Smart Panels: Electrifying the Connection Between Smart Homes and the Grid

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ABSTRACT

Smart panels give occupants the ability to remotely turn on and off breakers in their electric panel and provide circuit-level power monitoring for those circuits. Smart panels can be controlled to save occupants money by automatically reducing loads during peak price periods, manage which circuits are powered by backup sources during a grid outage, and give occupants the ability to add new electric equipment while still maintaining the whole-building load below a maximum threshold to avoid electrical service upgrades. That capability can also provide relief to utilities facing continued load growth, avoiding distribution-level infrastructure upgrades, and improved demand response participation through house-level control. This project focused on quantifying the benefits to stakeholders, occupants, and utilities, using laboratory data. To understand the current capabilities of smart panels, laboratory testing was performed in a hardware-in-the-loop configuration under scenarios that include typical electrical appliances, electric vehicles, batteries, and photovoltaics. Results show that smart panel-enabled control schemes can reduce household energy consumption. However, the control schemes considered result in peak demand increases in the winter and meaningful comfort impacts in both the summer and winter, despite a pre-conditioning period. We found that by controlling all loads except for HVAC, the home still saved energy and cost while maintaining comfort for occupants. This work will inform energy models that capture the behavior of smart panels, which can be combined with a distribution grid model to understand how coordinated control could help defer utility upgrades and relieve other distribution grid issues.

Introduction

Background on Smart Panels and the Schneider Electric Panel

Many homes across the U.S. are projected to increase their electric loads for a variety of reasons. Multiple states have established programs to increase the adoption of electric HVAC and water heating. Electric vehicle (EV) adoption has also continued, with over 1 million EVs sold per year since 2022 (ANL 2026). Customers are also increasingly interested in installing batteries and solar panels for resilience as public safety power shutoffs become more common, with utilities in California (CPUC 2026), Hawaii (HECO 2026), and Colorado (Xcel 2026) all recently adopting policies to implement public safety power shutoffs during high fire risk events. The confluence of these factors leads to many homes increasing their electricity consumption compared to what the individual building electric panel and the local distribution system were originally designed for.

One of the largest potential issues with increasing the electric loads in a home is the limit set by the capacity of the existing electric panel. Homes can be limited by both the overall current rating of the panel and the number of available breaker slots. Older homes, particularly in regions where other fuels are commonly available, tend to have lower overall panel capacity and fewer available breaker slots (Murphy et al. 2026). Electric panel upgrades can be costly and require involving the utility, trade workers, and homeowners. When adding a single individual large load, circuit splitting or pausing devices may be able to meet customer needs (Sparn et al. 2024). These devices allow for one circuit to be shared by two devices, with one device having priority in the event that an occupant tries to use both at the same time. If multiple large electric loads are added, a smart panel could better coordinate the loads. The smart panel could then serve as a central hub making decisions in the event of multiple large loads being called simultaneously in the home and can ensure that the overall power draw of the house stays below the utility service threshold.

For many existing neighborhoods, the electrical distribution system infrastructure was built decades ago based on the needs of the time. Along with house-level constraints due to panel capacity or the service provided to a single home, the local distribution system can also face capacity limits if multiple homes add large electric loads. This could trigger a costly upgrade for the utility. Smart panels could help alleviate this concern by managing when certain loads turn on, thus reducing the peak load seen at the neighborhood level. To achieve this, coordinated control of multiple houses is required through a utility or aggregator. Smart panels provide the hardware that could be used for such coordination.

Customers can also directly benefit from providing control over loads in their homes, as the utility will not need to provide an upgrade to the neighborhood, which reduces costs for all ratepayers. Utilities in Vermont, Florida, and California have started pilot programs with smart panels to help understand the potential benefits that could be provided (Moran et al. 2025). This may also motivate utilities to provide smart panels to certain customer segments, as the utility can reap substantial monetary benefits on certain feeders from deferring upgrades (Bonner et al. 2025).

When controlling loads in residential buildings, costs and comfort for the occupants are important considerations. Occupants may be willing to give some control to the utility for select large loads, so long as they generally still behave as they normally would. If controls lead to large comfort impacts, such as the home's indoor temperature getting too hot or cold, hot water not being available for a shower, or an EV not charged when an occupant needs to leave, occupants will opt out and/or become dissatisfied with the program. For the space temperature, existing standards provide guidance on acceptable levels of comfort (ASHRAE 2023). For water heaters, 'unmet showers' is a novel metric that can be used to quantify any unmet loads that may negatively impact occupants (Maguire 2020). For EVs, any unmet charge before an occupant next drives their vehicle could be used to quantify unmet load due to managed charging. Since the smart panel is controlling loads directly at the panel, it does not always have information, such as the indoor temperature, necessary to determine the potential comfort impacts associated with control decisions. Additional sensors or the ability for panels to communicate with other devices like thermostats that do have the required information for understanding comfort impacts can alleviate this concern.

Schneider Electric's Panel

The Schneider Electric Panel is a residential electric panel that includes the meter socket, the main panel and a subpanel, surge protection, and an embedded energy monitor. Breakers in the panel are standard breakers but can be made "smart" by pairing them with relays that measure power consumption and can turn power off and on. The relays connect to the energy monitor, which communicates with the Schneider Home mobile app that allows users to view data and control relays. Schneider also makes smart outlets and light switches that integrate with the Schneider Home app.

The circuit-level relays in the Schneider Electric Panel allow users to create schedules for when these circuits will be turned on and off. This can be used to manage costs when the home is on a time-of-use (TOU) utility rate. Circuit-level control paired with whole-home power data can also be used to keep the total power consumption of the home below a specific limit. This is called Smart Power Manager and can help both homeowners and utilities manage peak loads. Homes may benefit from this feature if they are trying to add new electrical loads without increasing their utility service. This feature may also help utilities avoid infrastructure upgrades that could be triggered by many homes upgrading their utility service.

The goal of this project is to evaluate the functionality of the Schneider Electric Panel in a controllable but realistic environment. In this way, we can simulate the same household characteristics, weather conditions, and occupant behaviors, while changing various control schemes around TOU rates using the Schneider Home app to understand how these control schemes impact energy consumption, peak power draw, operating costs, and occupant comfort.

Methodology

Experimental Setup

All experiments were performed in the Systems Performance Laboratory within the Energy Systems Integration Facility at the National Laboratory of the Rockies (NLR). The Systems Performance Laboratory has three mock homes with electrical and water infrastructure, along with all typical major appliances (Sparn, 2018). For this project, the Schneider Electric Panel was installed in one of the mock homes, and all the existing circuits were fed from breakers in the panel. In addition to the standard breakers, four circuits also had relays installed in series with the breakers, which allows for circuit-level power data and on/off control. The relays were installed for the heat pump air handler, heat pump outdoor unit, heat pump water heater (HPWH) and electric vehicle service equipment (EVSE). The heat pump is a variable speed, 2-ton unit with 8 kW of electric resistance backup heat powered from the air handler circuit breaker. The water heater is an 80-gallon HPWH that is set to its hybrid operating mode. The EVSE is powered from a 40A breaker, with a maximum power draw of ~6.6 kW. In addition to these larger loads that will be controlled from the Schneider relays, the home also includes: a 3-kW PV inverter fed from a PV simulator, an induction range, washer, dryer, dishwasher, refrigerator, about 100 W of lighting, and general receptacle circuits powering a humidifier and space heater. The equipment used for this project can be seen in Figures 1–3.

Figure 1. Laboratory setup showing Schneider Electric Panel, EV and EVSE, and PV inverter.

Figure 2. Laboratory setup refrigerator, heat pump water heater, dishwasher, range, washer, and dryer.

Figure 3. HVAC hardware-in-the-loop system: Outdoor unit sits inside the chamber, air handler is connected to duct loop, and thermostat sits inside lower blue environmental chamber

All of the equipment in the lab was subjected to "simulated occupancy" to ensure that the equipment operates in a realistic and repeatable fashion. For some equipment, this is as simple as running the same timed cycle on the dishwasher or clothes washer. For other appliances, more laboratory equipment or controls are needed. We have a controllable valve on the hot water plumbing that we use to impose a hot water draw profile on the water heater. Different hot water profiles were developed for the different simulated days based on different times of year and locations. The PV inverter is powered by a PV simulator, which is a DC power supply with software used to mimic the output from solar panels based on performance maps for known solar panels and insolation data from specific locations. The EV is scheduled to charge for a certain duration every day to mimic an average amount of driving. The HVAC equipment is subjected to a technique called hardware-in-the-loop (HIL) to ensure realistic operation. All HVAC hardware, including air handler, outdoor unit and thermostat, are installed in the lab (see Figure 3) and exchange data with a building model running in real time. The laboratory's layout and the HIL system architecture were originally described by Sparn (2018), while Ramaraj and Sparn (2022) provides a detailed explanation of the platform's configuration and validation for advanced control applications. Building conditions, including envelope characteristics, weather data, and internal loads, were modeled using EnergyPlus® (Crawley et al. 2001). Co-simulation was achieved by linking EnergyPlus with Simulink through the MLE+ toolbox (Bernal et al. 2012). Simulink was used to send data back and forth between the building model and the laboratory's data acquisition system. The HVAC HIL system ensures that the hardware experiences indoor and outdoor conditions that are representative of what they would experience in a real home, in a repeatable way.

Laboratory Test Plan

The laboratory test plan was developed to test the capabilities of Schneider Electric Panel in different locations, seasons, peak electricity periods, and control strategies. The Schneider Electric Panel was installed with four relays and three smart outlets that are controlled (turned on and off, or programmed with a schedule) via the Schneider Home app. The following sections describe the different scenarios that were tested.

Simulated Locations, Weather, and Peak Electricity Pricing

For this study, we chose to evaluate a home in San Bernardino, CA, in the summer and a home in Spokane, WA, in the winter. Spokane and San Bernardino were chosen because the local utilities have TOU rates available for residential customers and the locations have the potential for extreme temperatures in the seasons of interest. Building models for these locations were chosen by selecting single family housing units from the ResStock building stock modeling tool (NLR 2026). Each housing unit from ResStock is generated through a probabilistic representation of building characteristics based on data from several national surveys (e.g., Residential Energy Consumption Survey), and the units chosen here have characteristics that make up a plurality of the buildings to try to be as representative as possible. The San Bernardino home is a 1,750 ft^2 two-story home built in the 2000s with six occupants and has a 3-kW PV system. This home falls within the Southern California Edison service territory, and during the summer it has a single late afternoon/evening peak electricity pricing period.[1] The Spokane home is a 1,750 ft^2 single-story home built in the 1970s, with four occupants, and also has a 3-kW PV system. This home falls within the Avista Energy service territory, and during the winter it has morning and late afternoon/evening peak electricity pricing periods.[2] Table 1 outlines the peak and off-peak electricity costs for both locations along with the timing of the peak period(s). The schedules for the peak periods were used to determine the control schedules, and the electricity rates were used to calculate operating costs.

[1] Southern California Edison Residential TOU-D 4 PM–9 PM before baseline credit. https://www.sce.com/save-money/rates-financing/residential-rate-plans/time-of-use-plans

[2] Avista Energy Pilot TOU-A rate for Residential Customers: https://www.myavista.com/energy-savings/green-options/time-of-use

Table 1. Peak pricing cost and timing

Location	Off-Peak Period Cost	Peak Period Cost	Peak Period Timing
San Bernardino, CA	$0.34/kWh	$0.58/kWh	4 PM–9 PM
Spokane, WA	$0.096/kWh	$0.256/kWh	6 AM–9 AM
			5 PM–8 PM

Weather data is used to drive conditions for HVAC, PV, and water heating. The outdoor weather data was used by the building model in the HVAC HIL system. Based on the location, season, and occupancy of each home, we generated a custom hot water draw profile to drive the water heating loads. Draw profiles were generated using the Building America Domestic Hot Water Event Schedule Generator (Hendron and Burch 2010), which uses statistical distributions of usage from different residential end uses across a large number of homes to generate realistic unique days of discrete events. Finally, we matched sub-hourly insolation data from local sources for the weather days we selected and converted these into 1-second data for use in the PV simulator connected to the PV inverter ("Motte Rimrock Reserve California," n.d.; "UO SRML Monitoring Stations," n.d.).

Proposed Test Scenarios

For this study, we ran two baseline cases and four control strategy test scenarios (Table 2). The two baseline test scenarios represent the typical summer and winter weather cases. The four control strategies use the same typical weather data for both summer and winter and apply one of two control schemes. The Basic Control scheme uses relays and outlet controllers to shut off appliances during peak periods. These loads include the HVAC system, water heater, EVSE, lights, humidifier, and space heater (winter only). The Advanced Control scheme is similar to the Basic Control case in that it will shut off appliances during peak periods. However, using scheduling features, we pre-condition the home and water heater before the peak period to mitigate discomfort impacts. Both HVAC and water heating setpoints are adjusted 2 hours before the peak period to allow for enough time for pre-conditioning. Additionally, we schedule the EVSE to charge the EV after the peak period.

Table 2. Test matrix for laboratory testing

Test Name	HPWH Setpoint	HVAC Setpoint
Summer Baseline	125°F	72°F
Summer Basic Control	125°F	72°F
Summer Advanced Control	125°F baseline, 135°F preheat	72°F baseline, 69°F precool
Winter Baseline	125°F	68°F
Winter Basic Control	125°F	68°F
Winter Advanced Control	125°F baseline, 135°F preheat	68°F baseline, 71°F preheat

Household Load Specifications

In addition to the HVAC system and water heater loads, which are based on the household characteristics and weather, we also implemented the following household electricity loads—electrical vehicle charging, clothes washer, clothes dryer, dishwasher, light, humidifier, and for the winter tests, a space heater. The EVSE is connected to a 40A breaker to charge a 2020 Nissan Leaf at a maximum power of 6.6 kW. We determined the amount of daily charging needs based on the state averages for miles driven per year according to the Federal Highway

Administration 2019 Highway Statistics series[3]—35 miles for California and 20 miles for Washington. This corresponded to 3 and 2.5 hours of charging, respectively. For the remaining appliances, we followed the schedule outlined in Table 3.

Table 3. Household appliance schedules

Appliance	CA Summer	WA Winter	Operation	Controls
Washer	7:00 PM–8:00 PM		Normal cycle	None
Dryer	8:00 PM–8:30 PM		Normal cycle	None
Dishwasher	8:00 PM–9:00 PM		Normal cycle	None
Lights	6:00 AM–8:00 AM, 7:30 PM–11:00 PM	6:00 AM–8:30 AM, 5:00 PM–11:00 PM	N/A	Off during peak via outlet control
Range	6:30 PM – 7:00 PM		Highest setting on largest cooktop ring	None
Humidifier	Always on		High	Off during peak via outlet control
Space Heater	N/A	7:00 PM–10:00 PM	Highest heat and fan settings	Off during peak via outlet control

Results

Table 4 summarizes results for all the experiments, including total energy use, peak power, and operating costs. Figures 4 and 8 show circuit-level power data for the summer and winter baseline experiments, respectively. The PV measurements in these figures are negative because it is generating, not consuming, power. Similarly, the whole house power data goes negative in the middle of the day when the PV generation exceeds the household consumption and power is backfed to the grid. Figures 5 and 9 show the whole household power data for the baseline, basic, and advanced control cases for the summer and winter, respectively. Figures 6, 7, 10, and 11 show the power and temperature data of the baseline, basic, and advanced control cases for the summer and winter, respectively.

In addition to power and energy metrics, Table 4 also includes comfort and cost metrics. For this study, we define "exceedance degree-hours" as an HVAC comfort metric that accounts for duration and temperature deviation from baseline comfort defined as the maximum indoor temperature in the summer baseline case and the minimum indoor temperature in the winter baseline based on the thermal comfort metrics outlined in ASHRAE Standard 55 (ASHRAE 2023). For example, if the indoor temperature in the control case was a single degree higher than the maximum baseline temperature for two hours, that would result in exceedance degree hours of 2.0°C-hr. The "Water Volume Below Min Temp" for the water heater was calculated using the minimum comfortable water temperature of 105°F and calculating the volume of water drawn below that temperature. It is worth noting that even in the baseline cases, there is some water drawn that is below the minimum temperature threshold. The full set of HVAC and water heating results can be found in the Appendix.

[3] https://www.fhwa.dot.gov/policyinformation/statistics/2019/

Table 4. Results summary for the four baseline cases run: typical and hot summer and typical and cold winter

Test Name	Net Energy Consumption[1]	Peak Period Energy Consumption	Peak Period Energy Consumption Change	Max Power Draw	Exceedance Degree-Hours	Water Volume Below Minimum Temperature	Total Cost	Cost Change
Summer Baseline	32.1kWh	35.8 kWh	-	20.9 kW	-	12.0 gal	$19.51	-
Summer Basic Control	20.9 kWh	2.03 kWh	-94.3%	12.1 kW	22.4 °C-hr	13.5 gal	$8.24	-57.8%
Summer Advanced Control	27.3 kWh	3.95 kWh	-88.9%	15.5 kW	19.8 °C-hr	12.5 gal	$10.22	-47.6%
Summer Advanced, No HVAC Control[2]	30.4 kWh	9.09 kWh	-74.6%	14.8 kW	-	12.5 gal	$12.53	-35.8%
Winter Baseline	40.5 kWh	28.7 kWh	-	14.8 kW	-	14.4 gal	$8.24	-
Winter Basic Control	33.4 kWh	0.9 kWh	-96.8%	19.9 kW	9.1 °C-hr	14.1 gal	$3.15	-61.8%
Winter Advanced Control	38.9 kWh	1.5 kWh	-94.8%	26.3 kW	7.1 °C-hr	14.8 gal	$3.74	-54.6%
Winter Advanced, No HVAC control[2]	38.1 kWh	4.7 kWh	-83.6%	20.9 kW	-	14.8 gal	$4.41	-46.5%

[1] – Household Net Energy Consumption can be less than the Household Peak Period Energy Consumption because it includes generation from solar.
[2] – These results were created by combining the HVAC data from the baseline experiment with the data from the remaining equipment from the advanced control experiment.

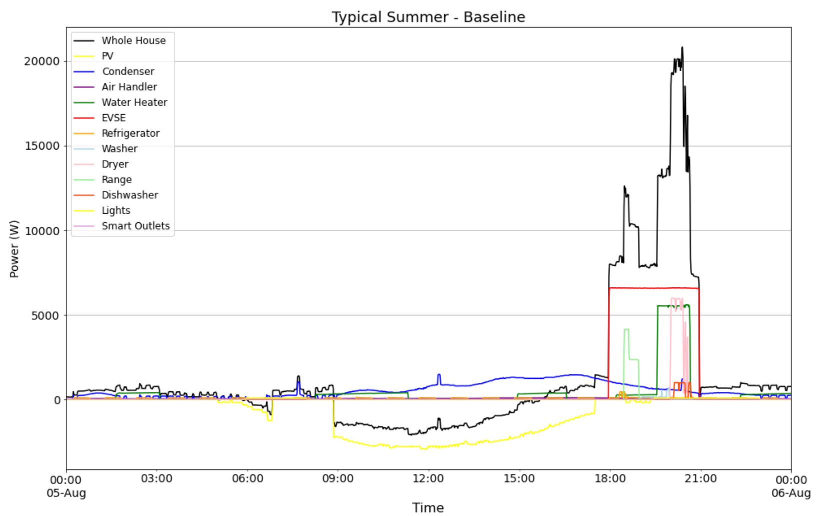

Figure 4. Circuit-level power data for typical summer – baseline case

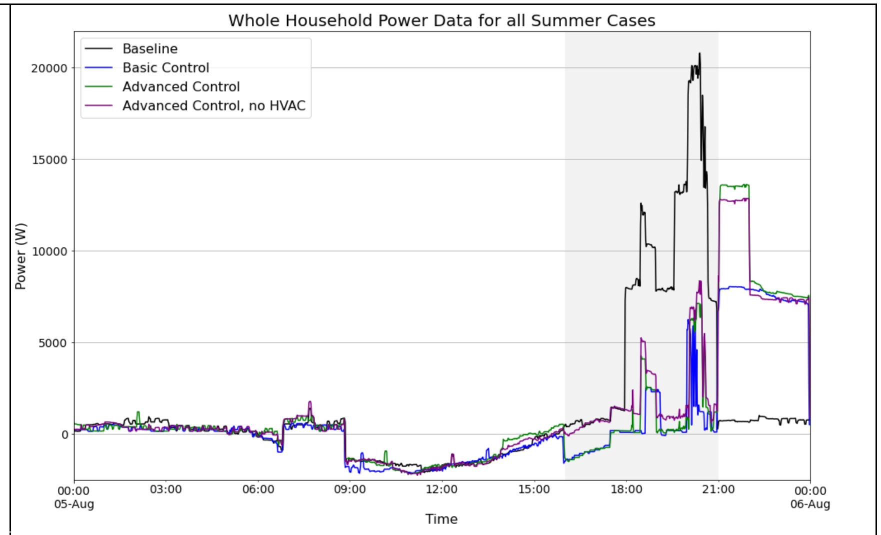

Figure 5. Whole household power data for summer baseline, control, advanced control, and advanced control without HVAC control cases

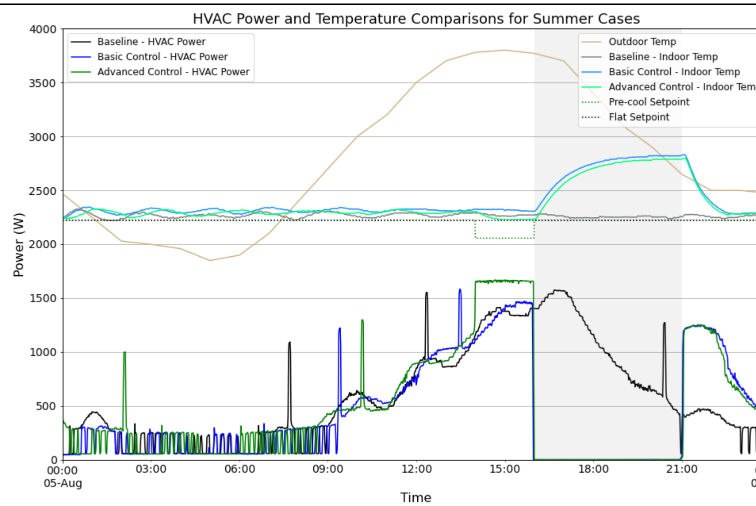

Figure 6. HVAC power and temperature data for summer baseline, control, and advanced control cases.

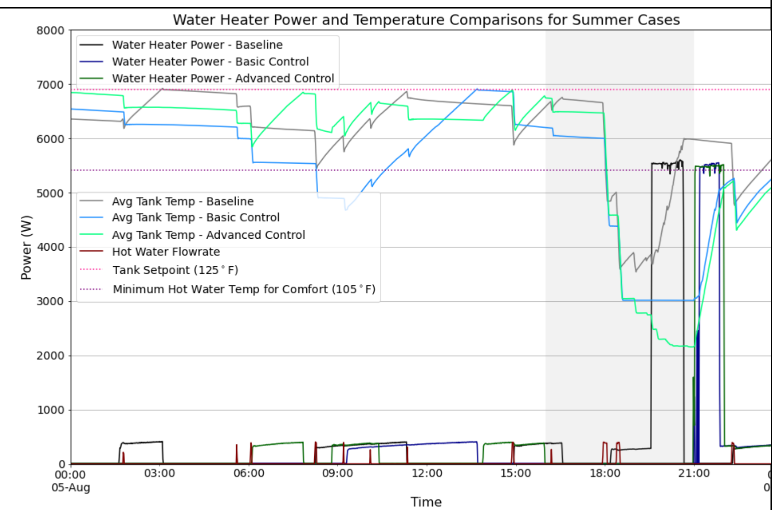

Figure 7. Water heater power and temperature data for summer baseline, control, and advanced control cases.

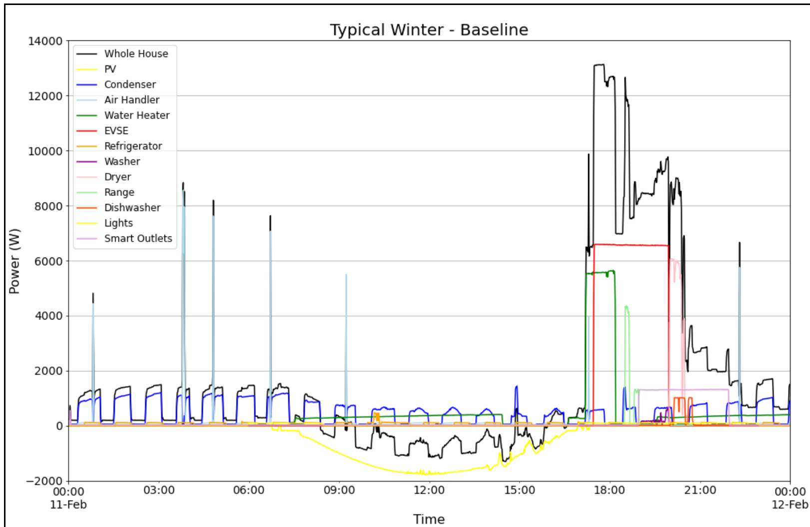

Figure 8. Circuit-level power data for typical winter – baseline case

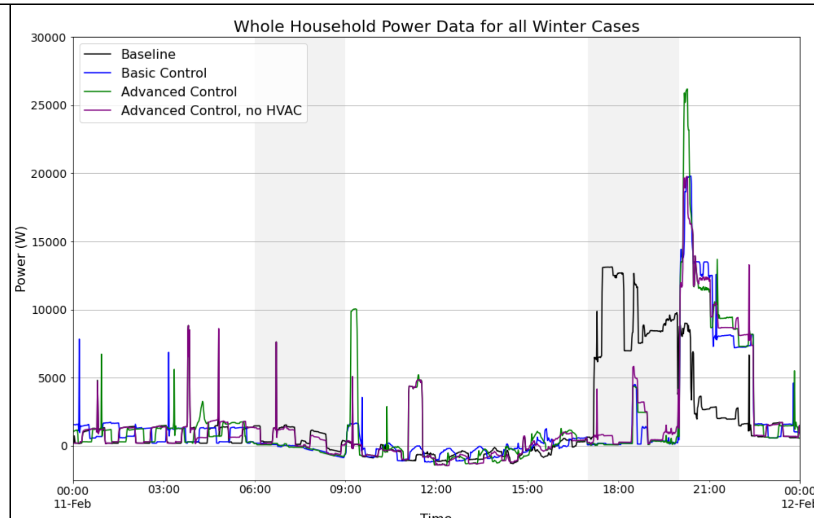

Figure 9. Whole household power data for winter baseline, control, advanced control, and advanced control without HVAC control cases

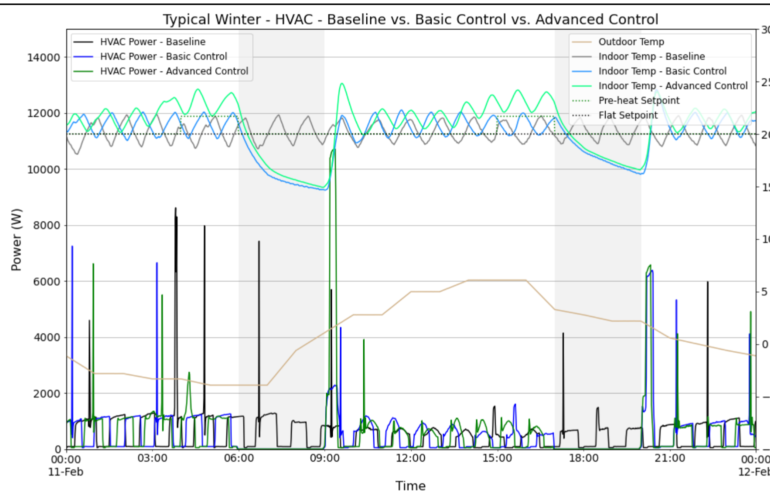

Figure 10. HVAC power and temperature data for winter baseline, control, and advanced control cases.

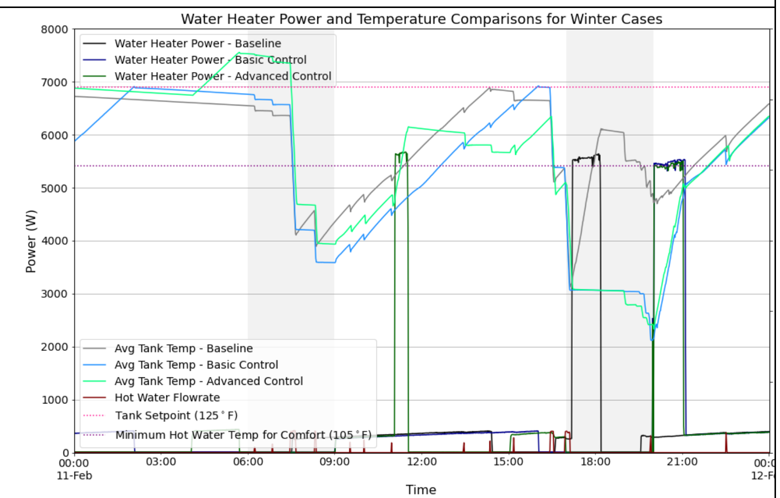

Figure 11. Water heater power and tank temperature data for winter baseline, control, and advanced control cases.

Analysis

Control schemes impact peak period energy consumption and power draw

Controlling the HVAC, water heating, EVSE, and specific plug loads reduced the net energy consumption for both control schemes in both the summer and winter experiments. Despite recovery periods where the HVAC and water heating systems ran at nearly their maximum capacity following the peak period, none of the control scheme experiments consumed as much net energy as the corresponding baseline experiments. Furthermore, by significantly reducing the energy consumption during the peak periods, a resident using these control strategies could conceivably reduce their winter and summer electric bills by anywhere from 48% to 62% with the specific TOU rates and schedules used in these experiments. Savings will vary considerably for other TOU rates and schedules.

While residents could leverage these controls around peak periods to unlock savings, they also have meaningful consequences for utilities. In the summer in San Bernardino, once the peak period ends the outdoor temperatures have fallen far below the daily high. Because of this, the HVAC system does not need to consume as much electricity in the evening as it would in the middle of the day to pull the indoor temperature back down to the setpoint. If a large portion of the building stock in similar climates adopted these types of control schemes in the summer, utility operations could be meaningfully impacted, including the possibility of a shift from an afternoon to evening peak. Regardless of timing, if the magnitude of the daily summer peak is decreased, this could result in fewer outages and lower operating costs for utilities—savings that could theoretically be passed on to customers.

However, in the winter in Spokane, the HVAC system relied on the electric resistance back up after both peak periods to bring the home back up to the setpoint. This resulted in a 41% and 78% increase in maximum power draw in the basic and advanced control schemes, respectively. Broad adoption of these control schemes in this climate during the winter would negatively impact utilities, creating a rebound effect immediately following these TOU periods, potentially negating benefits realized during those periods. Regardless of the climate zone or season, these control strategies are generally effective in reducing the overlap of large loads (i.e., HVAC, cooking range, EVSE, clothes dryer, water heating). Using smart panels to ensure that only one or two of these loads are overlapping could be an effective measure to reduce household and system peak demand.

Limited effectiveness of pre-conditioning for both HVAC and water heating

In both the summer and winter cases, the control schemes resulted in negative comfort impacts. On a typical summer day in San Bernardino using the basic control scheme, the indoor temperature rose from a setpoint of 22.2°C (72°F) to over 28.7°C (83.7°F) during the five-hour peak period from 4 PM to 9 PM (light blue line in Figure 6), resulting in 22.4°C-hr exceedance hours. Similarly, on a typical winter day in Spokane using the same control scheme, the indoor temperature dropped from the setpoint of 20°C (68°F) to 14.3°C (57.8°F) (light blue line in Figure 10) during the morning peak period from 6 AM to 9 AM, resulting in 9.1°C-hr exceedance hours.

To help offset these comfort impacts, the summer and winter advanced control experiments incorporated a pre-conditioning element to their respective control schemes. However, the 1.7°C (3°F) pre-conditioning for the HVAC system for both the summer and winter advanced control schemes resulted in little benefit with the maximum indoor summer temperature rising to 28.3°C (82.9°F) and the minimum indoor winter temperature dropping to 14.6°C (58.3°F). In both cases, these temperatures were less 0.56°C (1°F) away from the extreme temperatures experienced in the basic control cases. The summer and winter advanced control cases still accumulated 19.8°C-hr and 7.1°C-hr exceedance hours—only an ~11% and 21% decrease from the basic control cases, respectively. Everyone experiences comfort differently, but it seems unlikely that many people would accept this level of discomfort for the corresponding small cost savings.

We saw similar results when we pre-heated the water heater. Peak HVAC energy use during the hotter and colder parts of the summer and winter days generally aligned with the peak periods, but the water draw schedules for these households did not necessarily coincide with the peak periods (Figure 7 and Figure 11). In both the basic and advanced control cases for the summer and winter, the average water heater tank temperature dropped well below the water heater setpoint (125°F), but this resulted in almost no change in the volume of water drawn below the minimum comfort threshold, as compared to the baseline (Table 4). Given that a water heater tank serves as a type of thermal battery and thermal stratification ensures that the hottest water in the tank stays at the top, we observed that temperature of the water exiting the tank during those times was nearly unchanged. We concede that comfort issues could exist in households with different occupant behaviors and schedules, however we intentionally chose scenarios with more occupants, and therefore more hot water usage over a day, compared with the national average (Healy et al. 2021).

Removing HVAC controls provides a balance between cost savings and comfort

Based on these findings, we decided to analyze two more hybrid experiments where we considered the summer and winter advanced control cases without controlling the HVAC system (Summer and Winter Advanced, No HVAC Controls tests as shown in Table 4). It is important to note that we did not run these as separate experiments in the HIL laboratory environment, but rather we combined results from the baseline tests and the advanced control tests. We found this control scheme to produce the best balance of energy, cost savings, and comfort—resulting in 35.8% and 46.5% cost savings compared to the baseline summer and winter experiments—while maintaining the HVAC setpoints throughout. While this control scheme benefits residents in both locations, the impact on utilities depends on the location and season. During summer in San Bernardino, the net energy consumption, peak period energy consumption and maximum power draw all decrease—benefiting the utility. However, in the winter in Spokane, while net and peak energy consumption decrease, there is still a ~41% increase in peak power draw, which could impact a utility's operation, especially during and immediately following peak periods.

Conclusion and Future Work

Laboratory testing of the Schneider Electric Panel was used to investigate how this device can shift loads for a single home away from peak price periods. It was found that his technology utilizing various control schemes has direct benefits to the occupants as well as to the utility. However, for some control schemes these benefits are accompanied by significant comfort impacts, which may be partially mitigated by controlling thermostat setpoint via API or by excluding the HVAC system from the advanced control strategy.

Breaker-level control has drawbacks related to comfort and the potential impact on performance and longevity of large appliances. For example, the water heater did not always turn on correctly following the peak period shut off and needed to be manually reset. This type of unexpected recovery behavior could impact other large appliances that do not typically lose power regularly. HVAC manufacturers have also warned against shutting off power to a compressor without turning the equipment off first, as this can impact longevity of the equipment. Controlling HVAC equipment via a setpoint change using a smart thermostat is the preferred method to reduce energy use, while still ensuring some level of comfort. Some combination of smart controls at the device level and breaker-level control may provide the right balance of energy and cost savings with lifetime and comfort impact.

The results of this lab testing could be used to inform energy models for evaluating the benefits of this technology over a full year and across a broader range of conditions. The benefits of this technology are highly sensitive to the both the household (e.g., building specifications, utility rate, and local weather) and behavioral/control (e.g., setback timing and magnitude), characteristics, so using simulation models to evaluate the outcomes under a wider range of conditions would give a more holistic picture of the potential benefits for an entire state or utility service territory.

Some additional distribution grid benefits, such as deferring upgrades under electric load growth scenarios, could be realized through coordinated control of multiple panels in a neighborhood. The OCHRE™ (Blonsky et al. 2021) tool was designed specifically for modeling residential buildings with advanced controls connected to the local distribution grid and could be used to integrate the findings from this lab testing to explore these and other potential deployment scenarios. There are many potential benefits to the deployment of this technology, both to homeowners and electric utilities, and using the results from the lab testing to tailor the applications will help ensure that all stakeholders benefit.

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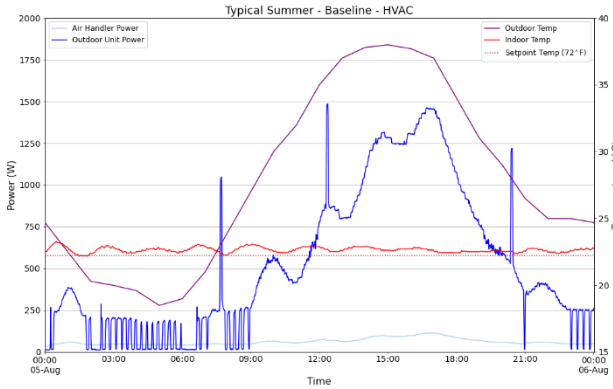
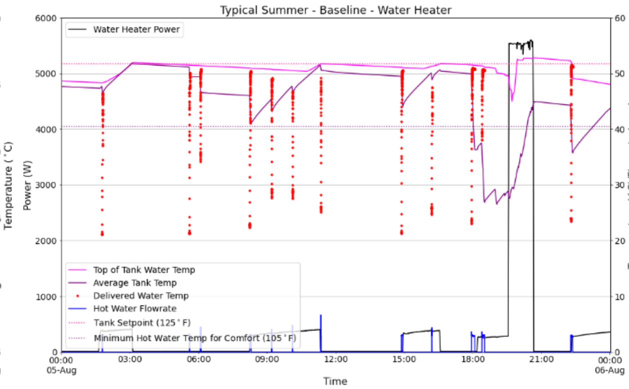
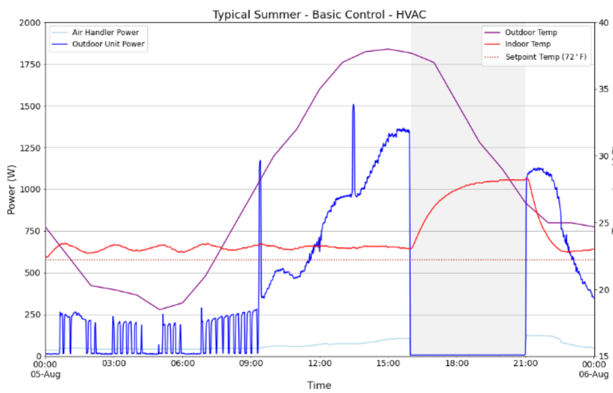
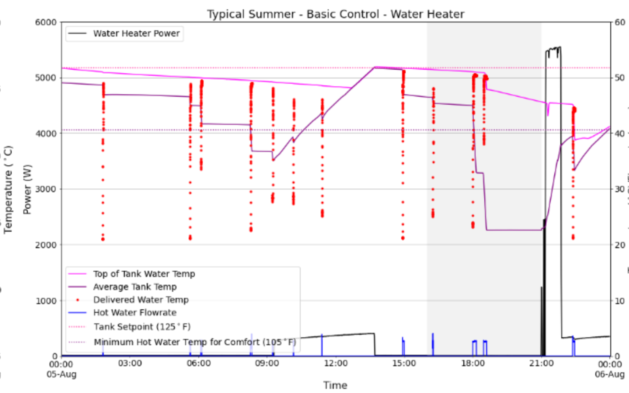
Appendix

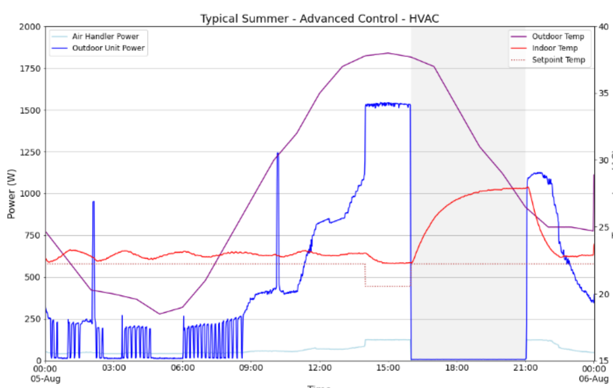
The following plots show the detailed HVAC and water heating results for all the cases completed at this point.

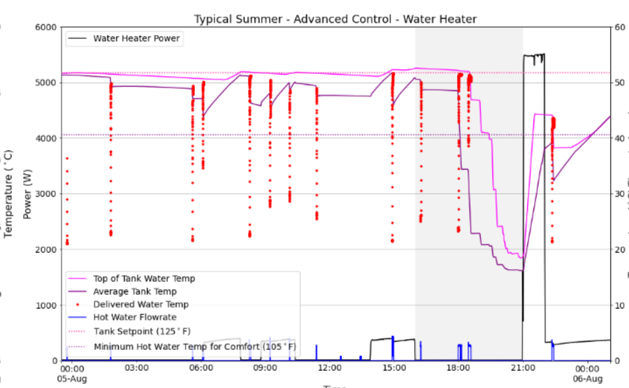


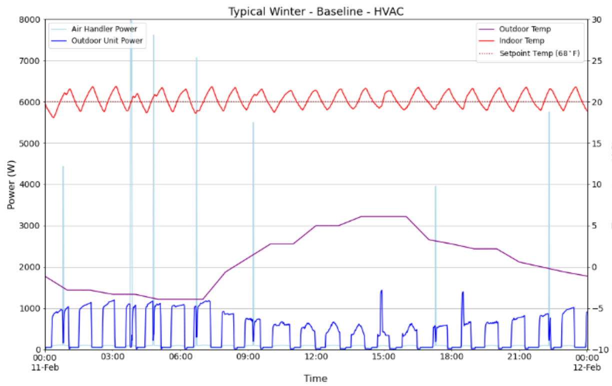


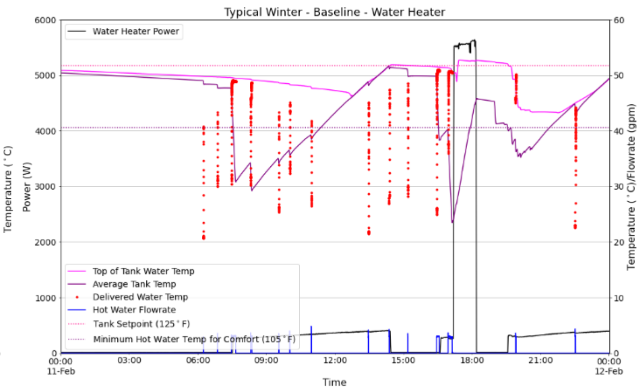


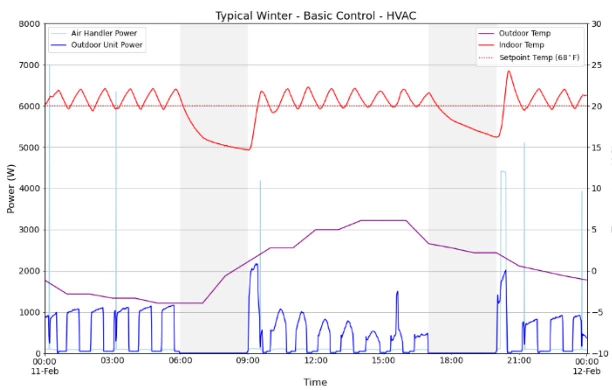


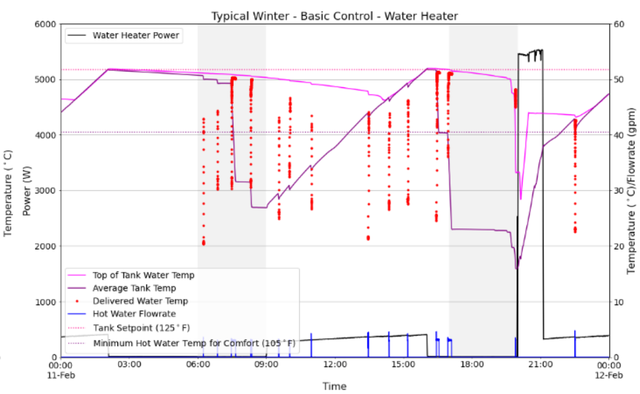


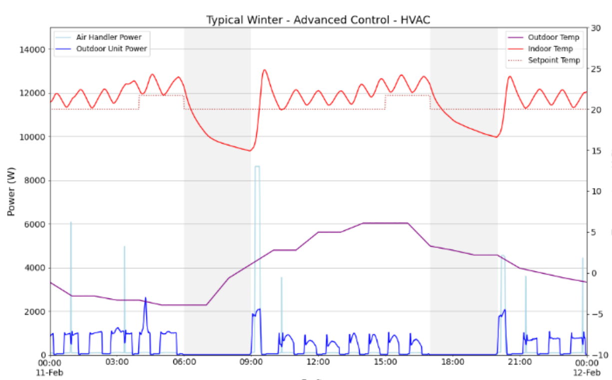


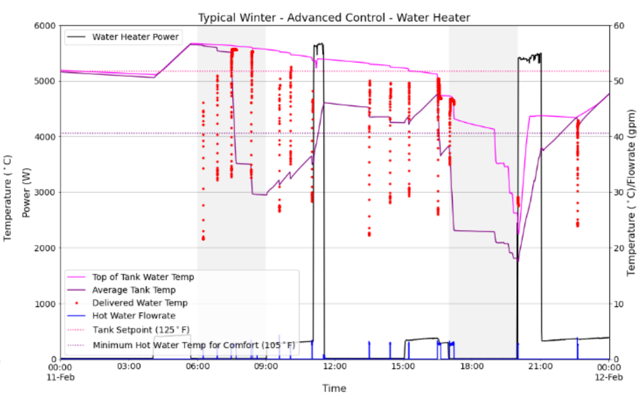

Typical Winter - Baseline - HVAC
Air Handler Power
Outdoor Unit Power
Outdoor Temp
Indoor Temp
Setpoint Temp (68°F)
Power (W)
Temperature (°C)
Time
11-Feb
12-Feb


Typical Winter - Baseline - Water Heater
Water Heater Power
Top of Tank Water Temp
Average Tank Temp
Delivered Water Temp
Hot Water Flowrate
Tank Setpoint (125°F)
Minimum Hot Water Temp for Comfort (105°F)
Power (W)
Temperature (°C)/Flowrate (gpm)
Time
11-Feb
12-Feb


Typical Winter - Basic Control - HVAC
Air Handler Power
Outdoor Unit Power
Outdoor Temp
Indoor Temp
Setpoint Temp (68°F)
Power (W)
Temperature (°C)
Time
11-Feb
12-Feb


Typical Winter - Basic Control - Water Heater
Water Heater Power
Top of Tank Water Temp
Average Tank Temp
Delivered Water Temp
Hot Water Flowrate
Tank Setpoint (125°F)
Minimum Hot Water Temp for Comfort (105°F)
Power (W)
Temperature (°C)/Flowrate (gpm)
Time
11-Feb
12-Feb


Typical Winter - Advanced Control - HVAC
Air Handler Power
Outdoor Unit Power
Outdoor Temp
Indoor Temp
Setpoint Temp
Power (W)
Temperature (°C)
TimeStamp
11-Feb
12-Feb


Typical Winter - Advanced Control - Water Heater
Water Heater Power
Top of Tank Water Temp
Average Tank Temp
Delivered Water Temp
Hot Water Flowrate
Tank Setpoint (125°F)
Minimum Hot Water Temp for Comfort (105°F)
Power (W)
Temperature (°C)/Flowrate (gpm)
Time
11-Feb
12-Feb