# Laboratory Resources and Techniques to Evaluate Smart Home Technology

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# Laboratory Resources and Techniques to Evaluate Smart Home Technology

***Bethany Sparn, National Renewable Energy Laboratory***


## ABSTRACT

Smart home technologies promise to make residential buildings more comfortable, less costly to operate, more energy efficient, and more integrated with the grid, but these systems are difficult to evaluate in traditional laboratory spaces. To aid in the development and evaluation of new home energy management systems, the National Renewable Energy Laboratory (NREL) built the Systems Performance Laboratory (SPL) within the Energy Systems Integration Facility. The SPL has electrical infrastructure for three residential buildings, complete with smart meters, breaker panels, and a full complement of major and minor appliances in each "home." Cord and plug power connections mean that appliances can easily be swapped for different models. Distributed energy resources, such as residential photovoltaic inverters and home batteries, are also available for integration. Sensors monitor the power consumption of all loads, and controllers can simulate occupancy to drive the appliances in realistic ways. A novel hardware-in-the-loop (HIL) application was developed to drive air-conditioner cycling by combining a building simulation with a physical air conditioner and a thermostat. This system allows us to simulate air conditioner performance in any climate with any building construction. Another application of the HIL technique uses a grid simulation to model the grid impact for different control strategies related to smart home technologies. This laboratory is a powerful, flexible tool that can be employed to evaluate the effect that home energy management and other smart home technologies will have at the appliance, whole-home, and distribution feeder levels—all of which are important perspectives for different stakeholders.


## Introduction

The advent of the Internet of Things brings potential for homes to be filled with smarter, more responsive devices and appliances. The capabilities that these new technologies enable range from improved comfort and convenience, to increased energy efficiency, to reliable demand response and grid services, but many questions remain. There are basic questions about interoperability among all the appliances. There are questions related to the impact of a home potentially using more energy to take advantage of cheaper electricity when more renewables are available. The ability to more easily and reliably participate in grid service programs, such as demand response or peak load reduction, opens the door to a multitude of other uses for smart appliances in the home, but how do we characterize the response of smart devices to different grid service requests? How can we ensure that consumers receive the desired comfort and performance from their homes in a cost-effective manner while also providing useful services to the local utility grid?

This field of research is still in its infancy, so it is difficult to know which research questions will be the most important and relevant going forward. To accommodate the different directions that might come with the adoption of smart homes and smart device technologies, researchers at the National Renewable Energy Laboratory (NREL) designed and built a laboratory focused on studying how residential buildings might interact with the grid of the future. The Energy Systems Integration Facility (ESIF) was built in 2013 to provide a research space dedicated to optimizing the nation's energy system (Van Becelaere 2017). The ESIF includes electrical, water, and fuel infrastructure. On the electrical side, the facility has capabilities to test or simulate megawatt-scale components or look at the energy consumption of residential-scale plug loads and everything in between. One laboratory in the ESIF is the Systems Performance Laboratory (SPL), a space designed for research focused on residential buildings and their integration with the electric utility grid. The SPL is intended to be a flexible resource that can be used to evaluate a wide range of smart home technologies—from studying innovative power sensors, to testing smart appliances, developing algorithms for home energy management systems (HEMS), and evaluating how different control strategies implemented across many homes will impact the utility grid (NREL 2016).

Other research facilities around the country and the world can also be used to evaluate smart home technologies, but they are generally implemented as "lab homes"—homes that have been built for residential energy research, are usually unoccupied, and are instrumented with many sensors and controllers (Crocker 2017; Ghaffarianhoseini et al. 2013; PNNL 2018). Lab homes are a valuable tool that can be used to evaluate many important aspects of smart home technologies, particularly those related to interoperability and deployment in real homes. But the SPL enables more early-stage research, more flexibility in the connected building systems, and, most importantly, integration with resources that can evaluate the grid-level impact of these technologies.

Figure 1. One of the homes in the SPL, including an electric vehicle. *Source:* Dennis Schroeder, NREL 38890

## Laboratory Design

The SPL was designed to accommodate a range of research types and be a flexible, evolving space. The initial planning for the SPL focused on investigating the interactions between the electrical distribution system and residential communities, developing/evaluating new sensors and controls for building control systems, and testing relevant equipment under extreme weather or grid conditions. The lab was also intended to be a place for collaboration among researchers in industry, other national labs, and academia. With these goals in mind, the following criteria were used to guide the lab design:

- The lab should include multiple "homes" that can be monitored and controlled simultaneously to simulate a community-scale load profile.
- Each home should have the necessary electrical and water infrastructure for a typical residential building, but it should be easy to switch out the physical appliances installed.
- Including heating, ventilating, and air-conditioning (HVAC) loads is essential for this laboratory space, but some means of driving the equipment in a realistic fashion must be developed.
- The lab should include necessary sensors and controls infrastructure to operate each home individually or as a group, and the data acquisition system should accommodate additional sensors and controls as necessary.

With these requirements in mind, the lab was built and became fully operational in 2014. The lab contains three separate homes, which allows multiple projects to run concurrently or enables more complex projects with multiple homes/occupant profiles. The lab also has the capability to interface with other resources in the ESIF, including a high-performance computer (HPC) and megawatt-scale electrical infrastructure.

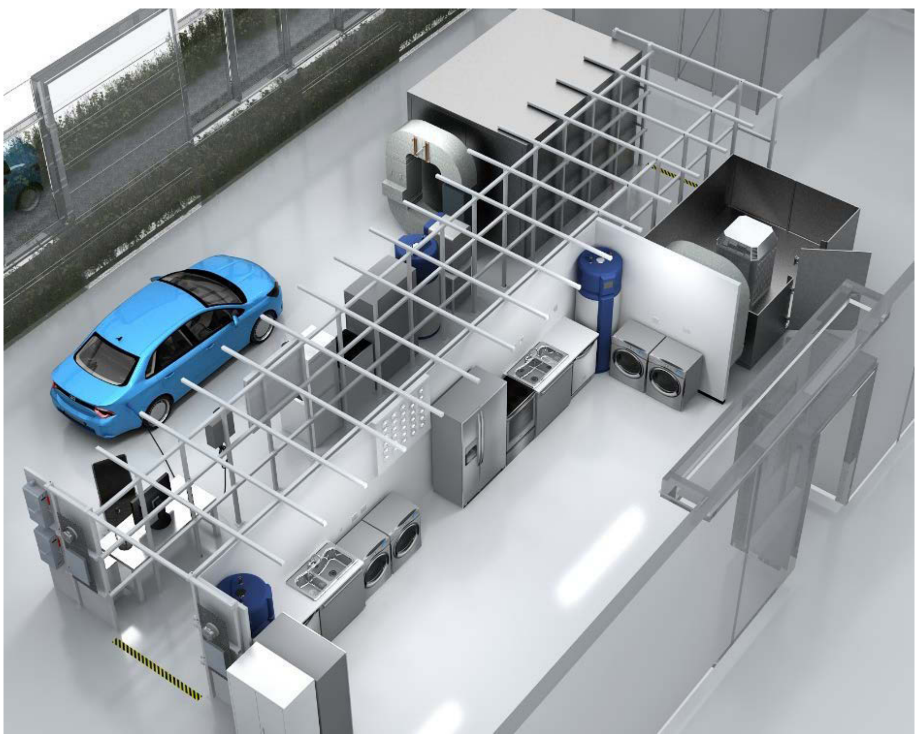

Figure 2. Rendering of the SPL showing all three homes as built. *Source:* Illustration by Josh Bauer, NREL

The SPL includes the electrical infrastructure for three homes, each with an advanced metering infrastructure utility meter feeding a 150-A breaker panel, with dedicated power meters on each circuit, and a whole-home power meter measuring real and reactive power. A full complement of major appliances is installed in each home, though only two of the three homes have an HVAC system. The system needed to drive the HVAC equipment (to be discussed further) is too large for the laboratory to accommodate three separate versions. In addition to the major appliances, the homes have several outlet banks on separate circuits to accommodate a variety of plug loads and small appliances. With the exception of the HVAC equipment, all of the appliances have been installed using cord and plug connections to allow the appliances to be replaced more easily. Two of three homes currently have photovoltaic (PV) inverters installed and can accommodate additional distributed energy resources (DERs), such as stationary batteries, natural gas generators, or electric vehicle supply equipment (EVSE). The third home can also accommodate DERs, but they have not yet been needed. The homes can also be powered from a variety of sources, including facility power (default), a grid simulator (also known as a programmable AC power supply), or through the ESIF research electrical distribution bus. The homes can also be powered as a group or individually via step-down transformers located outside the building.

In addition to the physical infrastructure, the SPL includes data and network resources that can be tailored to individual projects. The lab includes a National Instruments-based data acquisition system that enables a wide range of configurability options—a user might need sensors related to a single appliance, a whole home, or all three homes, and the data acquisition system is able to accommodate this. The data acquisition system collects circuit-level power data for all appliances, water flow and temperature data for appliances that use water, ambient temperature and humidity data, and airflow and temperature data for the HVAC system. Additional sensors can be added as needed.

Many smart appliances or advanced sensors rely on a connection to a manufacturer-specific cloud for data processing or scheduling. Other devices have additional features available via mobile applications when connected to the Internet. To accommodate the variety of communicating devices, we installed multiple wireless networks with different features and security levels. The existing networks can be modified if needed or additional networks can be temporarily installed to accommodate different network and security requirements.

## Simulated Occupancy

The homes in the SPL are designed to electrically represent real homes, but the actual load profiles depend on how the equipment is operated. We apply simulated occupancy—a technique used to establish occupancy-related energy use—to all of the relevant appliances in the lab. The details of the project will determine how the simulated occupancy is designed, but it is common to start from the appliance schedules in the Building America House Simulation Protocols (Wilson et al. 2014).

Depending on the appliance, the controls needed to impose simulated occupancy vary. Appliances that run continuously—the refrigerator, water heater, and HVAC system—can be controlled in an autonomous fashion; whereas other appliances—the dishwasher, clothes washer, and dryer—require manual interaction and are more difficult to automate. The clothes washer, dryer, and dishwasher are operated manually on a schedule. To ensure that the washer and dryer's operation is realistic, we use a load of white T-shirts and laundry detergent. Once the T-shirts have been washed, they are moved to the dryer. The dishwasher is loaded with dishes, and, when possible, a cycle is chosen that does not rely on "soil sensing" so that the dishes do not have to be dirtied before each cycle. Some newer smart appliances have options to set when the cycle begins (either with a delay function or via a mobile application). Otherwise, a researcher will manually begin the cycle at the desired time.

The appliances that operate continuously are paired with systems that load them in an appropriate manner. To drive the refrigerators, there is thermal mass in the fridge and freezer compartments (liquid and frozen water, respectively) and incandescent light strings in both compartments to add heat on a schedule that mimics the addition of room temperature food. The water heater supplies hot water to appliances that need hot water and to a fixture with controls on the hot water line. A controllable solenoid valve is scheduled to impose a simulated hot water draw profile on the water heater, which we vary to simulate a range of homeowner profiles. The HVAC system requires a more complex hardware-in-the-loop (HIL) system to drive the equipment in a realistic fashion. HIL is a technique that combines hardware and software in a continual feedback loop and is applied here to drive the air conditioner without needing all the components of a real house (Sparn et al. 2018). Figure 3 shows a diagram of the HVAC HIL system.

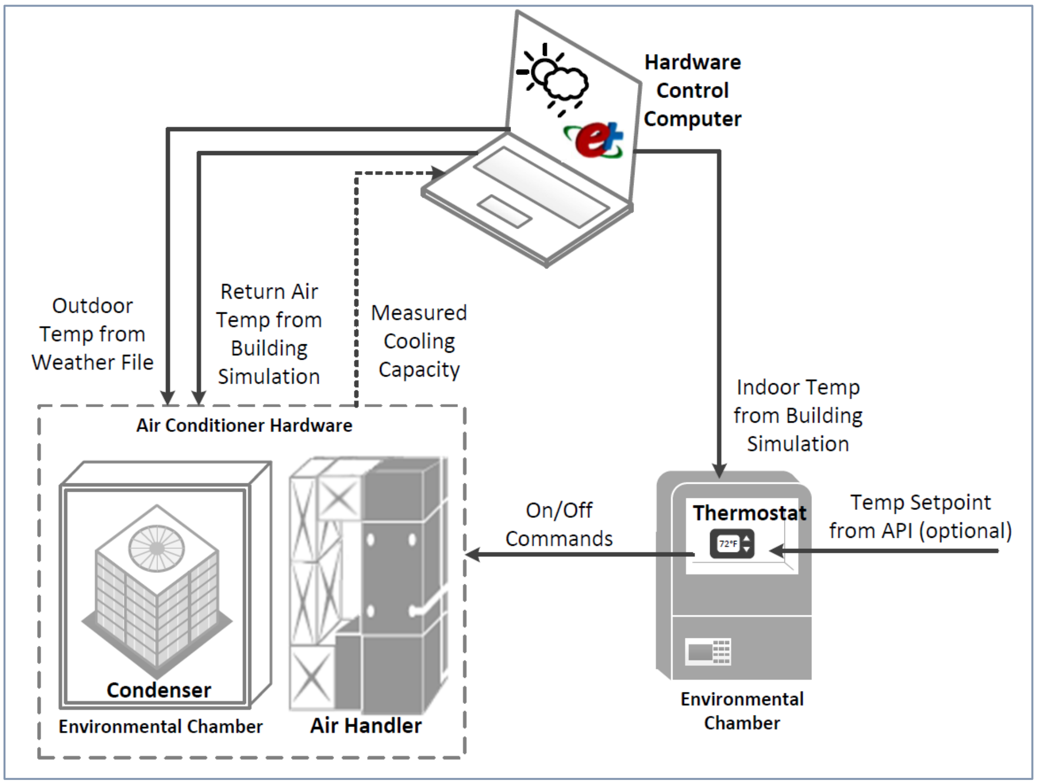


Figure 3. HVAC HIL system. *Source:* Illustration by Bethany Sparn, NREL

An EnergyPlus building model runs in real time at one-minute intervals using an hourly weather file for the location of interest. The EnergyPlus model uses the building characteristics, internal gains, outdoor temperature, solar insolation, and real-time data from the physical air conditioner in the SPL to calculate the indoor temperature as the air conditioner turns on and off. This configuration allows us to recreate the operation of an air conditioner or heat pump in homes with different building characteristics or in different climates.

The outdoor condensing unit is located inside an insulated chamber where the temperature is controlled to match the outdoor temperature from the weather file. The air handling unit portion of the air conditioner/heat pump is installed in a duct loop with heaters to ensure that the return air temperature matches the value found by the EnergyPlus simulation. Airflow and air temperature measurements at the outlet of the air handling unit are used to determine the amount of cooling delivered by the air conditioner and that measurement is used by the EnergyPlus simulation, instead of data from a simulated air conditioner as is typically done. There are two HVAC HIL systems in the SPL: one system currently houses a SEER 21, two-speed, two-ton air conditioner; and the other system contains a 3-ton, SEER 18, variable-speed heat pump.

The air conditioner is controlled by a thermostat that sits in a small environmental chamber that is controlled to match the indoor air temperature as determined by the EnergyPlus simulation. Multiple brands of Internet-connected thermostats have been used for control, which allows the set point to be controlled via an application programming interface (API). The set point temperature of the thermostat can be set on a schedule, or dynamically changed via API, depending on the research need.


Figure 4. Photos of one of the HVAC HIL systems; the environmental chamber used to house the thermostat is shown in the inset. *Source:* Main photo by Dennis Schroeder, NREL 38915; inset photo by Bethany Sparn, NREL.

## Representative Projects

The intent of the SPL was to accommodate a wide range of projects, big and small, simple and complex. This section describes a variety of projects that have been conducted in the SPL during the three years that the lab has been fully operational.

### Least Complex: Sensor and Component Testing

The simplest experiments that have been conducted in the SPL involve single components or sensor evaluations. The residential infrastructure in the SPL provides a convenient and controllable environment for evaluating new sensors. This might involve a study of the installation process, usability, or accuracy of the sensor. Other simple projects involve the evaluation of a collection of devices tested independently. Examples of these types of projects are given next.

**Nonintrusive Power Meter Testing.** Several projects in the last few years focused on evaluating different circuit breaker-level power meter solutions. Whisker Labs makes a novel power meter that sticks to the front of the breakers (see Figure 5) and measures the electric and magnetic fields at the breaker as a means of calculating power flow (Sparn et al. 2017). The laboratory tests were intended to evaluate the installation process and the accuracy of the meters. The SPL is an ideal test bed for these projects because the breaker panels are consistent with a house, contain a variety of load types, and already have high accuracy power meters on every circuit. The Whisker Labs sensors could be installed in minutes, without requiring access to the interior of the breaker panel. The laboratory testing in the SPL found that the single-circuit accuracy was ±10%, with a typical interference rejection ratio of 10:1 for power on nearby circuits. Whisker Labs has continued to improve their technology and are now only measuring power at the main breakers in an electrical panel using the same stick-on meter technology, which should eliminate the interference that we measured in the SPL.

Figure 5. The Whisker Labs meters installed on the front of breakers in an electrical panel in the SPL. *Source:* Dennis Schroeder, NREL 41583

**Development and Demonstration of Communicating Appliances**. Another example of a simple experiment conducted in the SPL was a collaboration between NREL and the Electric Power Research Institute (EPRI) to develop and demonstrate the functionality of several connected appliances using open communication standards (Hudgins et al. 2018). A collection of residential appliances that were compatible with the CTA-2045 and SunSpec standards were installed in the SPL and underwent multiple rounds of testing to understand and improve their response to a standard set of grid service commands, such as load shed, load add, or grid emergency (CTA 2018; SunSpec Alliance 2015). Two water heaters (a standard electric resistance and a heat pump water heater), a thermostat controlling an air conditioner, a pool pump, EVSE used to charge an electric vehicle, and a PV inverter were installed in two of the SPL homes and subjected to simulated occupancy to measure normal operation and the change in operation when various commands were issued.

The appliances were evaluated individually to understand how each manufacturer implemented the standard commands. The initial round of testing was used to evaluate which commands were implemented, which commands were missing or had problems, and if there were any usability issues. Based on the feedback from the initial tests, the manufacturers made improvements to hardware or software (or both), and a second round of testing was conducted. The SPL provided the required infrastructure to install the appliances, apply simulated occupancy in a repeatable fashion, and collect data needed to quantify the impact of the controls.


Figure 6. Residential appliances installed in the SPL as part of the NREL/EPRI project. Clockwise from upper left: thermostat, heat pump water heater, PV inverter, EVSE, and pool pump. *Source:* Photos provided by EPRI

### More Complex: Whole-Home Control

The next step in complexity is the coordinated control of multiple connected devices in a single home. One such project included a full complement of controllable appliances (PV inverter, home battery, refrigerator, dishwasher, clothes washer, dryer, electric resistance water heater, and thermostat connected to a heat pump) and an NREL-developed HEMS called **foresee** (Jin et al. 2017).

The connected devices communicate with **foresee**, running on a small computer, as shown in Figure 7, over a combination of wired and wireless protocols. Interoperability challenges are an area where laboratory testing can aid in the development of smart home technologies. Even when a controller has demonstrated compatibilities with a range of individual devices or communication protocols, integrating multiple systems can present new problems.

In addition to using the infrastructure to configure **foresee** and the connected appliances in a realistic environment, this project took full advantage of the simulated occupancy tools developed for the SPL. A series of use cases determined the impact of the advanced controls that are built into **foresee**, which uses multi-criterion decision-making and model-predictive control to improve whole-home efficiency and provide reliable grid services. We tested scenarios that are relevant in different climate regions, with the simulated occupancy tailored to reflect that location. This project was cosponsored by Bonneville Power Administration, so two of the simulation locations were Portland, Oregon, and Spokane, Washington. The final location chosen for the laboratory evaluation was Honolulu, Hawaii, because of the city's unique challenges with excess rooftop solar. For each location, we used an EnergyPlus house model that reflected typical construction in that location for the HVAC HIL system.

Figure 7. **foresee** user interface shown with PV inverter and home battery within the SPL. *Source:* Dennis Schroeder, NREL 45575

These scenario tests compared the home's daily energy usage profile under normal operation (no **foresee** control), under optimized control aimed at energy efficiency, and during a day with some type of demand response (load add or load shed). In all cases, a time-of-use (TOU) price structure was applied and used to determine the daily cost of energy, another metric used to assess the results.

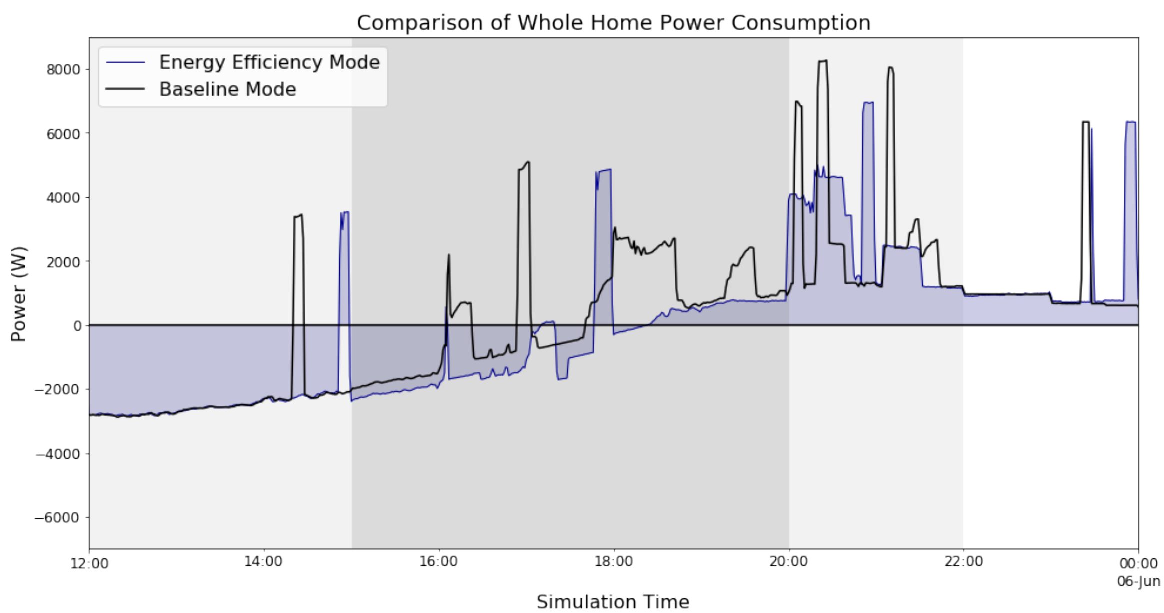


Figure 8. Power data collected in the SPL showing the load pattern under two conditions: baseline mode (no control) and energy-efficiency mode. The gray shading represents the TOU rate structure, with the darkest band representing the most expensive rate.

Figure 8 shows preliminary results for half of a Portland day where two cases were run: baseline without control and energy-efficiency mode. The black line represents the case without **foresee** control, and the blue shading shows when **foresee** was used to improve energy efficiency and reduce costs. The gray shaded areas represent the TOU schedule, with the darkest section corresponding to the highest rate period; the light gray shows the medium rate periods; and the white section shows the lowest rate. The case with **foresee** running shifted some of the high-power loads and used the battery to offset some of the power consumption during the highest price periods. On this day, nearly 2 kWh of energy were saved, resulting in about 20% cost savings.

### Most Complex: Control of One Home in Coordination with Large-Scale Simulation

To date, the most complex project that has been executed in the SPL involved an application of the HIL concept. In this case, the "hardware" was one of the homes, complete with multiple controllable appliances and a HEMS, which was connected to a simulation of an electrical distribution feeder running on the HPC in the ESIF, as shown in Figure 9 (Sparn et al. 2018). The feeder simulation included 20 homes, with one home replaced by the hardware home in the SPL. Each simulated home had its own dedicated HEMS that was optimizing control to achieve minimum cost under a TOU utility tariff while maintaining comfort. The collective grid impact of the individual control decisions among the 20 homes was determined in the feeder simulation, and any changes to feeder voltage were reflected in the SPL through a grid simulator used to power the home. Simulated occupancy and weather was applied to the devices in the home—PV inverter, EVSE, air conditioner, and water heater—and the power use profile of the SPL home was sent in real time to the feeder simulation to represent one of the homes on the feeder.

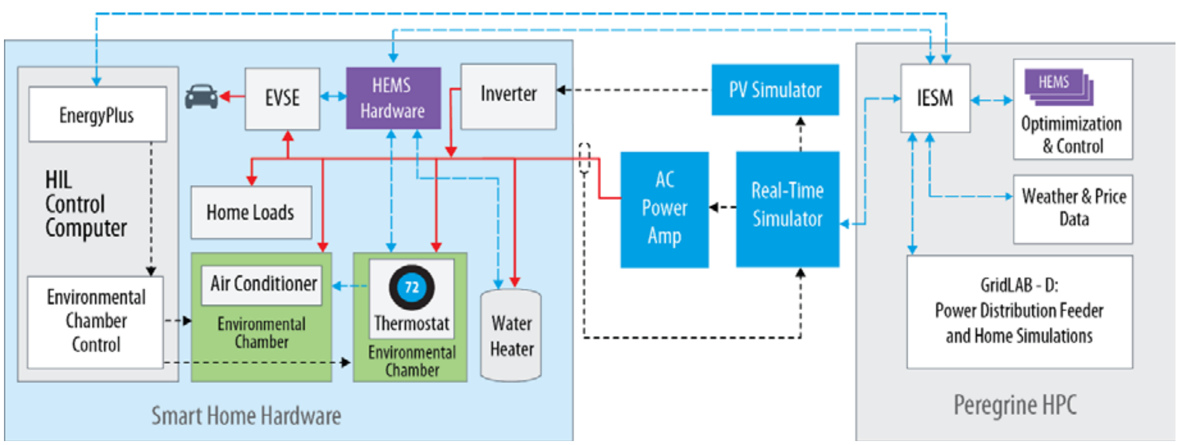


Figure 9. Diagram of the Smart Home Hardware-in-the-Loop experiment. Source: Illustration by Anthony Castellano, NREL

This project, known as the Smart Home Hardware-in-the-Loop, made use of the HPC in the ESIF and several tools that were developed to enable this experiment. The feeder simulation runs on the HPC, and the individual HEMS for each home are also optimized using the HPC. Weather and utility tariff information feed into both the HEMS optimizations and the feeder simulation. A cosimulation platform was developed in an earlier project that enables all the different simulation components to exchange data and control signals at the right time. Other standard ESIF equipment was needed to make the connection between the simulation and the SPL home, including a grid simulator to power the home with power consistent with the feeder simulation, a PV simulator to supply DC power to the PV inverter, and a real-time simulator to manage the control to the grid simulator and PV simulator. Preliminary results in Figure 10 show that the HEMS control shifts energy usage away from the high-priced time periods, leading to both energy and cost savings at the house level; however, results from the feeder simulation show that the time-based controls lead to slightly more variation in grid voltage.

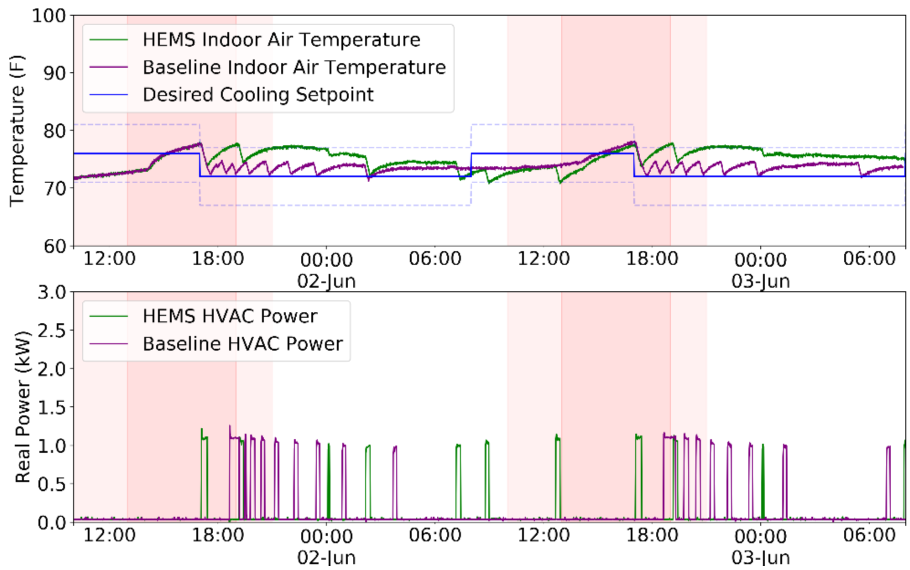


Figure 10. Comparison of temperature and power data from the air conditioner hardware during two days under baseline control and HEMS control. The dashed blue lines indicate the bounds on the set point temperature. The pink shaded areas represent the TOU rate, with the darkest sections representing the highest cost periods.

## Conclusions

Visitors to the SPL see a laboratory that looks and feels familiar because it contains smart home appliances and other residential equipment, but the lab was deliberately built to facilitate a new kind of research at NREL. The SPL enables researchers from across NREL and around the world to test everything from sensors and control components to sophisticated control algorithms in a controlled and controllable environment. The laboratory infrastructure includes major and minor appliances for three homes, along with sensors and controllers to apply simulated occupancy to all the different loads. DERs such as PV inverters and home batteries can be brought into the homes to explore new options for powering homes and providing stability to the grid. The homes can be integrated with other assets in the ESIF, which allows us to evaluate the grid-level impacts of the controls being explored for residential buildings. SPL has been used to evaluate novel sensor technologies, investigate whole-home energy and cost savings from HEMS systems, and understand the impact those controls will have on the electric grid when implemented more broadly. SPL provides the environment and the necessary tools to investigate a wide range of research questions related to buildings-to-grid integration, with enough flexibility to adapt as research needs change.

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