature when rooms are unoccupied. The summer period also experiences periods with much lower occupancy, in fact, average occupancy during the period is only 10%. Practically, a prolonged setback in 90% of the rooms produces an effect similar to an increase of the whole building setpoint by a few degrees. Subsequently, we hypothesize that if vacancy in rooms during the academic period was more prolonged, and more synchronous with vacancy in adjacent rooms, the same level of whole building average occupancy would yield greater savings. Figures 3 and 4 show detailed data for Malcolm during spring and summer.

Simulation of the Ideal Setback Scenario

The measured temperature and equipment runtime behavior during occupied and vacant periods in actual rooms was complicated and not always consistent. Initial observations of field measurements indicated that while equipment runtime was reduced substantially during vacant periods, whole building chilled water consumption did not decrease correspondingly. We were confused. In order to better understand the dynamics at play, we developed an idealized thermal zone model in order to clearly describe the fundamentals behind what ‘should’ occur for zones that experience a setback.

The Simulink model (illustrated in Figure 5) simulates zone temperature and cooling system energy consumption for a simple room described as an air volume with thermal mass capacitance representative of a structure, and thermal resistance representative of insulation between the zone and ambient. The cooling system is described as a perfect energy conversion device with fixed capacity and fixed efficiency. Heat is transferred between the zone and ambient according to a one dimensional heat transfer model that is sensitive to the temperature difference between indoors and outdoors. For this simple model, solar gains and internal gains are ignored, and latent cooling is not considered. As zone temperature drifts above the control set point, the cooling system activates and heat is removed from the zone until the temperature declines to 0.5°F below set point. Thus, when cooling capacity exceeds sensible load, the cooling equipment will cycle on and off. The simple model can be used to simulate behavior with varying environmental conditions; however, this evaluation assesses system behavior with constant outdoor temperature. This approach illuminates some of the fundamental mechanisms that drive the opportunity for energy savings through active setback during vacant periods.

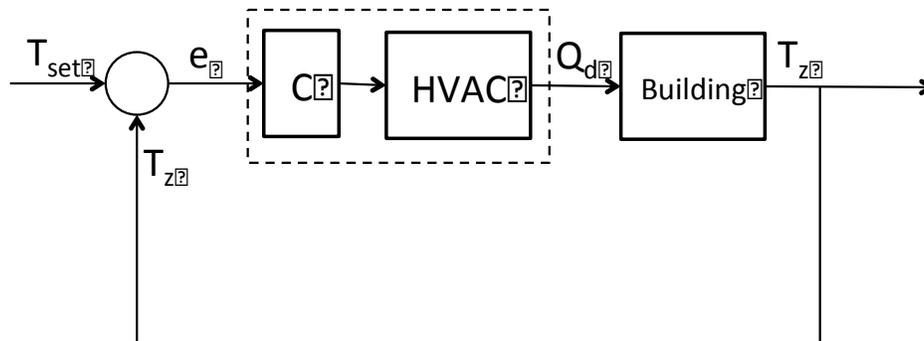


Figure 5: Schematic Simulink Model of Thermal Zone and Cooling System

Figure 6 below illustrates the zone temperature, ambient temperature, and cooling system energy consumption for a zone across a period of vacancy. We find that the system response can be broken into four conceptual periods:

1. Cyclic operation to maintain comfort setpoint – energy consumption during this period is driven by the load, (here only a function of the indoor-outdoor temperature difference).
2. Drift from setpoint to setback temperature – the cooling system is OFF (no energy used).
3. Cyclic operation to maintain setback temperature – energy consumption is driven by the load. Indoor outdoor temperature difference is lower, therefore less energy is required to maintain the setback than would be used to maintain the original comfort setpoint.
4. Recovery from setback to setpoint temperature – energy consumption is greater than what is required to maintain a setpoint. The capacity must be greater than the load in order to shift temperature.

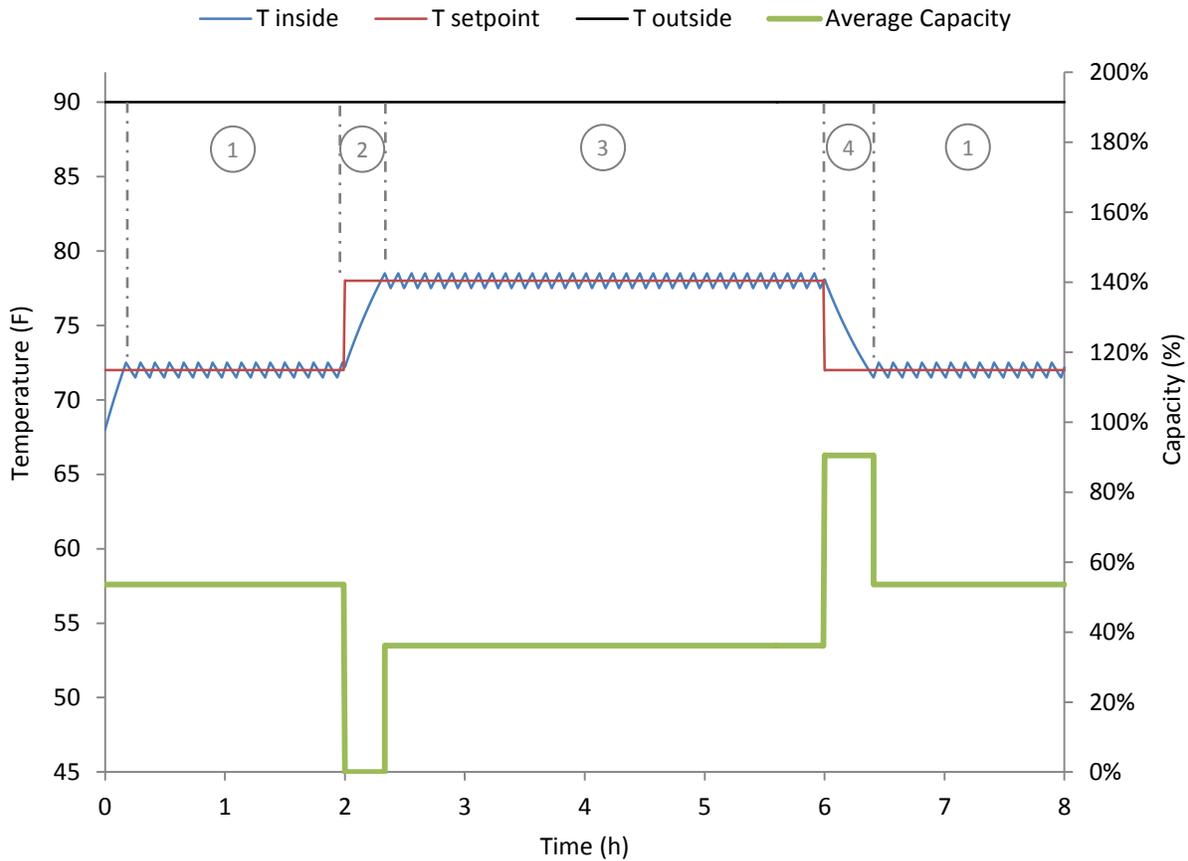


Figure 6: Temperature and Energy Consumption for Thermal Zone and Cooling System

These simulations reveal that the ‘extra’ energy consumption required for recovery from setback (period ④ in Figure 6) is very close to the amount of energy ‘saved’ while the system is off during the drift period (period ②). This means that, for the ideal case, the energy savings opportunity is mostly limited to that period of cyclic operation that maintains setback temperature (period ③). During this period the energy requirement is less than it would be to maintain a cooler set point (period ①). From this simple analysis we draw several conclusions:

1. Short periods of vacancy do not offer an opportunity for savings.
2. If temperature does not drift all the way to the setback little or no savings is achieved
3. If load is driven by any factor other than the indoor-outdoor temperature difference, the opportunity for energy savings is diminished (since the load is not a function of setpoint).

We also recognize the following:

1. In more realistic scenarios, outdoor temperature is not constant. The setback strategy will increase savings if the drift period occurs during a hot part of the day, and the recovery period occurs during a cooler part (the indoor-outdoor temperature difference is reduced).
2. Cooling system efficiency will impact energy consumption. For a conventional cooling system that is less efficient at high ambient temperatures, greater energy savings is achieved if the drift occurs during a hot part of the day, and recovery during a cooler part.
3. Similarly, cooling system energy consumption is largely affected by latent performance. In some climates cycling is less efficient than steady operation, while in other climates cycling can be more efficient. These factors, along with equipment size, will impact the potential for energy savings from occupancy responsive thermostats. For example, in Western climates where cooling system efficiency is improved by cycling, operation during recovery periods could be less efficient because the cooling system operates for longer without cycling.

Review of other Occupancy Responsive Thermostat Studies

To be clear, this study does not conclude that occupancy responsive adaptive thermostats do not save energy. It does conclude that savings is highly sensitive to the scenario in question. The savings potential within the buildings studied was significantly impacted by the building mode of operation. The very low savings observed during academic periods in this evaluation came as great surprise to the researchers, and after great scrutiny we have identified a number of reasons that the technology failed to achieve savings for the residence halls in that scenario. There are certainly a wide variety of applications where occupancy responsive thermostats, adaptive setpoint scheduling, and other ‘smart’ thermostat features should deliver energy savings. In fact, it is even likely that the networked control features that allow for global setpoint limitation did provide energy savings for this installation, even while this study illuminates that the occupancy responsive functions (on their own) provide little measureable value during the academic periods. To be fair to the technology, there are a growing number of research reports and case studies that show savings for occupancy responsive thermostat controls. Some of the resources we are familiar with are summarized in Table 3, along with the savings they have claimed.

Despite the wealth of studies that have indicated savings, we encourage greater scrutiny of this technology and its applications as it continues to evolve. Many of the field studies listed here measure reduction in system runtime as a proxy for energy savings. However, for the buildings that we studied it is clear that there is not always a reliable correlation between system runtime in each room, and cooling energy consumption for the building as a whole. We believe it is easy to overestimate the savings for this technology, as the dynamics that erode savings opportunity are fairly complex. The building efficiency industry is more familiar with estimating the impact of occupancy-sensing for lighting controls, but the effect for heating and cooling is burdened by many dynamic factors that severely complicate the equation.

Table 3: Review of recent studies on occupancy-thermostats and key conclusions

Author	Title	Study	Savings
California Statewide Utility Codes and Standards Program. Heschong Mahone Group.	Codes and Standards Enhancement Initiative – Guest Room Occupancy Controls	Simulation	12-24%
Sullivan, GP. Blanchard, J. Pacific Northwest National Laboratory.	Guest Room HVAC Occupancy Based Control Technology Demonstration.	Field	10-25%
San Diego Gas & Electric. Energy Efficiency Engineering.	Guest Room PTAC/PTHP Energy Management System	Field	10-70%
Business Wire	Networked Telkonet SmartEnergy Reinforces New York University’s Sustainability Initiatives	Field	10%
Telkonet	Case Study – Galt House Hotel	Field	38%
Telkonet	Case Study - Telkonet Smart Energy. Radisson Hotel & Conference Center, Green Bay, Wisconsin	Field	42%
Telkonet	Case Study - Telkonet Smart Energy, Habitat Suites, Austin Texas.	Field	17-25%

Simulation studies can easily over-simplify the mechanisms at play and conclude an unrealistic degree of energy use reduction. For example, the installations that were monitored for this study received a substantial financial rebate from the local utility as part of a custom calculated rebate program that justified energy and demand savings with an annual building energy simulation. We can conclude in hindsight that the model was not accurate. We caution against any study that uses room-by-room runtime reduction as a proxy for energy savings, and strongly recommend that future evaluations conduct careful analysis of the whole-building heating and cooling energy consumption, according to *ASHRAE Guideline 14: for Measurement of Energy and Demand Savings*. None of the studies we are familiar with use this type of controlled approach, and some utilize measurement methods which we believe could actually overestimate baseline energy consumption. For example, comparison of adjacent rooms with and without occupancy-responsive features does not control for thermal interaction between rooms (so baseline rooms without setback may use more energy by carrying part of the load for rooms with setback).

Recommendations and Conclusions

Based on the results shown here, we believe that there are applications where occupancy responsive, adaptive, and otherwise ‘smart’ thermostats can derive substantial savings. Some of the applications that might be most appropriate include:

1. Single family homes (large fraction of vacancy, wholly controlled mechanical system, and independent thermal zone dominated by external loads)
2. Small and medium businesses – especially offices (large fraction of vacancy, independently controlled systems, limited thermal interaction between zones, dominated by external loads).
3. Laboratories – (or other spaces where ventilation rates can be controlled on an occupancy signal, and conditioning loads are dominated by outdoor conditions)

4. Hotels – (large fraction of vacancy, limited thermal interaction between occupied zones and vacant zones – predict better savings where vacancy is organized in blocks).

For residence halls, this study indicates that energy savings during the summer period is substantial, but that the technology does not achieve substantial savings for cooling during academic periods. There may be energy benefits associated with other features for these thermostats but the occupancy-adaptive algorithms do not result in a measurable impact during academic periods. The authors support broader adoption of the technology for residence halls, but recommend careful consideration for the specific application, and measured expectations for the annual energy savings.

We suggest that decisions about where to deploy occupancy responsive thermostats first test whether or not, when, and how far the zone temperature will drift when the conditioning system is off. If cooling loads are mostly transferred to adjacent rooms, and zone temperature does not drift very far, then occupancy responsive set-back may not capture savings.

This analysis does not capture the potential for savings that is available from improved programming and scheduling capabilities. This should be estimated separately for any application in question. A large portion of the savings reported from other residence halls that have installed this technology is suggested to have come from the ability to constrain set-point limits. Most ‘smart’ thermostats provide networked communications that allow for simple management and set-point control in hundreds of rooms at once. Further, systems can easily be shifted to extreme set-backs during holidays.

If estimating the potential for savings for future projects, we recommend a number of application-specific characteristics that should be considered:

1. Mild climates will achieve a smaller magnitude of savings than extreme climates.
2. Application should minimize the number of areas that are not controlled by occupancy responsive functions, especially when the zones have some thermal interconnection.
3. The technology should be applied where zone-by-zone control can be accomplished, and where doing so does not result in diminished equipment performance.
4. During academic periods, residence halls operate with a relatively high degree of occupancy, and occurrences for vacancy are spread across a building in a very irregular and heterogeneous way. When vacant rooms are surrounded by occupied and conditioned zones, the tendency to drift toward a set-back temperature is diminished – thermal load for a vacant room in set-back is transferred to adjacent conditioned zones.
5. During academic periods, a large fraction of vacancy events persist for a relatively short time. For short periods of vacancy, a large fraction of the theoretical savings opportunity is consumed by the energy use required for recovery.
6. The adaptive set-back strategy will have a more significant impact in inefficient buildings, where the indoor load is more closely coupled to environmental conditions, and a relaxed set-point results in a larger total energy benefit. Buildings with large ventilation conditioning load are also good candidate for this technology.

We also recommend two quick and easy tests that should help to identify savings potential for a potential building:

1. Test rooms proposed for occupancy responsive controls by adjusting set-point and observing thermal behavior. If the temperature does not drift to a set-back then there is little opportunity for savings (other mechanisms are conditioning the zone).
2. Consider occupancy throughout the year. Long periods of vacancy, or low average occupancy offer larger savings opportunity. If vacancy periods align with periods of peak conditioning requirements, the building has more potential savings.

This field study of occupancy-responsive adaptive thermostats in university residence halls indicated very little energy savings during academic in-session periods, even though the buildings were only occupied at 50–60% on average. The study indicates that savings increase to 20–30% during summer periods with very low and sporadic occupancy. We identify several factors that contribute to these surprising results, and use a simple simulation to demonstrate some of the fundamental mechanisms involved. We note the technology does offer valuable energy savings opportunity but that the dynamics are complex. We recommend characteristic that should define the most appropriate applications for this efficiency measure, and we caution that future studies of the technology should apply careful methods to avoid overestimation of energy savings impacts.

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