Validation of HVAC Hardware-In-the-Loop Simulation for Advanced Control Strategies in Smart Homes

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National Renewable Energy Laboratory

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Validation of HVAC Hardware-In-the-Loop Simulation for Advanced Control Strategies in Smart Homes

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ABSTRACT

Residences with smart thermostats can use advanced control strategies to manage their cooling/heating demand, but it is difficult to evaluate optimal control strategies for flexible heating, ventilation, and air conditioning (HVAC) systems in a traditional laboratory setting. The HVAC hardware-in-the-loop (HIL) system combines physical HVAC equipment and a physical thermostat with a simulated house to enable realistic operation of the hardware in any climate. This HIL platform allows researchers to evaluate advanced control strategies for homes with different construction or vintage types, as well as different climates and occupancy schedules. To demonstrate the capabilities of the HVAC HIL system, experimental results with a SEER 16, HSPF 9.5, 3 ton single-speed air source heat pump (HP) are validated against past field data collected from a heavily instrumented, unoccupied, retrofit house located in Sacramento, California. Three different cooling strategies are recreated in the HVAC HIL platform, including two different pre-cooling schedules that were designed to shift energy use away from the evening peak. The room temperatures, HP energy use, and runtime show good agreement between the field data and HIL experimental results for three cooling strategies. The total condenser energy use difference is within 0.4% for baseline cooling, 4.8% for simple precooling, and 6% for advanced precooling compared with the field data. The total runtime difference for a single day is 3.2% for baseline cooling, 9% for simple precooling and 12% for advanced precooling between the HIL lab and field data.

Introduction

With continued advancement in sensing and networking technologies, our everyday home appliances are more connected, automated, and responsive than ever before. Smart home technology focuses on improved comfort, convenience, and better user experience along with increased energy efficiency, reliable demand response, and grid integration. With space conditioning (space heating and air conditioning) accounting for about 51% of energy consumption in U.S. residential buildings (U.S. EIA 2015), smart thermostats can enable advanced and intelligent control strategies with demand response implementation to manage heating and cooling demand. Demand response for HVAC equipment has typically been done by using a relay to shut off power during the event. On the other hand, set point control results in lower energy usage while maintaining better temperature control and occupant comfort in comparison to no control (Saha, Kuzlu, and Pipattanasomporn 2013).

Deploying advanced control strategies for load shifting can have unintended consequences in occupied homes unless they are tested exhaustively before implementation. Testing on real buildings is expensive, has more risks, and takes a substantial amount of time, whereas the simulation-based control approach may not match the actual occupant interactions or realistic HVAC loads even though it is less risky, faster, and less expensive (Du et al. 2019). The test platform should include the entire system covering all the complexities of building and validating the HVAC system and other individual components. To accommodate and evaluate the interoperability among various smart devices and study how residential buildings interact with the grid of the future, a hardware-in-the-loop (HIL) system provides emulation capabilities to integrate real hardware equipment into the simulation in a continuous feedback loop under real-time constraints. The high-fidelity response of actual physical equipment can be captured for any scale of simulation and any control strategy for different applications.

Few HIL test platforms were designed with limited capabilities for testing building HVAC systems for specific applications (Du et al. 2019; De La Cruz et al. 2017; Conti et al. 2020), and heavily instrumented, unoccupied lab homes were constructed to evaluate smart home technologies (Crocker 2017; PNNL 2018). Lab homes are expensive, and weather can't be controlled, in contrast to the HIL approach. The flexibility of HIL test platforms to adopt smart home technologies and interoperability among all the appliances remains a big question, so characterizing the response of smart devices to different grid service requests becomes challenging. To address this, the Systems Performance Laboratory (SPL) in the Energy Systems Integration Facility (ESIF) at the National Renewable Energy Laboratory (NREL) has capabilities to evaluate a wide range of smart home technologies in a controlled and controllable environment. The capabilities include studying innovative power sensors, testing smart appliances and HVAC equipment under extreme weather or grid conditions, developing algorithms for home energy management systems, evaluating the impact of different control strategies on the electric utility grid, addressing cybersecurity questions related to the Internet of Things and many more adaptable features (NREL 2016). The lab space designed for research focused on grid-interactive-efficient buildings (GEB) includes necessary water, fuel, and electrical infrastructure, novel sensor technology and control components to test sophisticated control algorithms, major and minor smart appliances for three homes along with sensors and controllers to apply simulated occupancy for different loads, HVAC test setup, photovoltaic inverters, and home batteries for distributed energy resources (DER) integration and other assets to investigate a wide range of research questions related to buildings-to-grid integration, with enough flexibility to adapt as research needs change (Sparn 2018). Most of all, this HIL platform allows researchers to evaluate advanced control strategies for homes with different construction or vintage, as well as different climates and occupancy schedules.

However, for these kinds of systems, only testing and validation of individual components are inadequate to characterize equipment response in complex grids under dynamic real-time situations (de Jong 2013). Testing and validation of the entire system involving building complexities and transient behavior of individual components are crucial to ensure quality and reliability while studying smart homes and their integration with DER-integrated grids of the future. This paper presents the experimental validation of HVAC HIL system against the past field data collected from a heavily instrumented retrofit house located in Sacramento, California. A SEER 16, HSPF 9.5, 3 ton single-speed air source HP is used for experimental testing. Three different cooling strategies are recreated in the HVAC HIL platform, including two different pre-cooling schedules that are designed to shift energy use away from the evening peak.

HVAC Hardware-in-the-loop Architecture Overview

The HVAC HIL experiments are all performed in the SPL at NREL. Sparn (2018) had described the laboratory design and capabilities of the SPL along with the architecture of HVAC HIL system in detail. The HIL setup mimics the HVAC system of the residential building of interest in the laboratory environment without the need for an actual home. Hardware and software inform one another in a continuous loop to drive the HVAC equipment in a realistic fashion. Figure 1 shows the block diagram of the HVAC HIL system and Figure 2 shows the laboratory setup for HIL experiment.

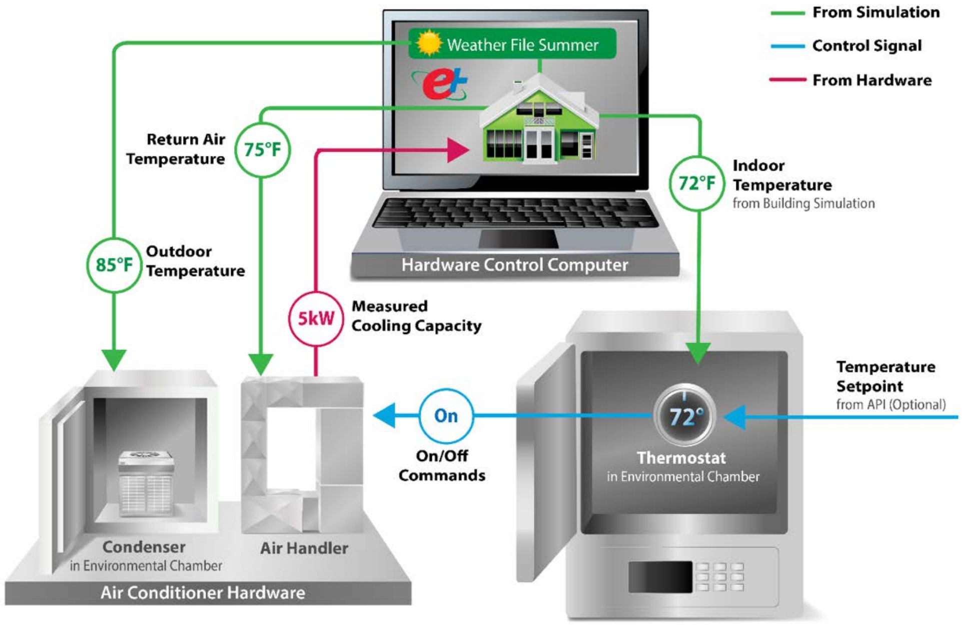

Figure 1. HVAC HIL system in the Systems Performance Laboratory

Figure 2. Hardware installed in the SPL for HIL experiment. The grey chamber on the left contains the condenser with the air handler and duct loop next to it. The top blue chamber on the right houses the thermostat.

Buildings are complex systems with interactions among the outdoor environment, building envelope, loads, and occupants. EnergyPlus® (Crawley et al. 2001) is used to run the building model in the experiment controller, using an hourly weather file for the location of interest. The EnergyPlus model includes the characteristics of the building, outdoor temperature, solar insolation, and internal loads to calculate how the indoor temperature changes as the HVAC equipment is turned on and off. The EnergyPlus simulation has been modified to run in real-time, without any HVAC model. The simulation infrastructure for the HVAC HIL system uses MLE+ (Bernal et al. 2012) to connect Simulink (Simulink 2021) to EnergyPlus for co-simulation. Simulink is used to connect the simulation to the lab's data acquisition system, which allows real-time data transfer from the hardware to be sent to the EnergyPlus simulation. This configuration allows us to recreate the operation of an air conditioner or HP in homes with different building characteristics or in different climate zones.

The outdoor condensing unit is located inside a large, insulated chamber. The chamber temperature is controlled using heaters and cooling coils to match the outdoor temperature from the simulation weather file. The air handler section of the indoor unit is installed in a duct loop with heaters and cooling coils to ensure that the return air temperature matches the value found by the EnergyPlus simulation emulating the building loads. Airflow and air temperature measurements at the outlet of the air handler are used to determine the heat transfer to the house, which is used in the EnergyPlus simulation, as an alternative for a simulated HVAC system as is typically done.

The HVAC equipment is controlled by a smart thermostat that sits in a small environmental chamber that is controlled to match the indoor air temperature, as determined by the EnergyPlus simulation. The setpoint temperature of the thermostat can be preset on a schedule or dynamically changed through the application programming interface (API). Any of the demand response activities in the form of load shifting, peak clipping, or valley filling that modifies the end-use consumption pattern or any advanced control strategies can be easily implemented.

The data acquisition system collects indoor air temperature and power consumption data for the HVAC equipment and logs that data for post-processing. The data can also be sent in real-time to other simulation tools as necessary. The HIL simulation updates at 1-minute intervals, while the lab sensors are sampled at 1-second intervals.

Validation of HVAC HIL System with Greenbuilt Field Study

Greenbuilt Field Study

To demonstrate the capabilities of the HVAC HIL system in SPL, field results from the Greenbuilt retrofit test house (Sparn et al. 2014) were used for experimental validation. The 1980s era, all-electric Greenbuilt house in Sacramento, CA was retrofitted in 2009 with cost-effective energy efficiency measures by Greenbuilt Construction in a joint effort with NREL. The house was remodeled with common retrofit measures, such as increasing wall and attic insulation, and more advanced technologies, such as motorized exterior shading and a Control4 home control system. Among other equipment upgrades, a SEER 16 central HP was installed to handle the home's space conditioning needs. The house was unoccupied during the testing period, so small space heaters were used in each room to simulate hourly occupancy and sensible heat gains based on Building America House Simulation Protocols (Hendron and Engebrecht 2010). The house was equipped with a wide range of monitoring and control equipment. Because we are interested in evaluating different control strategies for flexible HVAC systems, the

Greenbuilt field data from three cooling strategies with the HP are used for validating the experimental results from the HIL setup.

HVAC HIL System Experiment

The initial building model based on the Greenbuilt house characteristics (Booten and Tabares-Velasco 2012) was developed using BEopt^{TM} (Building Energy Optimization Tool) software (Christensen et al. 2006), which generated an EnergyPlus (v9.4) input file for simulation. The building model was calibrated against the Greenbuilt field data, independent from HIL testing. The occupancy profiles and sensible load from appliances are consistent with the Building America House Simulation Protocols. Details of physical attributes of the 1,748 ft^2 single-family detached home are listed in Table 1. Figure 3 shows a screenshot of the 3-D view of the building model from BEopt software. The local weather data for Sacramento, CA from 2010, when the field study was conducted, was used in the HVAC HIL simulation to match the field conditions as closely as possible. A SEER 16, HSPF 9.5, 3 ton single-speed air source HP, similar to the HP used in Greenbuilt house, was installed in the HVAC HIL setup for experimental evaluation. The HP was controlled using an identical Control4 thermostat managed by the control interface.

Table 1. Building construction information

Building Model Input	Values
Exterior Wall Construction	R15
Foundation	Uninsulated slab
Roofing	R42 cellulose
Window	2-pane low-E argon
Lighting and Appliances	Fluorescent lighting, and ENERGYSTAR® appliances

Figure 3. 3-D view of BEopt building model

Cooling Strategies

With the goals of peak load reduction and energy savings, three different cooling strategies including a baseline cooling strategy and two different pre-cooling schedules were recreated in the HVAC HIL platform. It is worth noting that the precooling strategies would probably be implemented differently if the experiments were developed today, but we followed the schedules that were developed in 2010 to validate our laboratory HIL setup.

- Baseline cooling- The thermostat was set at a constant temperature of 76°F (24.4°C) all day.
- Simple precooling - The house was precooled to 71°F (21.7°C) during off-peak hours from 9:00 a.m. to 3:00 p.m. and the HP was turned off for rest of the day. This test was conducted to check if all the cooling built-up during the off-peak hours could be retained for the well-insulated house during all other times of the day.
- Advanced precooling - The thermostat was set to 71°F (21.7°C) during off-peak hours between 9:00 a.m. and 3:00 p.m., high as 79°F (26.1°C) during peak hours between 3:00 p.m. and 7:00 p.m., and 76°F (24.4°C) for the rest of the day. This advanced precooling schedule is an extended version of simple precooling with the focus not only on energy savings but also on indoor comfort.

Validation Results

HIL experimental results were validated for specific days of each field test of the three different cooling strategies. The Greenbuilt field tests were conducted during the summer of 2010. The exact days from those experiments were July 19th, September 11th, and August 17th for baseline cooling, simple precooling, and advanced precooling, respectively. The field measurements were collected at 1-minute time intervals while HIL measurements were sampled at 1-second intervals. The results limited to the indoor temperature and HVAC energy use (HP condenser unit and indoor air handler) are presented here. Figures 4, 5, and 6 show the 24-hour time-series plot of the power consumption of the HP condenser unit and air handler unit along with the indoor room temperature measurements from the HIL experimental test and field test data for baseline cooling, simple precooling, and advanced precooling strategies respectively. The temperature and HP power consumption are plotted together to show the cycling of the HP when room temperature crosses the setpoint temperature. The laboratory data sometimes shows a spike in power consumption at the beginning of a cooling cycle. This in-rush current is normal but is not always captured by data acquisition due to its very short duration. For all three cases, temperature and power measurements show a good agreement between the HIL experiment and field data. HP condenser energy and total equipment runtime for a single day are used as metrics for comparison between HIL experimental results and field data as listed in Table 2 for all three cooling strategies. Solely relying on condenser energy data for comparison might not be sufficient because there is a slight difference in power consumption of the condenser between the lab and field, despite the HP being identical in size and SEER rating.

Figure 4 shows the baseline case with a fixed setpoint temperature. There are long cycles from noon until evening when the outdoor air temperature is generally high. The total condenser energy consumption for the 24-hour test period is 13.09 kWh in the HIL experiment, which is 0.4% higher than the 13.04 kWh of condenser energy use from the field data. The total runtime of the HP is 335 min from HIL experiment versus 346 min from field data, a 3.2% difference.

For the simple precooling case in Figure 5, there is a long HP cycle when it is turned on at 9 a.m., followed by a few shorter cycles after the house has been cooled. The subsequent long cycles in the early afternoon show an increase in power consumption as the cooling load increases with outdoor temperature. The total HP energy use for a single day from the HIL experiment is 5 kWh, versus 5.25 kWh from field data - a 4.8% difference. The runtime difference between the HIL experiment (142 min) and field data (156 min) is 9%.

Advanced precooling comparison results are shown in Figure 6. This strategy has some additional cooling during the evening hours compared to simple precooling. The total condenser energy use for one day from HIL experiment is 8.18 kWh while it is 8.7 kWh from field data which is 6% higher. The total runtime field data (266 min) is 12% higher compared to HIL data (234 min). Shifting the cooling load away from peak hours using simple and advanced precooling strategies reduces HP energy use and runtime compared to baseline cooling. Advanced precooling provides more comfort with little extra energy.

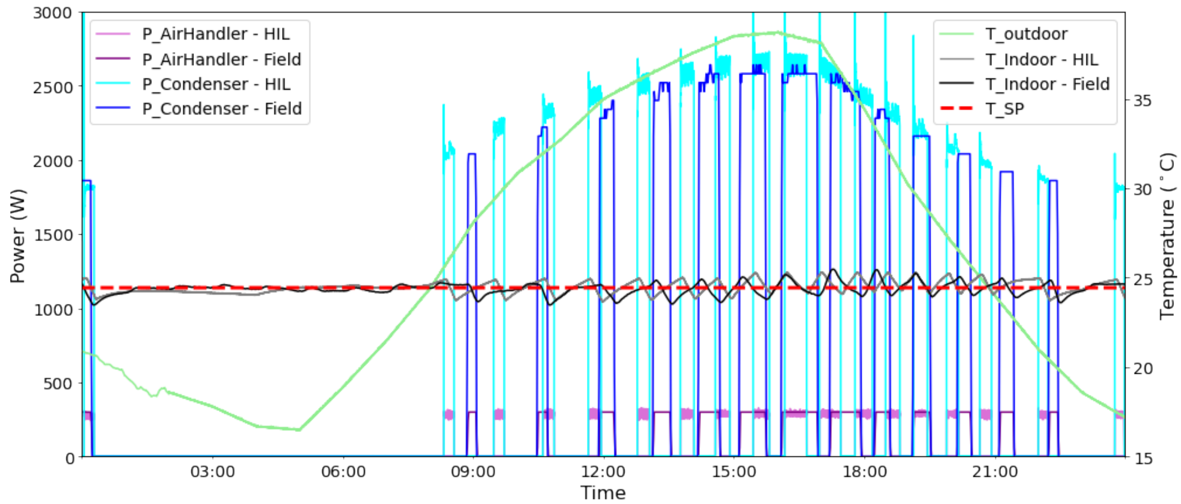

Figure 4. Baseline cooling HIL experimental validation results with Greenbuilt field data.

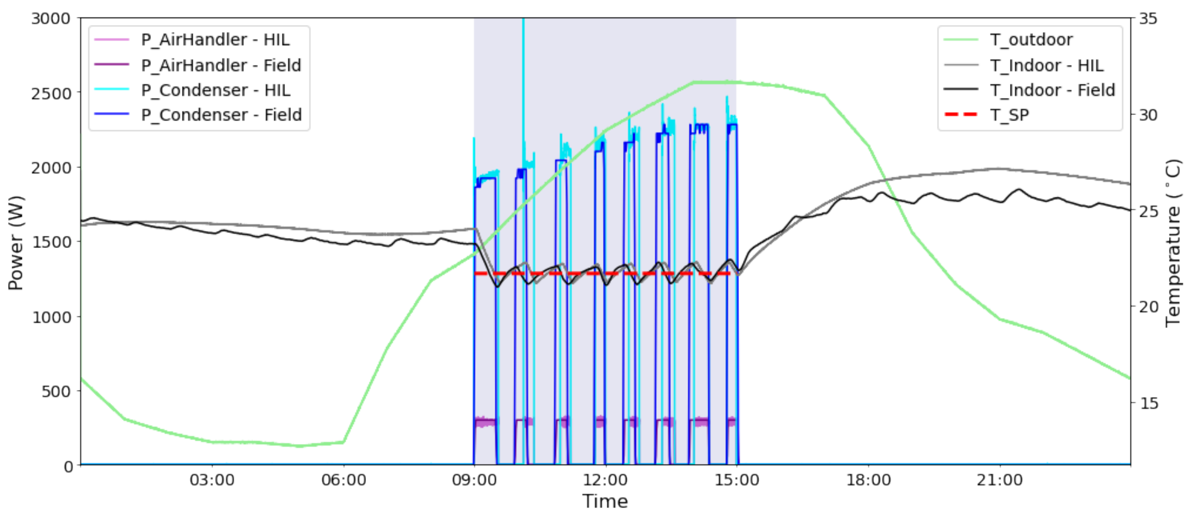

Figure 5. Simple precooling HIL experimental validation results with Greenbuilt field data

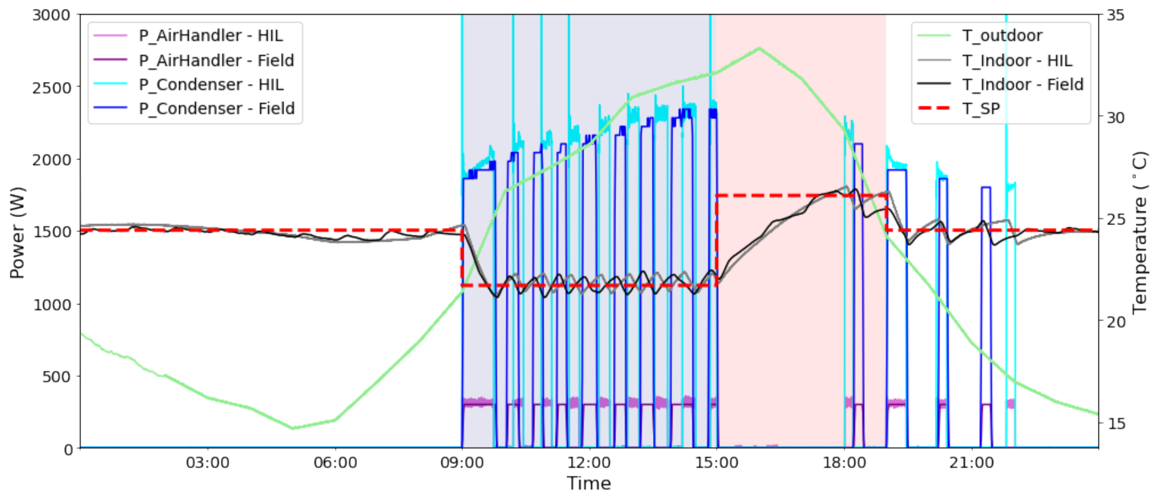

Figure 6. Advanced precooling HIL experimental validation results with Greenbuilt field data

Table 2. Single day total HP cooling energy and runtime comparison between the HIL experiment and Greenbuilt field data for three cooling strategies.

	Baseline	**Simple Precooling**	**Advanced Precooling**
HP Condenser Energy – HIL [kWh]	13.09	5.00	8.18
HP Condenser Energy – Field [kWh]	13.04	5.25	8.7
HP Condenser Energy – Difference	0.38%	4.8%	6.0%
Runtime – HIL [min]	335	142	234
Runtime – Field [min]	346	156	266
Runtime – Difference	3.2%	9.0%	12.0%

In both field and HIL data, the indoor temperature varied up to 2°C around the setpoint, but there were times when the field and HIL data did not match well (~0.5°C maximum difference). These differences in temperature are reflected in the HP performance in terms of condenser power and equipment runtime. There are a few potential causes for the differences in the indoor temperature between the field data and HIL: indoor temperature measurements at the field site, the way internal gains were implemented in the field trial, the operation of the thermostat, and errors from the EnergyPlus simulation model. The indoor temperature from the field data is the average measurement from the five temperature sensors in each room of the Greenbuilt house. However, the temperature difference across each room varied up to ±2°C. The dissimilarities in indoor temperature measurement and airflow patterns within the house might cause some differences in the field and lab temperature data. The Greenbuilt lab home was unoccupied and so to ensure that the home was subject to internal gains in a realistic way, small electric resistance heaters were placed around the house and operated on a timer based on the Building America House Simulation Protocols. However, the heaters caused small hourly spikes in temperature, as seen in the early morning hours of the field data in Figure 4. We adjusted the internal gain schedule in EnergyPlus to try to match these, but we could not perfectly match the short increases in temperature that occurred every hour. Another cause for differences in the indoor temperatures was due to the thermostat behavior. We were able to use the same model of Control4 thermostat, but we still saw some differences in operation. This could be due to the thermostat's temperature control algorithms and different deadbands. The initial EnergyPlus simulation model (Booten and Tabares-Velasco 2012) had 4% total energy use difference compared with the field results for all three cooling strategies. The EnergyPlus simulation under-predicted peak loads by 4% – 26%, with the best prediction results from the baseline case, while the results from advanced precooling are the worst. Because the same EnergyPlus building model was used for our HIL experiment, a similar trend is observed with the HIL experimental results with HP runtime and condenser energy lesser than the field data. The difference was higher for advanced precooling compared to simple precooling and baseline cooling mainly because the model could not capture rapid changes in load. The more complex the control strategy gets, the further the building model underpredicts the load/runtime. Improving the building model simulations to capture dynamic responses can reduce modeling errors propagating into the experiment.

Despite these minor discrepancies, the room temperatures, HP condenser energy use, and runtime show a good agreement between the field data and HIL experiment for all three cooling strategies.

Conclusions

This paper presented the experimental validation of HVAC HIL system in SPL with the field data to characterize HVAC equipment response during demand response experiments. Three different cooling strategies were recreated in the HVAC HIL platform, including two different pre-cooling schedules that were designed to shifting energy use away from the evening peak. The 24-hour time-series comparison of room temperatures, HP energy use, and run time showed a good agreement between the field data and HIL experimental results for all three cooling strategies. The laboratory data on HVAC energy consumption, when used to provide grid services, could be used to develop models mapping a home thermostat’s energy-shedding and -shifting setpoint change to the seconds-level resolution energy consumption of the HP. The total condenser energy use difference was within 0.4% for baseline cooling, 4.8% for simple precooling, and 6% for advanced precooling compared with the field data. The total runtime difference for a single day was 3.2% for baseline cooling, 9% for simple precooling and 12% for advanced precooling between the lab and field data. EnergyPlus simulation models can be improved to capture dynamic load response, which is more prevalent in advanced control strategies.

The validation study gives more confidence in the HVAC HIL system to conduct experiments on smart home control and evaluate how different control strategies implemented across multiple residential buildings will impact the electric grids of the future. This study also supports future work of de-risking direct field implementation, and to investigating a wide range of research questions related to buildings-to-grid integration.

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