Connected Homes Solution

Source: California Public Utilities Commission, "Building Electrification and the CPUC," Docket Number 18-IEPR-09 TN#223758, June 11, 2018.

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Project Summary

Timeline:

Start date: 10/1/2018

Planned end date: 10/31/2021

Key Milestones

1. Achieved over 25% demand reduction for electric furnace demand control; 3/31/2021
2. Complete successful demonstration and impact quantification of demand control for three systems—electric furnace, electric-resistance water heater, and heat pump air-conditioning—and coordinated control of multiple home systems; 9/30/2021

Budget:

Total Project $ to Date:

- DOE: $3.87M
- Cost Share: $0

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- Cost Share: $0

Key Partners:

ecobee	
Univ. of Oklahoma	
Shifted Energy	

Project Outcome:

Develop a prototype behind-the-meter control system that enables existing homes to participate in providing services to the electric power grid using existing legacy home equipment and appliances while being inexpensive and easy for a homeowner or occupant to install and use. The services will help grid operators (e.g., a local electric utility or aggregator) ensure the reliability and resilience of the grid.

Team

Hayden Reeve, Ph.D.
Portfolio Manager, Transactive Systems

Michael Brambley, Ph.D.
Principal investigator

Ke Ma, Ph.D.
Lead, Control and Testing

Jaime Kolln
Lead, Platform Development

Jereme Haack
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Lead, Water Heaters

Alex Vlachokostas, Ph.D.
Lead, Data Curation

Roshan Kini, Ph.D.
Lead, Software Development

Austin Rogers, Ph.D.
Analysis Lead

Challenge

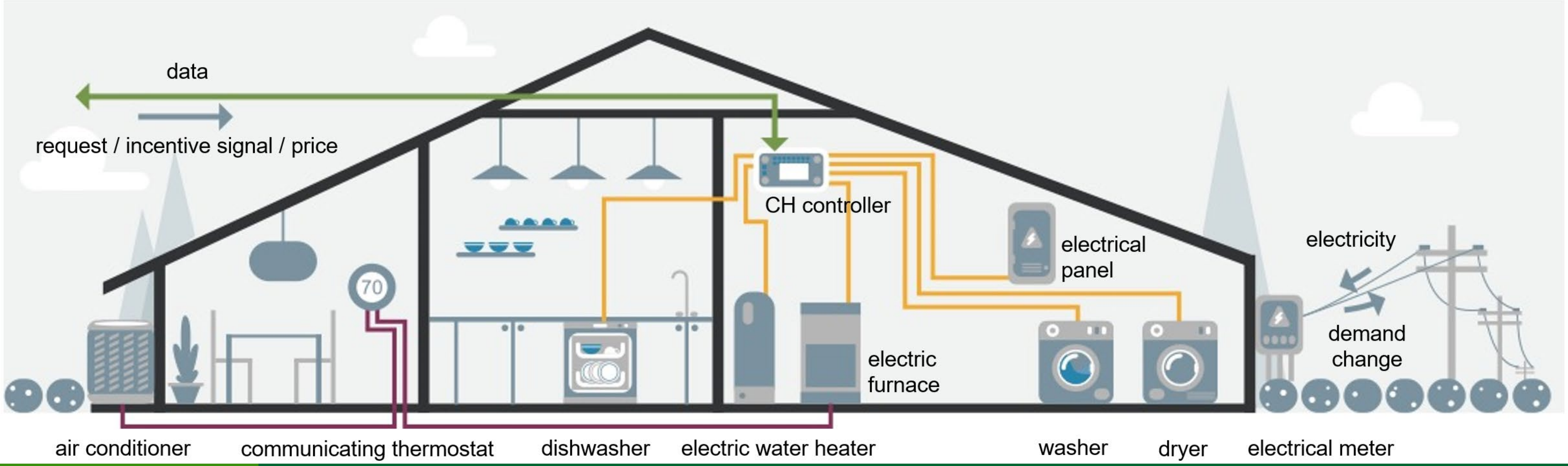
Unlocking the demand flexibility of existing homes for a clean renewable energy system

Problem Definition

- The world is faced with a potentially existential problem—global climate change
- The nation is now committed to a decarbonized future energy system based on increased electrification and 100% clean renewable solar and wind generation
- The variability of these resources though must be managed to ensure a resilient power grid
- Energy storage (like batteries) and demand management are the two primary resources for addressing this variability
- On the demand side, the U.S. has 120 million existing home, which use ~36% of all U.S. electricity
- Nearly all existing homes have non-connected appliances, which are not grid-ready
- Connected appliances have entered the market, but at higher prices
- Many existing homes (~60%) are occupied by low-income to moderate-income households (~42% earn < $40K/y, 58% earn <$60K/y)
- Unlikely to purchase higher-priced connected equipment and appliances
- They are more likely to install a retrofittable solution if the cost is low enough
- Unlocking this large demand management resource

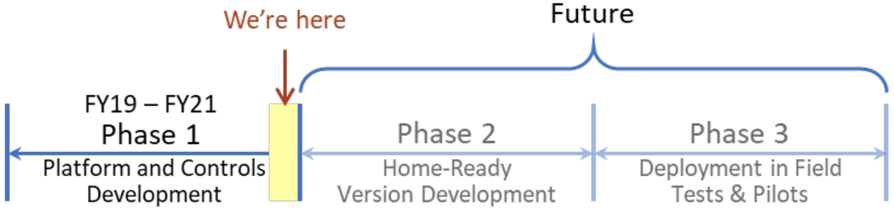
Approach — Solution

- **Solution:** A behind-the-meter control system that enables existing homes *with common (non-connected) equipment and appliances* to interact with the electric power grid to provide grid services in exchange for an incentive (e.g., a more favorable electric rate or an incentive payment).
- **Key design drivers/objectives:**
  - Maximize net value to occupants
  - Lowest possible total cost
  - Automate system set up and configuration
  - Retrofittable
  - Minimize additional new sensors
  - Accommodate each household's preferences for comfort and convenience and when to opt out
  - Control must capture the unique characteristics of homes and their equipment
  - Leverage existing platforms for field deployment
  - Compatibility with different incentive mechanisms and grid services
  - Cyber security best practices

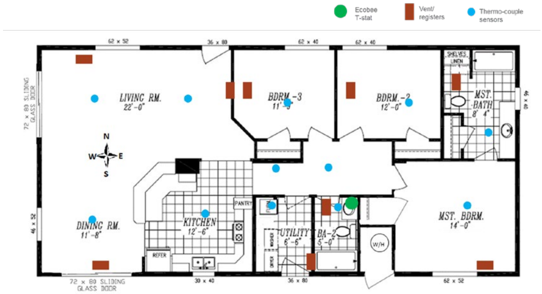


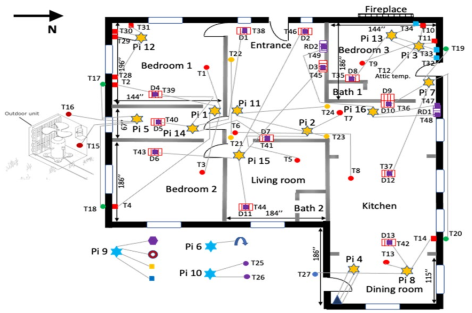
Approach — Overview

- Timeline – Long-Term View of Connected Homes



- Major Tasks
  – Task 1 Device Characterization and Retrofit Adaptation/Development
    - Characterize ERWH Retrofit Devices
    - Adapt existing retrofit device or develop new device
    - Test and verify functionality of retrofit device
  – Task 2 Platform Development and System Integration
    - Enhance, Test, and Maintain the Platform, Device Central
    - System Integration, functionality testing, and enhancement
  – Task 3 Control Development and Testing
    - Model development
    - Develop and adapt control methods
    - Implement control methods as agents in VOLTTRON™-based platform
    - Test control in laboratory and Lab Homes/OU test home
  – Task 4 Stakeholder Engagement – Interactions with DOE, technical advisers, vendors, U. of Oklahoma (OU), and professional/trade organizations, and present and publish results
- Equipment and Appliance Focus
  – Electric resistance furnaces
  – Electric resistance water heaters (ERWHs)
  – Heat pump air conditioning (new control method)
  – Coordinated control of heat pump air-conditioning and electric resistance water heating





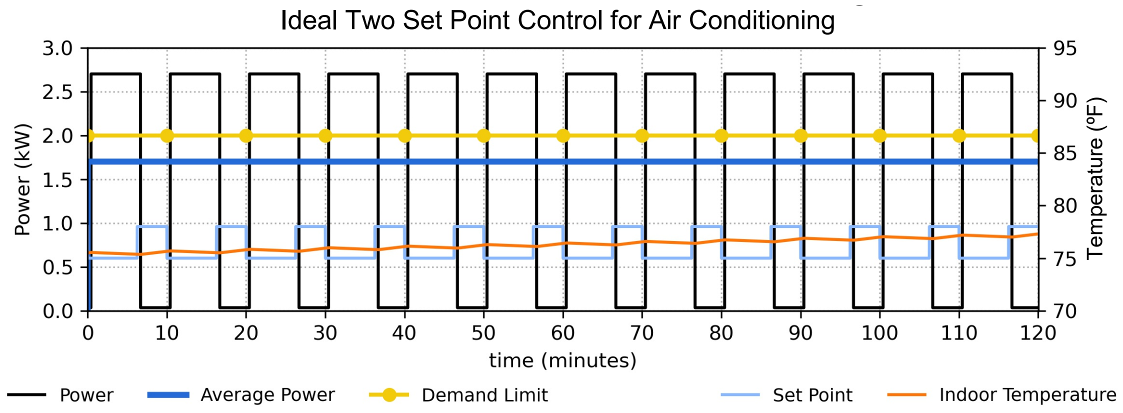
Approach — Technical

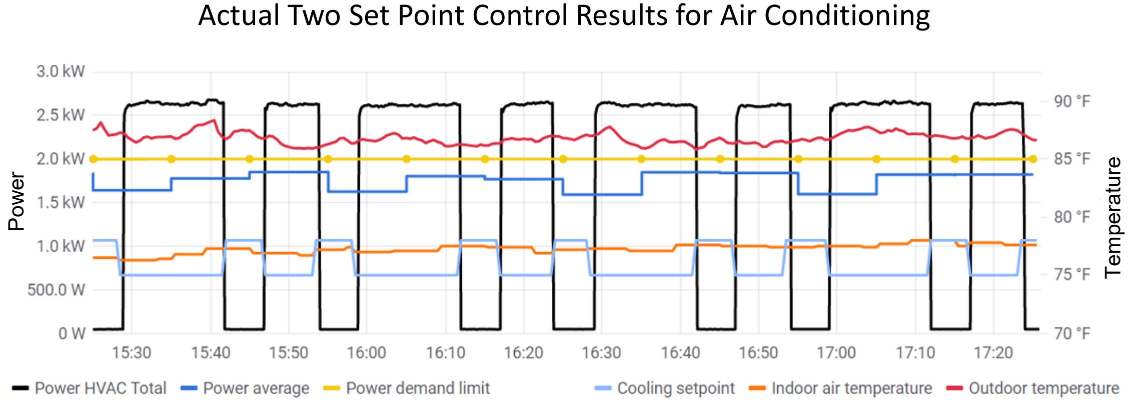
Adaptable control solution: unique to each home, multiple incentives, and multiple grid services

- **Developing a solution usable in multiple ways**
- **Two Set Point Control**
  - Used to achieve a specified demand limit
  - At start of each control interval, calculate **Allowable Run Time** from demand limit and expected operating power

$$\text{Allowable Run time} = \text{Control Interval} \times \frac{\text{Demand Limt}}{\text{Operating Power}}$$

  - **Occupant-driven comfort:** household provides desired temperature and highest acceptable temperature
  - For cooling, these temperatures become respectively a **low set point** to turn the system on and a **high set point** to turn the system off for cooling
  - The algorithm **inherently prioritizes comfort:**
    - The high and low set points represent occupant-established comfort bounds
    - When indoor temperature reaches the high set point (cooling mode), average power in the control interval is permitted to exceed the demand limit to ensure comfort
  - Enhancements can be made to account for:
    - Network and system delays
    - Compressor minimum off time
    - Multiple stages (e.g., sequencers for electric furnace)





Approach — Technical

- **Model Predictive Control for ERWHs**
  - Control scheme that fully exploits the *storage capability* of water heater to shift peak load to off-peak times without sacrificing occupant comfort by anticipating future water draws and electricity price variations
  - ERWH model
    - Lower temperature measurement correlates well with energy in most operating conditions

$$T_{lower}(t + \Delta t) = T_{lower}(t) + \ ae(t) - bf(t) - l$$

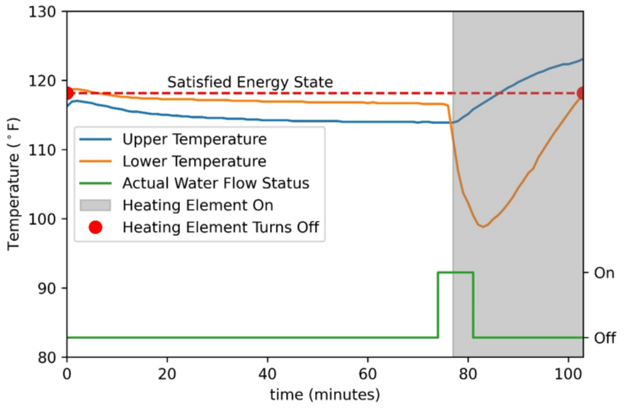
t represents time

e is the electric energy (kWh) used by a resistance heater in the time step indicated

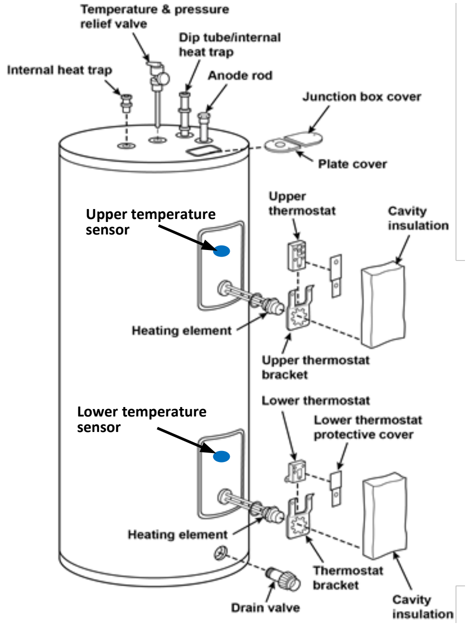
f is the net heat loss (kWh) associated with hot water discharge and cold water entering in the time step Δt

l is the heat loss (kWh) through the water heater wall in the time step

(Figure) An example heating cycle. The temperatures decrease because heat loss occurs as the water heater sits idle; the lower temperature decreases quickly when water is drawn and increases when the heating element is on.



- Model predictive control (MPC)
  - Each time step, optimal energy usage (e*) for the next 24 hours; however, only the solution for the current time step is implemented
  - Requires forecast for water usage and electricity price
  - Optimization



$$\min_{e(t)} \sum_{t=s}^{s+T-1} [\lambda(t)e(t) - cT_{lower}(t)]$$

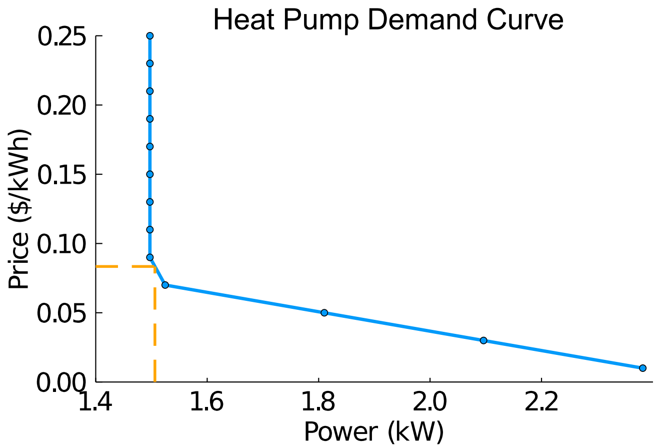
subject to

- water heater model initialized with current measurement
- lower temperature is within the acceptable temperature range

- Implementation
  - Each time step, use an API call to the Shifted Energy retrofit controller to implement the MPC result
  - Note that field deployment could be done with just the lower temperature sensor

Approach — Technical

- **Transactive Coordination of Heat Pump Cooling and ERWH**
  - Heat pump cooling and water heater will respond to the utility price separately if there is *no* physical coupling between the two
  - Utility may impose a demand limit target P_{lim} in addition to the price signal
  - Use internal transactive market to find the *internal* clearing price λ_{clear} under which the sum of heat pump power P_{hp} and water heater power P_{wh} satisfies the demand limit target P_{lim}, when $P_{hp} + P_{wh} \leq P$
  - The internal clearing price will be greater than the price signal from the grid



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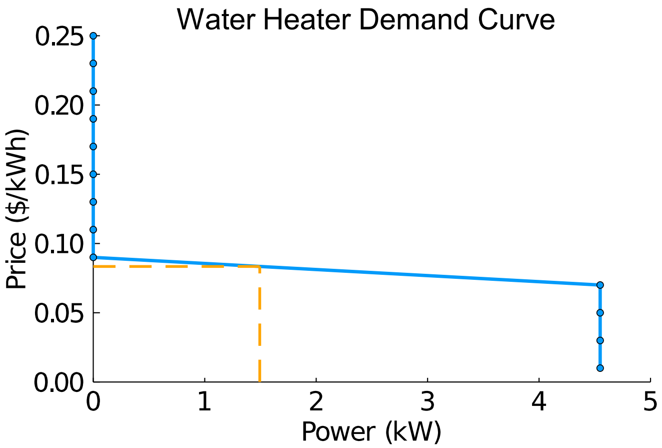

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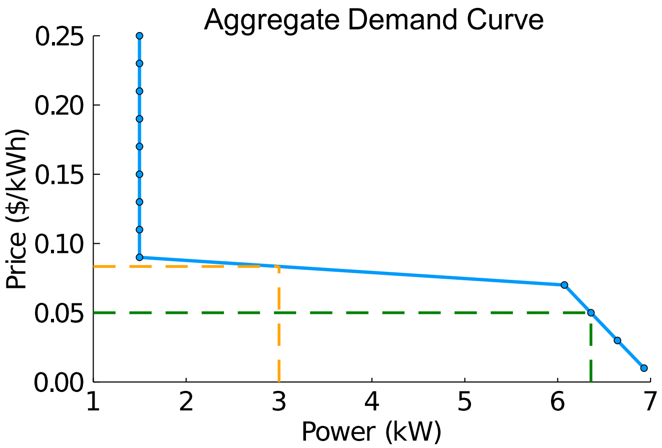


Generate heat pump demand curve given current indoor/outdoor air temperature and occupant preference

Generate water heater demand curve given current lower temperature and water draw prediction

Generate aggregate demand curve by adding the two demand curves horizontally

Let P_{lim} = 3kW. If total power under current utility price ($0.05/kWh) violate P_{lim} (6.36 kW > 3 kW), find λ_{clear} under which the corresponding power = P_{lim}.
λ_{clear} = $0.083/kWh.

Find P_{wh} that corresponds to λ_{clear}.
P_{wh} = 1.49 kW.
Use Shifted Energy API to realize P_{wh}.

Find P_{hp} that corresponds to λ_{clear}.
P_{hp} = 1.51 kW.
Use two-setpoint control to realize P_{hp}.

Impact

Enable 120 million existing homes to provide grid services at low-cost and minimal effort

Impact from unleashing the demand flexibility of the entire existing homes sector!

How project contributes to program goals

- *Modernized infrastructure (higher level goal): Create a more resilient grid.* By providing demand flexibility from the largely untapped existing homes subsector, this project will contribute to modernizing the grid infrastructure.
- *Equity (high level goal): Prioritize addressing long-standing and persistent racial injustice*. By providing a technology for which 40% to 58% of the homes are low- to moderate-income, the outcome will be lower electricity costs from participation in demand management programs
- *Economy-wide emission reductions of 50% in 2030 and carbon-free electricity generation by 2035* will benefit from demand management by existing homes balancing the variability of much more wind and solar generation
- *Grid-interactive efficient buildings (GEBs) Goal: Triple the energy efficiency and demand flexibility of the buildings sector by 2030*—Solution will contribute by greatly enhancing demand flexibility contributions to the grid by enabling the existing buildings sector to provide grid demand flexibility much sooner (i.e., in the next few years) than feasible through new connected appliances/equipment procurements alone

Comparative advantages & why the solution represents enhancement over state of the art

- Will enable 120 million existing homes with legacy appliances/equipment to participate in providing grid services
- Adaptable to multiple demand management programs providing many different grid services: energy services, peak load reduction, grid balancing services, frequency regulation

Impact

Comparative advantages & why the solution represents enhancement over state of the art (continued)

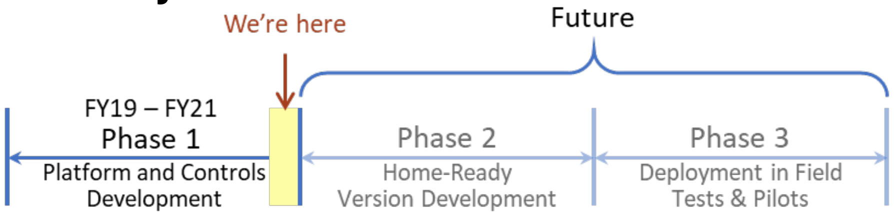
- Compatible with several incentive mechanisms
  - Current: time-of-use prices, real-time prices, critical peak prices, demand limits
  - Future: carbon responsive signals, day ahead energy markets, shorter time interval signals including for frequency regulation
- Control respects occupant preferences (e.g., acceptable indoor temperatures)—enhances acceptance by households
  - household determines how much to adjust demand, when, and for how much reward
- Automatic set up and configuration to customize for each home and lower set-up costs
- Lower cost retrofit solution for low- and moderate-income homes compared to purchase of new connected appliances
- Promotes a whole-home approach to demand management rather separate programs for individual appliances, giving more flexibility to households
- Provides the grid an additional end-user sector—existing homes--from which to obtain services

How the potential impact will be realized (future, not yet funded)

- Testing in unoccupied test homes (funded current work)
- Initial proof of performance through testing in 10 to 20 occupied homes using simulated signals
- Pilot of 100 to 500 existing homes to validate at scale partnering with vendor, utility, and/or aggregator
- Market introduction and scaleup to pilot with > 1000 homes in collaboration with utility or aggregator and a vendor
- Commercialization activities by PNNL Technology Deployment and Outreach Office including IP licensing

Progress

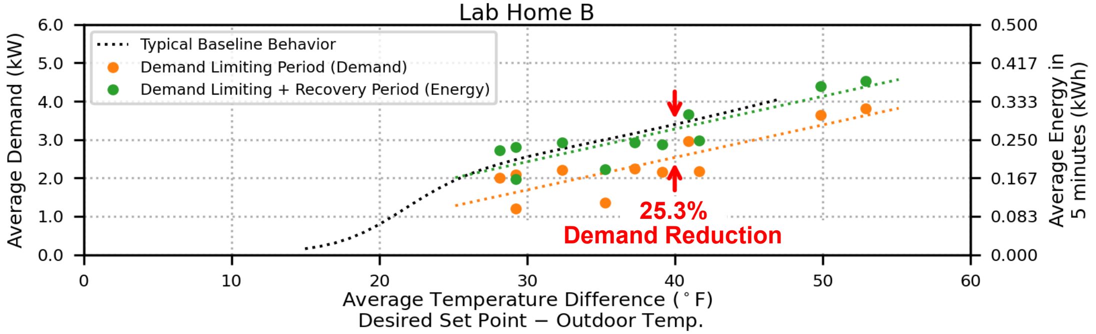
Stage of Project



- **Current scope: Late-stage**
- Phases 1 - 3: Mid-stage

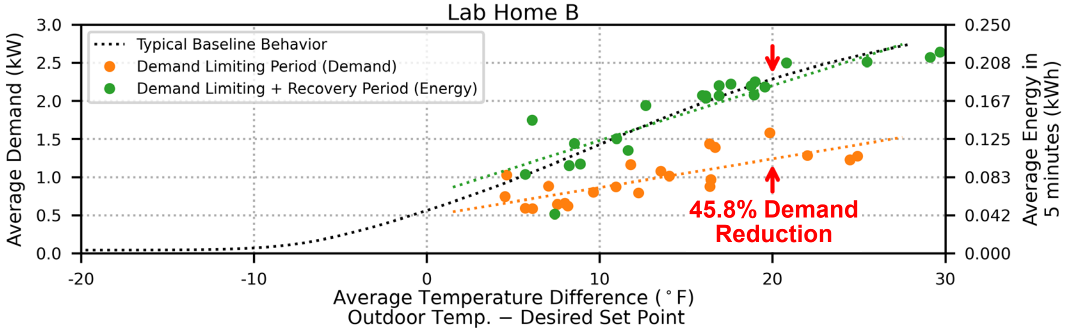
Accomplishments

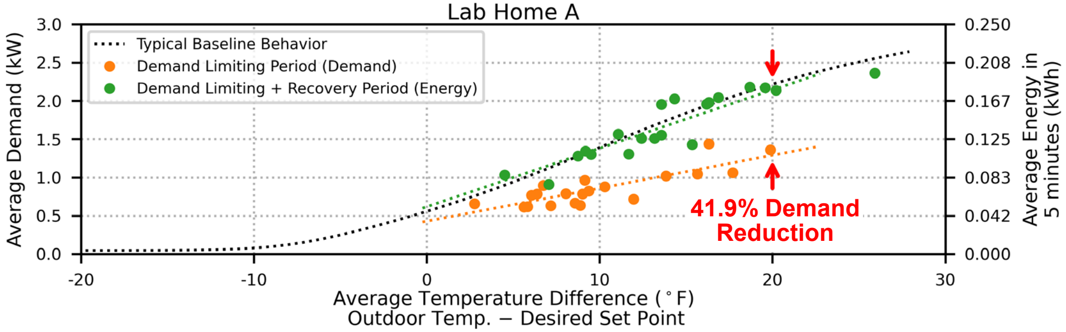
- **Completed Two Set Point Control Development and Testing for Electric Furnaces (March 2021)**
  - Estimated **average demand reduction = 25.3%** compared to baseline for ΔT = 40ºF in 4-hour tests
  - Average energy impact ≈ 0
  - Tests have also been run for real-time and TOU price signals



Accomplishments (continued)

- **Completed Development and Testing of Two-set point Control for Heat Pump Cooling** (**June 2021**)
  - Improved control over model-based control using predicted indoor temperature
  - Average demand reduction is 45.6% for Lab Homes B and 41.9% for Lab Homes B at ΔT = 20ºF in 4-hour tests
  - Consistently meets demand limit, exceeding the limit on once per hour

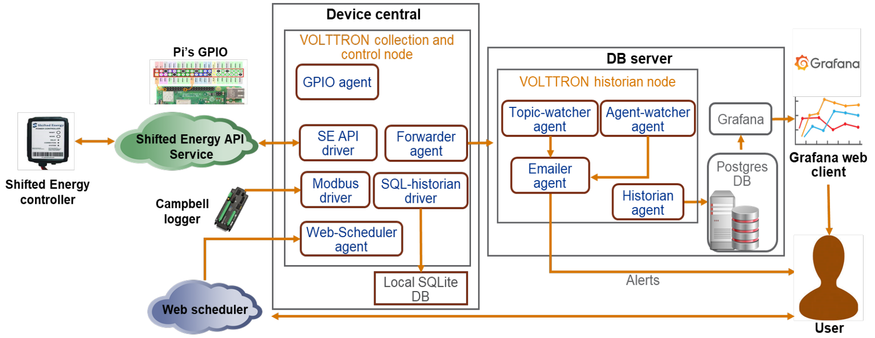




Progress

Accomplishments (continued)

- **Completed design/installation/set up of water heater test bed in PNNL laboratory (October 2020)**



  – Tests can be set up and run remotely according to a combination of a schedule and conditionals for initial conditions
- **Completed installation of water heater testing apparatus in both PNNL Lab Homes (July 2021)**
  – Identical design as laboratory installation except two discharge points—one of two showers and the kitchen sink—can be automatically controlled for hot water discharge.
  – The U. of Oklahoma test home has an installation without the discharge points controlled

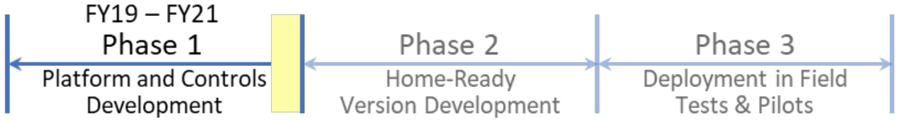
Accomplishments (continued)

- **ERWH originally planned laboratory control testing completed (July 2021)**
  – Example Results

  – Note: All FY2021 water heater milestones were delayed as a result of significant vendor delays in delivering information, software, and hardware.
- **Additional laboratory testing under different conditions is now planned through mid-September**

Stakeholder Engagement

- **Stage of Project**



  - **Current scope: Late-stage**
  - Phases 1 - 3: Mid-stage

- **Active Stakeholders**
  - ecobee:
    - Developed real-time access to 30-second and 1-minute thermostat data and provided technical support for the last 1 ½ years.
    - Leader in smart thermostats behind only Nest in fraction of the market.
    - ecobee thermostat was selected for use in Connected Homes (CH) development and testing because of its large number of adjustable parameters, their significant market presence, and willingness to provide enhanced capabilities in support of the project
  - Shifted Energy (SE):
    - SE's Ara water heater controller was selected as a commercial device on which to build the water heater control capability based on the characteristics of the controller and interface with ERWHs
    - SE has provided access to Ara functions not ordinarily exposed, enhancements for higher time resolution data, and activation of PNNL control signals.
    - SE provides services to Hawaii Electric Company (HECO) to help it navigate the clean energy revolution—specifically control for residential and commercial equipment and appliances to support the electric power grid

ecobee

SHIFTED ENERGY

The UNIVERSITY of OKLAHOMA

Stakeholder Engagement

- **Active Stakeholders (continued)**
  - The University of Oklahoma:
    - Performing tests under subcontract on the CH control for equipment to characterize its performance in the university's test home in a warm humid summer climate and moderate winter climate
- **Other Stakeholder Interactions**
  - Consortium for Energy Efficiency (CEE)
    - Connected Homes staff attend semi-annual program meetings of the CEE and meetings of the Connected and Integrated Homes committees between the semi-annual ones.
    - Provide opportunities to learn about CH related activities of CEE, utilities, other researchers, and some vendors and network with their representatives.
  - ASHRAE
    - As a past Chair and current corresponding member of ASHRAE Technical Committee, TC 1.5 Smart Building Systems, Mike Brambley attends subcommittee and full committee meetings, which include discussions and committee activities on GEBs and the smart grid.
    - Mike Brambley chaired three seminars at ASHRAE Winter and Annual Conferences on various aspects of GEBs over the last two years including topics about impacts on energy use, efficiency, demand reductions, and comfort.
    - PNNL CH core team member, Austin Rogers presented on "Demand reduction and Energy Impacts in Grid-interactive Homes" in one of these seminars of the ASHRAE Virtual Annual Conference in June 2021.
  - Company contacts: PNNL has been exploring relationships with several companies for the purpose of identifying development and commercialization partners for potential future work.
  - Plan to propose a stakeholder workshop on key needs for enabling existing homes and equipment to become grid interactive

Remaining Project Work

FY2021 Remaining Work

- Complete delayed ERWH platform milestones
- Complete testing of coordinated control of heat pump air conditioning and ERWH water heating – Final milestone for FY2021
- Perform additional laboratory testing of ERWH control for additional situations (through mid-Sept.):
    - several sequential days of operation
    - impact of “unscheduled” hot water draws
    - and others
- Complete initial work on selected automated set up capabilities
    - automated determination of equipment performance characteristics & learning home water draw patterns
- Document control methods and test findings in presentations and papers (September/October)

Elements of Future Vision

- Phase 1: Platform and Controls Development
    - Two set point control for heat pump heating
    - MPC control for heat pump cooling and heating for load shifting
    - Carbon-responsive controls (with NREL)
- Phase 2: Home-Ready Version Development
    - Stakeholder workshop
    - Develop and integrate priority capabilities
    - Commercialization efforts
- Phase 3: Testing and demonstration with collaborators in Field Tests and Pilots

Thank You

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REFERENCE SLIDES

Project Budget

Project Budget: Total DOE funding received over 3-years is $3.87M.
Variances: In FY21, project has been spending within 6% of plan.
Cost to Date: : ~$3.4M has been costed to the project to date, with ~$.5M remaining to wrap-up the project.
Additional Funding: At this time, future funding is unknown.

Budget History					
FY 2019 – FY 2020 (past)		FY 2021 (current)		FY 2022 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$2.87M	$0	$1M	$0	TBD	TBD

Project Plan and Schedule

Project Schedule												
Project Start: 10/1/2018	Completed Work											
Projected End: 10/31/2021	Active Task (in progress work)											
	Milestone/Deliverable (Originally Planned)											
	Milestone/Deliverable (Actual)											
	FY2019				FY2020				FY2021			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
Product requirements document												
Advisory committee established												
Characterizations of electric furnaces, electric-resistance water heaters, and smart thermostats complete												
Device Central enables local communication with thermostat												
Development and testing of electric furnace control completed												
Development and testing of heat pump cooling control completed												
Current/Future Work												
Water heater retrofit device adaptation or development completed*												
Retrofit solution for legacy water heater integrated into control system platform*												
Testing of ERWH control completed*												
Testing of coordinated control of ERWH and heat pump cooling completed*												

*All milestones related to water heaters were delayed significantly as a result of significant vendor delays in delivering information, software, and hardware.