NREL

Evaluating Thermostats' Deadbands Using HVAC Hardware-In-the-Loop Experiment for Advanced Control Strategies

Preprint

Sugirdhalakshmi Ramaraj and Bethany Sparn

National Renewable Energy Laboratory

Presented at the 2025 ASHRAE Winter Conference
Orlando, Florida
February 8-12, 2025

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated under Contract No. DE-AC36-08GO28308

Conference Paper
NREL/CP-5500-91372
September 2025

Evaluating Thermostats' Deadbands Using HVAC Hardware-In-the-Loop Experiment for Advanced Control Strategies

Preprint

Sugirdhalakshmi Ramaraj, and Bethany Sparn

National Renewable Energy Laboratory

Suggested Citation

Ramaraj, Sugirdhalakshmi, and Bethany Sparn. 2025. *Evaluating Thermostats' Deadbands Using HVAC Hardware-In-the-Loop Experiment for Advanced Control Strategies: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5500-91372. https://www.nrel.gov/docs/fy25osti/91372.pdf.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated under Contract No. DE-AC36-08GO28308

This report is available at no cost from NREL at www.nrel.gov/publications.

Conference Paper
NREL/CP-5500-91372
September 2025

15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

NOTICE

This work was authored by NREL for the U.S. Department of Energy (DOE), operated under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Building Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

Cover photos (clockwise from left): Josh Bauer, NREL 61725; Visualization from the NREL Insight Center; Getty-181828180; Agata Bogucka, NREL 91683; Dennis Schroeder, NREL 51331; Werner Slocum, NREL 67842.

Evaluating Thermostats' Deadbands Using HVAC Hardware-In-the-Loop Experiment for Advanced Control Strategies

Sugirdhalakshmi Ramaraj, Ph.D. **Bethany Sparn**
Member ASHRAE

ABSTRACT

Thermostats play a crucial role in energy consumption, user control, and occupant comfort by serving as the interface between the heating, ventilation, and air conditioning (HVAC) system and the building's occupants. The deadband, also referred to as temperature differential, is defined as the temperature difference between the desired setpoint and upper threshold or lower threshold for the HVAC equipment to turn on or off. It is a key factor influencing energy efficiency and user satisfaction. This paper presents a comparative analysis of the deadbands of five different thermostats, tested with a residential heat pump, aiming to identify variations in their deadband settings and implications for energy usage and management. The experimental study was conducted using a HVAC hardware-in-the-loop (HIL) system that allows thermostats to be connected with physical HVAC equipment, driven by conditions in a simulated residential building. The study explores the trade-offs between energy efficiency and occupant comfort and highlights how different thermostats cycle differently based on their deadband settings. The findings offer valuable insights into how thermostat deadband affects comfort and energy use, as well as the cycling frequency of a heat pump.

INTRODUCTION

As energy efficiency become increasingly critical in modern building operations, heating, ventilation, and air conditioning (HVAC) systems, especially heat pumps (HP), have emerged as key targets for optimization. Capable of both heating and cooling, heat pumps are significant energy users in most buildings. They play a pivotal role in demand flexibility making them a critical component for energy optimization during demand response (DR), load shifting, and advanced control strategies. Heat pumps are often controlled with thermostats to improve performance, energy savings, and occupant comfort. One of the critical parameters that determine the performance of thermostats is the deadband: the temperature range around the target setpoint within which the thermostat does not activate heating or cooling. Deadband plays a crucial role in determining the frequency of heat pump cycling and, consequently, energy consumption. A wider deadband can reduce the number of system cycles, leading to potential energy savings. However, it may also compromise occupant comfort if the temperature swings exceed acceptable limits. Narrower deadbands ensure more precise temperature control but at the cost of increased energy consumption and more cycling, which can affect equipment lifespan.

There is limited research that specifically explores the variations in deadband settings across different thermostats and their implications for energy usage. Understanding how different thermostats implement deadbands is crucial since the deadband has a large impact on comfort and the lifetime of the equipment.

This paper presents a comparative analysis of the deadbands of five different thermostats, three of which are considered

Sugirdhalakshmi Ramaraj is a Researcher at the National Renewable Energy Laboratory, Golden, CO.
Bethany Sparn is a Senior Researcher at the National Renewable Energy Laboratory, Golden, CO.

"smart thermostats" by ENERGY STAR, when tested with a heat pump in a HVAC hardware-in-the-loop (HIL) system. The HIL platform, which simulates a real-world residential environment, allows for a side-by-side evaluation of how these thermostats operate the heat pump on a summer day with varying set points. By exploring the trade-offs between energy efficiency and occupant comfort, the study highlights how differences in deadband settings affect the cycling behavior of heat pump systems. The findings of this research provide valuable insights for both consumers and energy managers on how to select or configure smart thermostats to maximize energy savings while maintaining operational flexibility. Furthermore, the results underscore the importance of deadband settings in enhancing demand response capabilities and optimizing advanced control strategies in heat pump systems.

EXPERIMENTAL SETUP

HIL System Configuration

The experimental setup consists of an HVAC hardware-in-the-loop (HIL) system, which simulates a residential environment where thermostats are connected to actual HVAC equipment as shown in Figure 1. The HVAC HIL experiments were conducted at NREL's Systems Performance Laboratory (SPL). Hardware and software interacted continuously to simulate realistic HVAC operation. Sparn (2018) described the laboratory design and the architecture of HVAC HIL system. The experimental setup and validation of the HVAC HIL platform for advanced control strategies are described in detail by Ramaraj and Sparn (2022).

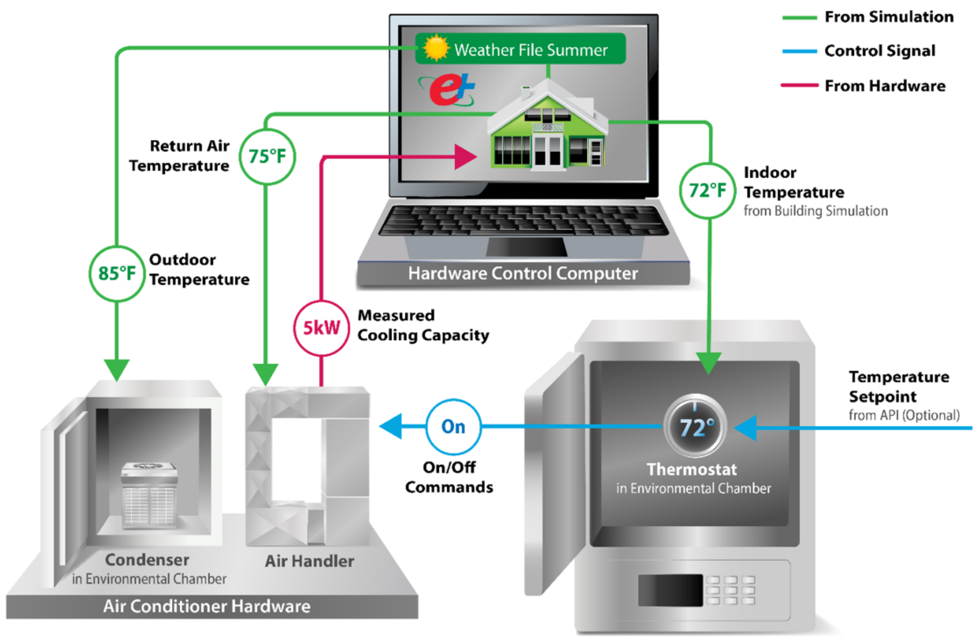

Figure 1 HVAC HIL system in the Systems Performance Laboratory

EnergyPlus® (Crawley et al. 2001), a building simulation software, was used to model the building's characteristics, outdoor conditions, and indoor loads. The simulation was modified to run in real time without an HVAC model. MLE+ (Bernal et al. 2012) connected Simulink to EnergyPlus for co-simulation. Simulink connected the simulation with the lab's data acquisition system, allowing real-time data transfer between the hardware and simulation.

The HVAC hardware included a central heat pump, with an outdoor unit, an indoor air handler, and a thermostat, along with a data acquisition system. The outdoor unit was placed in a temperature-controlled chamber matching the simulated outdoor temperature from a weather file. The indoor unit was connected to a duct loop with heaters and cooling coils to simulate return air temperature. Airflow and temperature measurements were used to determine heat transfer to the house, which was input into the EnergyPlus simulation. A thermostat sat in an environmental chamber that matched the indoor temperature from the EnergyPlus simulation and controlled the HVAC equipment. The data acquisition system collected various temperature measurements and power consumption data at 1-second intervals and the simulation was updated at 1-minute intervals.

Building Model and Cooling Strategy

The calibrated building model (Booten and Tabares-Velasco 2012) was based on a field study in Sacramento, California (Sparn et al. 2014). The model was created using BEopt^{TM} (Building Energy Optimization Tool) and converted into an EnergyPlus (v9.4) input file for HIL simulation. Ramaraj and Sparn (2022) described the home's physical characteristics, occupancy patterns, and internal loads used for the BEopt model. Sacramento weather data from 2010 was used to impose outdoor conditions for a particular summer day in August. A single-stage, SEER 16, HSPF 9.5, 3-ton single-speed air source heat pump, which matched the specifications of the heat pump from the Sacramento field study, was used in the HIL experiments for testing different thermostats in cooling mode.

We recreated a number of different control strategies that were employed during the original field study, including a case that we called "advanced pre-cooling" strategy, in order to validate the HVAC HIL platform. The advanced pre-cooling strategy involved a baseline set point temperature of 76°F (24.4°C) for most of the day, a pre-cooling setpoint of 71°F (21.7°C) in the hours before the peak (9:00 AM to 3:00 PM) and increasing the setpoint to 79°F (26.1°C) during the peak price hours (3:00 PM to 7:00 PM). This schedule has a very long pre-cooling period, but we used this schedule in our laboratory experiments because we were comparing laboratory results to the field study results that utilized the advanced precooling schedule. This advanced pre-cooling strategy is designed to optimize not only energy savings but also occupant comfort, by strategically managing cooling loads in response to demand and peak pricing periods.

RESULTS AND DISCUSSION

Five commercially available thermostats were chosen for HIL evaluation, which were found to represent a diverse range of deadband features. Most of the thermostats were communicating thermostats but one was a basic programmable thermostat without Wi-Fi. The HIL system makes it possible to evaluate thermostat deadband settings under consistent, repeatable outdoor conditions for August 17th using the Sacramento, CA weather data from 2010. Each thermostat was tested with the setpoint schedule from the advanced pre-cooling strategy for a 24-hour time period. The deadband settings for each thermostat are built-in, unknown and we did not attempt to change them, in order to mimic the real-world situation where the user has no control over the deadband. In addition to the five off-the-shelf thermostats, we also tested a baseline case where we imposed a perfect 0.9˚F/0.5˚C deadband above and below setpoint temperature using control from our data acquisition system. Indoor temperature was measured throughout the day for different setpoint temperatures with each thermostat while monitoring the HVAC system's response. The impact of these parameters on energy consumption and runtime was then analyzed to assess the impact on energy efficiency and comfort.

Data on HVAC energy consumption (HP condenser unit and indoor air handler), heat pump on/off cycling, indoor temperature variations, and thermostat setpoint temperatures were collected for a 24-hour time period for each thermostat and presented in the following figures. Figure 2 represents the baseline case without a thermostat where the upper and lower deadbands were set as 0.9˚F/0.5˚C for all setpoint temperatures and the operation of the HVAC hardware was controlled by the lab's data acquisition system. Figures 3-7 show the 24-hour time-series plot of the power consumption of the HP condenser and air handler along with the indoor and outdoor temperature measurements and the thermostat setpoint temperature for five different thermostats. By plotting the temperature and HP power consumption together, we can analyze the HP cycling behavior when room temperature crosses the setpoint temperature with the deadband and observe the deadband variations between the thermostats. Table 1 compares the condenser energy consumption and runtime of the five thermostats to the baseline deadband case. These data were analyzed to identify trends and differences in how each thermostat controlled the heat pump relative to a fixed setpoint schedule within the defined deadband. Additionally, the effect of varying deadband settings on occupant comfort was assessed by comparing temperature fluctuations against setpoint temperatures.

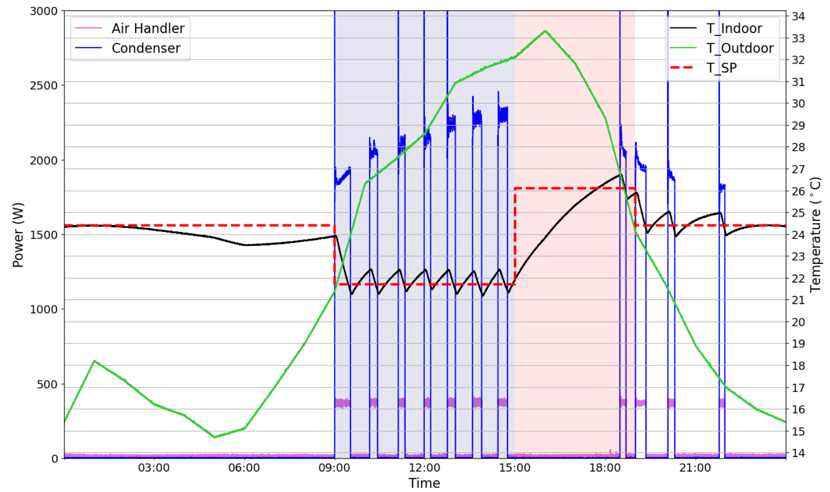

Figure 2 HP power and temperature measurements from HIL for baseline case with 0.5°C deadband.

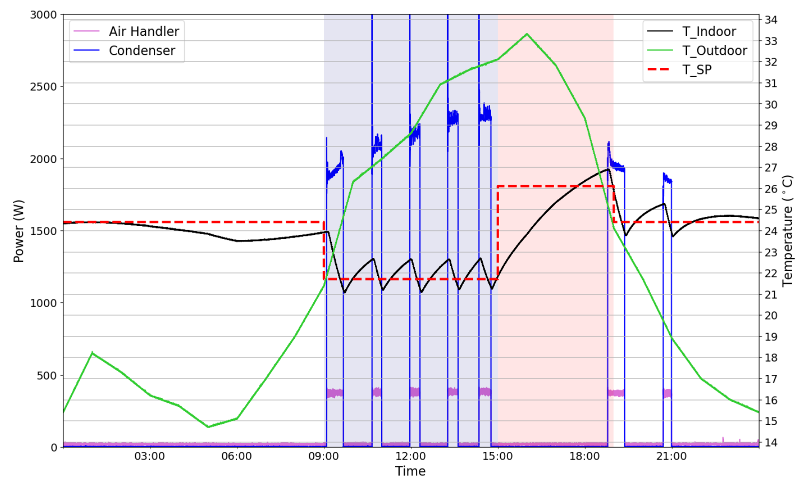

Figure 3 HP power and temperature measurements from HIL with Thermostat 1.

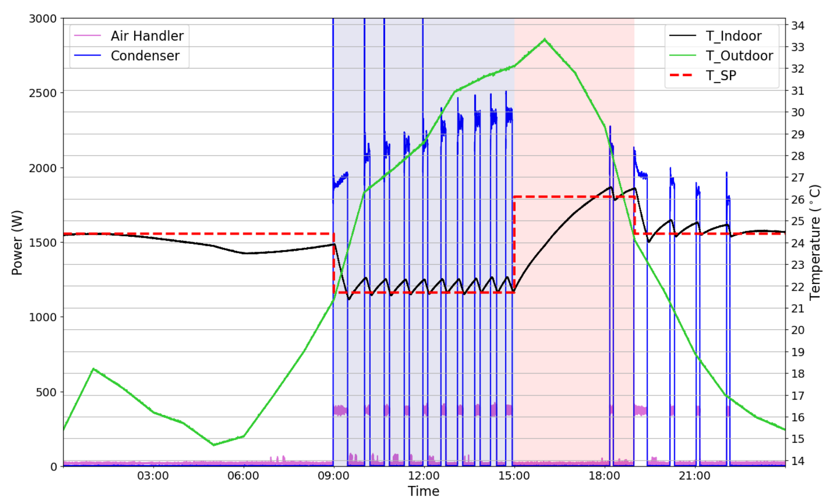

Figure 4 HP power and temperature measurements from HIL with Thermostat 2.

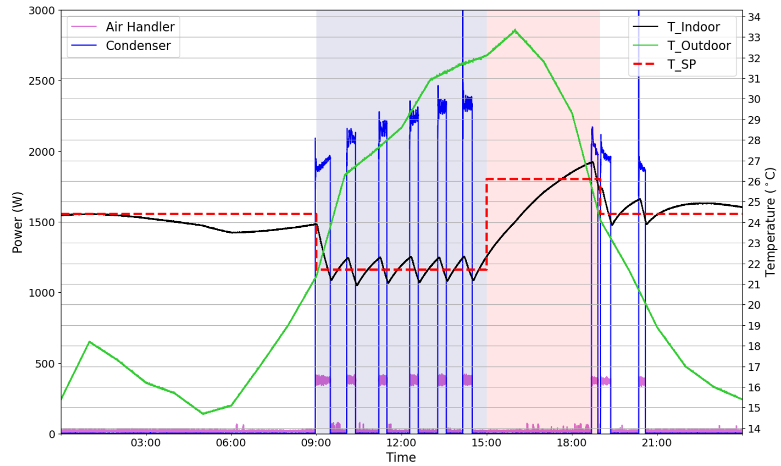

Figure 5 HP power and temperature measurements from HIL with Thermostat 3.

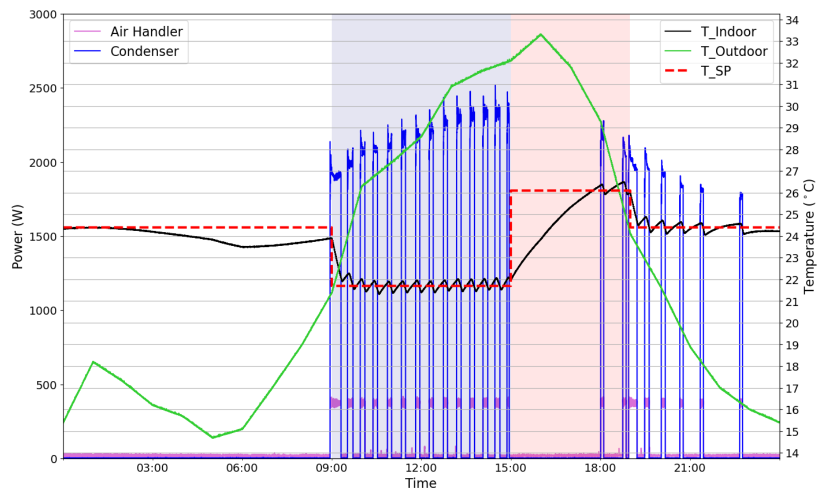

Figure 6 HP power and temperature measurements from HIL with Thermostat 4.

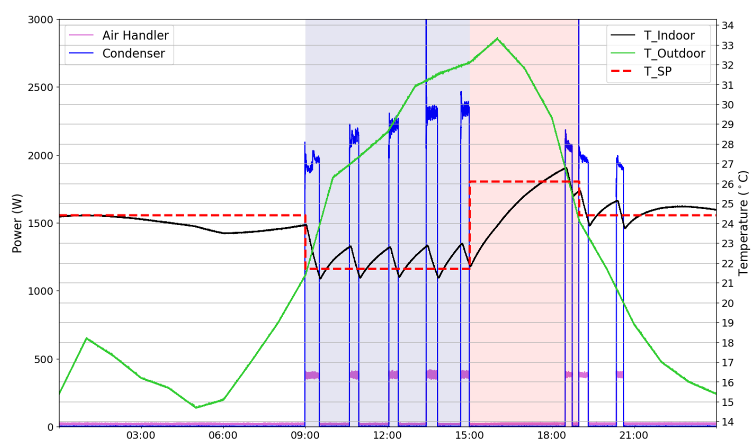

Figure 7 HP power and temperature measurements from HIL with Thermostat 5.

Table 1. Summary of HP Energy Consumption and Runtime for Different Thermostats

	Baseline	Thermostat 1	Thermostat 2	Thermostat 3	Thermostat 4	Thermostat 5
Condenser Energy [kWh]	6.3	6.0	6.3	6.0	7.0	5.9
Condenser Energy Difference [%] with baseline	-	-4.8	0	-4.8	11.1	-6.4
Runtime [mins]	185	174	182	173	200	168
Runtime Difference [%] with baseline	-	-6.0	-1.6	-6.5	8.1	-9.2

The baseline case, shown in Figure 2, controlled the heat pump to cycle with a constant 0.5°C upper and lower deadband for all setpoint temperatures. Thermostat 1 had larger upper and lower deadbands, so it cycled less often, as shown in Figure 3, resulting in less runtime and lower energy use. The comfort might be affected due to the large temperature variation from the setpoint temperature. From Figure 4, we can see that thermostat 2 had a narrow lower deadband, so the heat pump turned on more frequently, but overall energy use and runtime were very similar to the baseline case. Thermostat 3 and thermostat 5 had wider upper and lower deadbands and hence lower energy consumption and lesser runtime as observed from Figures 5 and 7, respectively. Thermostat 4 had very small upper and lower deadbands, resulting in frequent cycling, higher energy use, and longer runtime as shown in Figure 6.

The experimental results revealed significant variations in deadband characteristics among the different thermostats. Some thermostats exhibited wider deadbands, leading to fewer heat pump cycles, shorter runtime, and potential energy savings. However, wider deadbands will also result in greater temperature fluctuations, potentially affecting occupant comfort. Conversely, thermostats with narrower deadbands tended to maintain more stable indoor temperatures but at the cost of frequent cycling, increased runtime, and higher energy consumption. The study highlighted the inherent trade-offs between energy efficiency and occupant comfort. Thermostats that prioritized energy savings often did so at the expense of comfort, allowing for wider temperature swings. On the other hand, thermostats that maintained tighter control over indoor temperature resulted in higher energy usage and frequent cycling. These findings underscore the importance of selecting the right thermostat and customizable deadband settings, enabling users to strike a balance between comfort and efficiency based on their preferences and energy goals.

CONCLUSION

This study provides valuable insights into the deadband characteristics of five different thermostats and their implications for energy management. The findings highlight the trade-offs between energy efficiency and occupant comfort, emphasizing the need for careful consideration when selecting and configuring thermostats. Additionally, heat pumps operate most efficiently when they avoid frequent short cycling (rapid on-off behavior). A properly managed deadband helps prevent unnecessary activation, allowing the system to run longer, more efficient cycles, thus contributing to overall energy savings. By understanding the variations in deadband settings, building owners and occupants can make informed decisions to optimize HVAC system performance and reduce energy consumption. The findings emphasize the need for customizable and adaptive control strategies that balance the trade-offs between comfort and efficiency. As thermostats continue to evolve, their role in energy management and demand response will become increasingly important, making the optimization of deadband settings a key area for future research and development.

Implications for Demand Response and Energy Management

Along with setpoint changes, the variations in deadband settings among thermostats can have implications for demand response and energy management. While thermostat setpoint adjustments can directly control indoor temperature and provide immediate load reduction, deadband adjustments can indirectly influence HVAC operation by reducing cycling, offering more nuanced control over energy use without abrupt changes to indoor conditions. Thermostat deadbands can offer greater flexibility in managing HVAC loads, allowing for more effective participation in demand response programs. By shifting energy-intensive operations to off-peak hours, these thermostats can help reduce strain on the grid and lower energy costs for consumers.

Role in Demand Response (DR): A wider deadband can delay the activation of the heat pump during peak demand times. For example, if a utility initiates a DR event with setpoint changes, a wider deadband allows the indoor temperature to fluctuate more before the heat pump turns on, thus reducing the HVAC system's energy draw during critical times.

Advanced Control Strategies: In advanced control systems, it may be possible to dynamically adjust the deadband based on real-time data on occupancy, energy costs, and indoor temperature. During periods of high energy prices or when few people are in the home, the deadband can be widened, allowing for greater temperature fluctuations and reducing HVAC energy use. In contrast, during low-demand periods or times when people want better temperature control, the deadband can be narrowed to maintain more precise control of indoor conditions.

Future Research Directions

- Adaptive Deadband Control: Explore the development of adaptive control algorithms that can dynamically adjust the deadband based on factors such as occupancy patterns, external temperature, and user preferences.
- Integration with Demand Response Programs: Investigate the potential of smart thermostats with adjustable deadbands to participate in demand response programs, helping to manage peak loads and reduce energy costs.
- User Experience and Comfort: Conduct studies to assess the impact of different deadband settings on occupant comfort and satisfaction, providing valuable information for designing user-friendly interfaces and control strategies.

NOMENCLATURE

DR	demand response
HIL	hardware-in-the-loop
HP	heat pump
HVAC	Heating, Ventilation, and Air Conditioning
NREL	National Renewable Energy Laboratory

REFERENCES

Bernal, W., M. Behl, T. X. Nghiem, and R. Mangharam. 2012. "MLE+ a tool for integrated design and deployment of energy efficient building controls." In *Proceedings of the Fourth ACM Workshop on Embedded Sensing Systems for Energy-Efficiency in Buildings* 123-130.

Booten, C., and P. C. Tabares-Velasco. 2012. "Using EnergyPlus to simulate the dynamic response of a residential building to advanced cooling strategies." NREL/CP-5500-55583. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy12osti/55583.pdf.

Christensen, C., R. Anderson, S. Horowitz, A. Courtney, and J. Spencer. 2006. "BEopt (TM) software for building energy optimization: Features and capabilities." NREL/TP-550-39929. Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy06osti/39929.pdf.

Crawley, D. B., L. K. Lawrie, F. C. Winkelmann, W. F. Buhl, Y. J. Huang, C. O. Pedersen,... and J. Glazer. 2001. "EnergyPlus: creating a new-generation building energy simulation program." *Energy and buildings* 33(4): 319-331.

NREL (National Renewable Energy Laboratory). 2016. "Energy Systems Integration: Systems Performance Lab." NREL/FS-5C00-66736. Golden, CO: National Renewable Energy Laboratory. www.nrel.gov/docs/fy16osti/66736.pdf.

Ramaraj, S. and Sparn, B. 2022. Validation of HVAC Hardware-In-the-Loop Simulation for Advanced Control Strategies in Smart Homes. No. NREL/CP-5500-82562. *National Renewable Energy Lab (NREL), Golden, CO (United States)*. https://www.nrel.gov/docs/fy22osti/82562.pdf.

Saha, A., M. Kuzlu, and M. Pipattanasomporn. 2013. "Demonstration of a home energy management system with smart thermostat control." *2013 IEEE PES Innovative Smart Grid Technologies Conference (ISGT)* 1-6.

Simulink. 2021. "Simulation and Model-Based Design." MathWorks. Retrieved from https://www.mathworks.com/products/simulink.html.

Sparn, B., K. Hudon, L. Earle, C. Booten, P. C. Tabares-Velasco, G. Barker, and C. E. Hancock. 2014. "Greenbuilt Retrofit Test House Final Report." Golden, CO: National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy14osti/54009.pdf.

Sparn, B. F. 2018. Laboratory Resources and Techniques to Evaluate Smart Home Technology. No. NREL/CP-5500-71696. *National Renewable Energy Lab (NREL), Golden, CO (United States)*. https://www.nrel.gov/docs/fy18osti/71696.pdf.