A Scalable Hardware-and-Human-in-the-Loop (HwHuIL) GEB Building Equipment Performance Dataset

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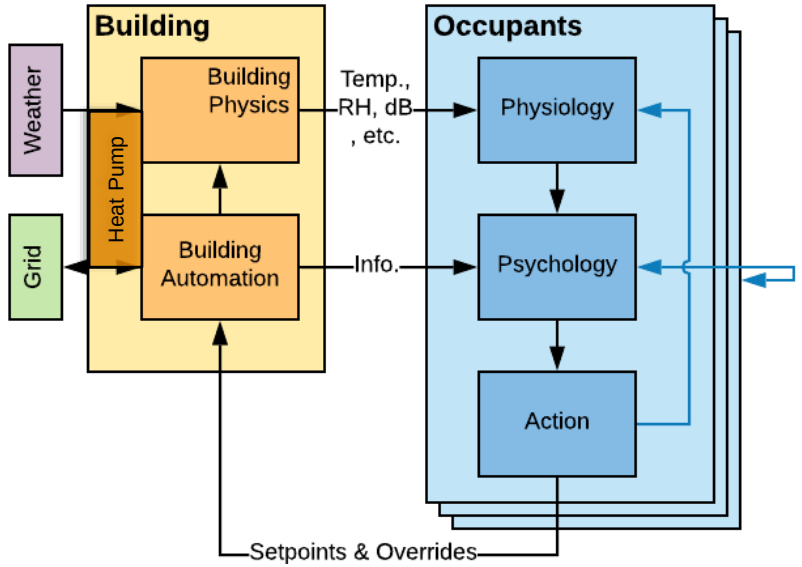
Project Summary

Objective and outcome

Human-in-the-loop (HuIL): A dataset of 20 homes in two climate zones for training models of occupant behavior for GEB control development

Hardware-in-the-loop (HwIL): A dataset of two heat pumps for training nonlinear dynamic models of heat pumps for GEB control development



Team and Partners

NEU: Dept. of Civil & Environmental Engineering, School of Architecture, College of Computer Science, College of Health Sciences

NREL: Residential Systems Performance Lab (SPL)

ecobee: data and cost share provider

Packetized Energy: Acquired

Stats

Performance Period: 4/1/2020 to 8/31/2024

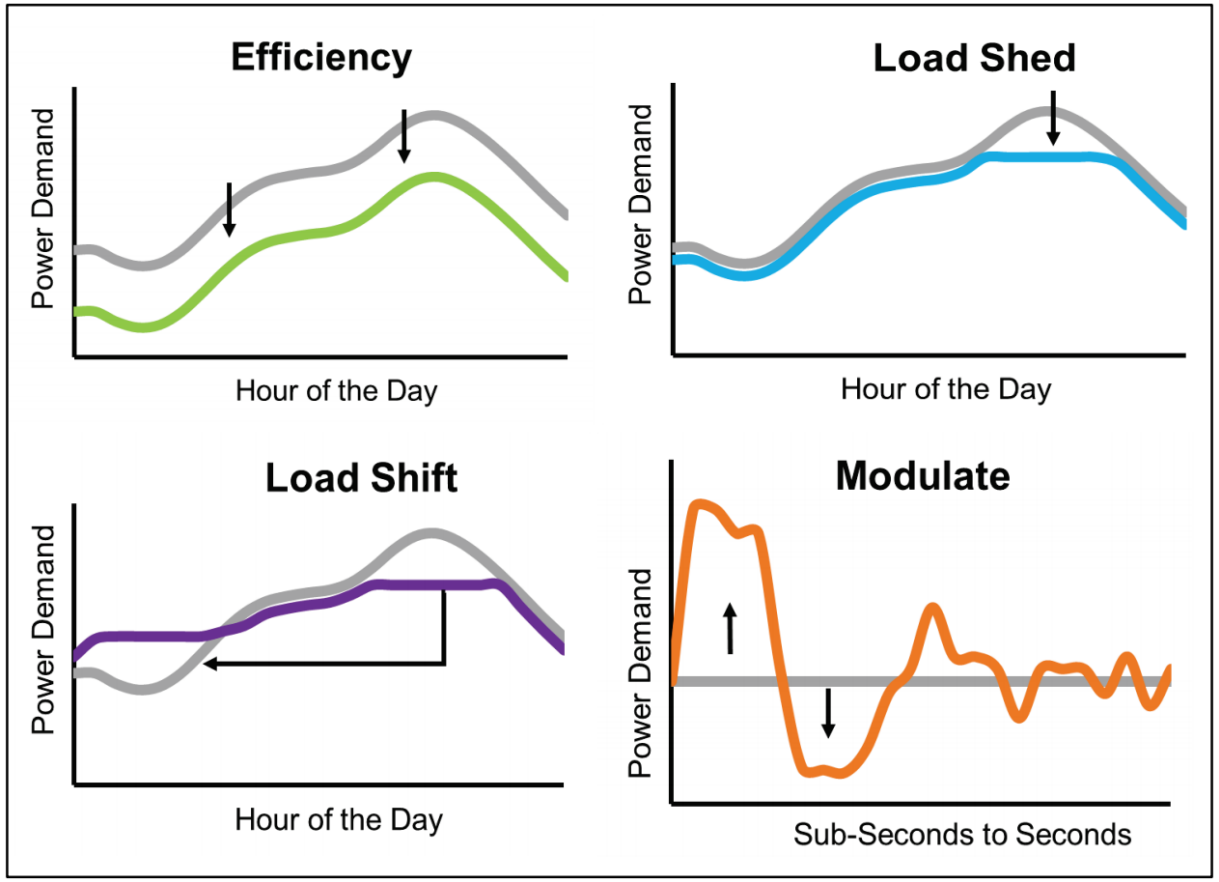
DOE budget: $1,752k, **Cost Share:** $563k

Go/No-go 1: IRB approval and 20 homes recruited

Go/No-go 2: Lab validation of HuIL GEB controls

Go/No-go 3: Publish HwIL and HuIL open datasets

Problem: Grid-interactive Efficient Buildings



Impact of Load Flexibility:
By 2030, the benefits of load flexibility could exceed **$15 billion/year** in US [2]

Need for Reliability:
Annual penalties assessed to DR resources: **$13 Million in 2010/2011** [1]

State of the Art
Utility remotely adjusts thermostat setpoints to modify load of HVAC

Same setpoint changes applied to all participants [3]

[1] PJM LLC, "Load Management Performance Report," Aug. 2018.
[2] R. Hledik, "The National Potential for Load Flexibility: Value and Market Potential Through 2030,"
[3] Seiden K, Olig C, Max D, Sherman M. National Grid Smart Energy Solutions Pilot - Final Evaluation Report. Worcester, MA: Massachusetts Electric Company and Nantucket Electric Company d/b/a National Grid; 2017
[4] US. Department of Energy, Grid-interactive Efficient Buildings: Overview

Problem

Coupled Grid-HVAC-Occupant system

Grid services, HVAC equipment, and occupant behavior are coupled: thermostat ↔ energy

Heat pump transients are poorly modeled

Unmodeled transitions between steady states (SS) in state of the art (SoA) quasi-SS heat pump models may last ~15min.

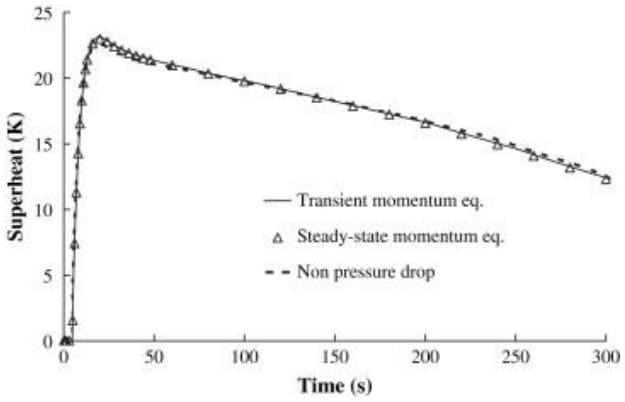
Occupant behavior is inherently dynamic

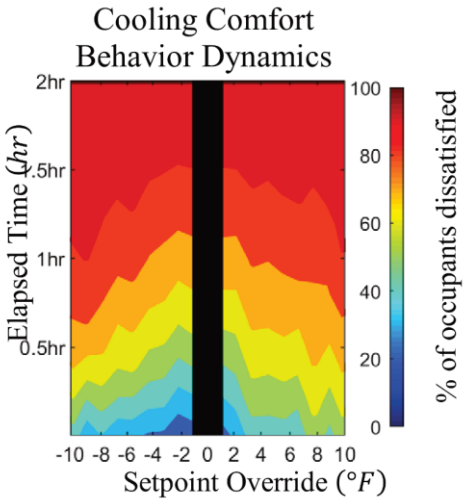
User overrides may occur w/in 15 min.

Penalties due to overrides are >$5M/yr

Heat pump Evaporator Outlet

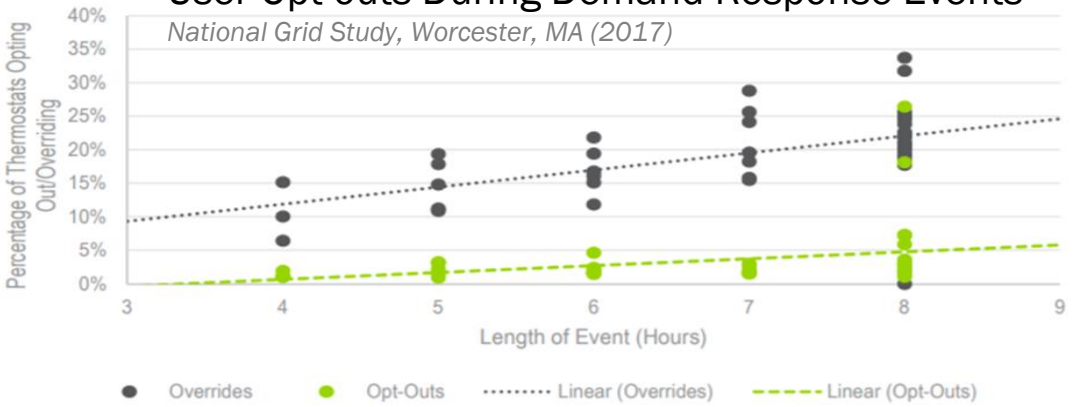
*Zhang, W, et al. **Intl. J. of Refrigeration**, Aug 2009*





User Opt-outs During Demand Response Events

National Grid Study, Worcester, MA (2017)



Alignment and Impact

Impact

Currently ~75M US households with central air.

Increase flexibility, reduce overrides, and increase market through GEB occupant centric control for heat pumps developed with project's datasets

A ~40GW increase in load flexibility w.r.t. SoA at an installation and retention costs of ~$50/pp/yr

Deliverables

HwIL dataset *of HP performance providing grid services in multiple homes, climate zones, and grids.*

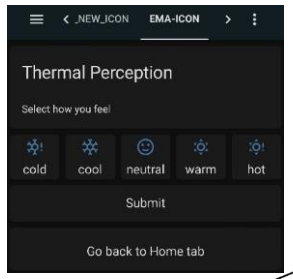
Replace current steady-state models for performance simulation and control

HuIL dataset *of 20 homes in two climate zones with providing different grid services*

Replace current steady-state comfort models with dynamic behavior models for performance simulation and control

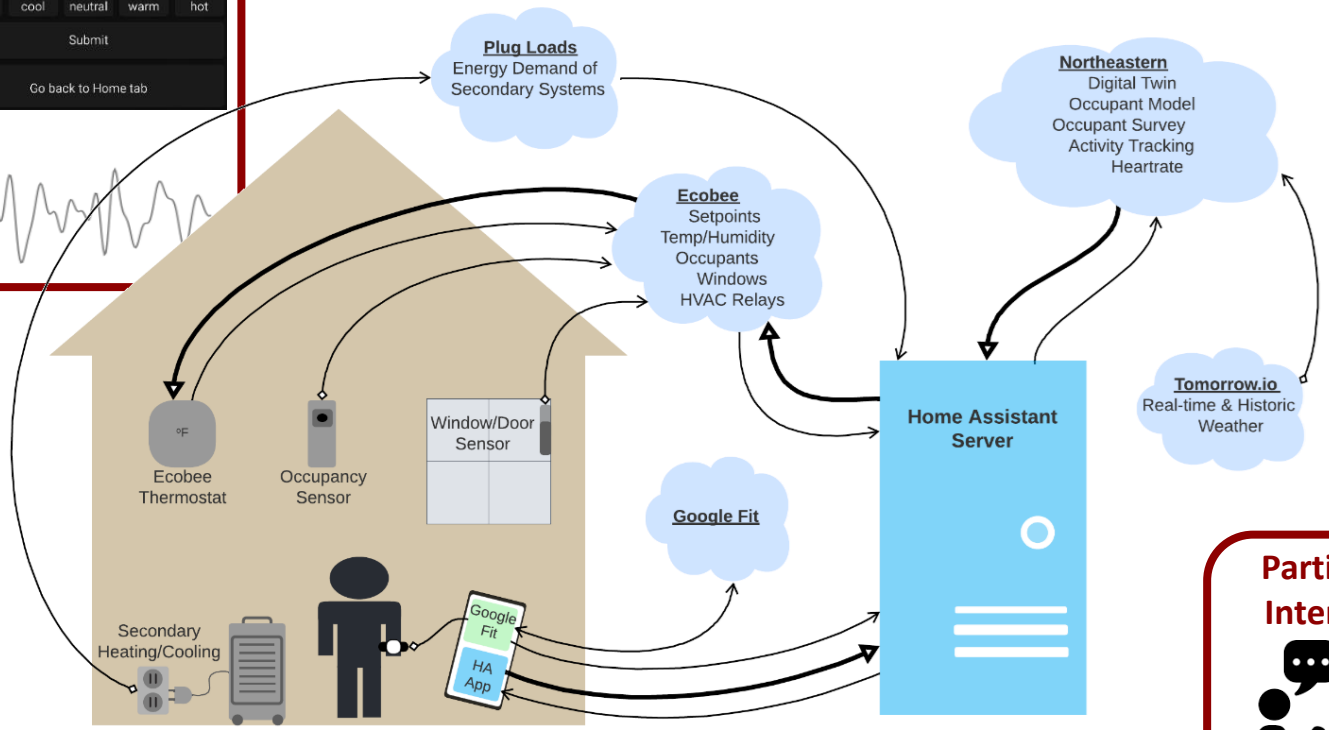
Approach: HuIL – Whole Energy Homes

Just-in-Time Micro-Surveys



20+ homes in multiple regions

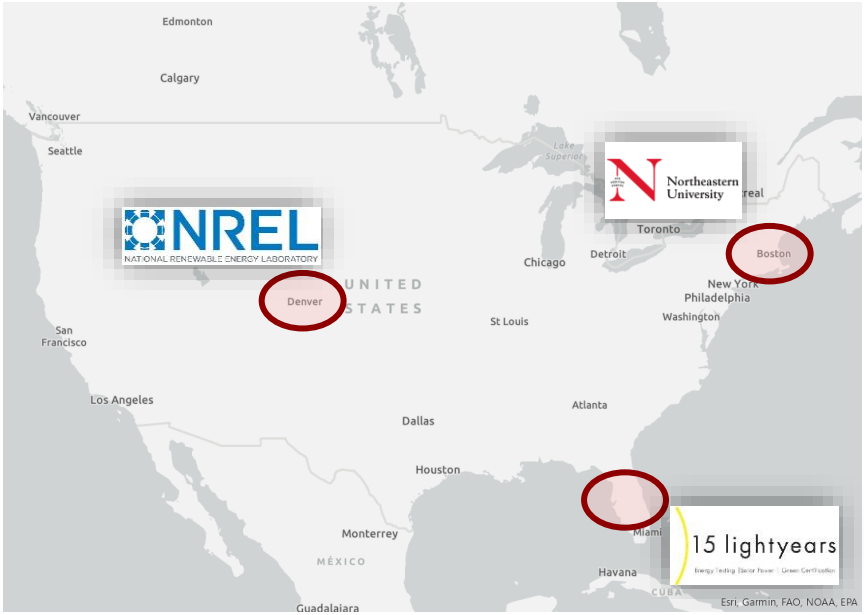
- Single-family detached
- Forced-air heating and cooling systems



Two-year duration

- Participant Interview & Initial Documentation
- Phase 1 – Monitoring
  - *Completing Boston/Denver in May '23*
  - *Starting Orlando in June '23*
- Phase 2 – GEB

Participant Interviews



Approach: Hardware in the Loop simulation

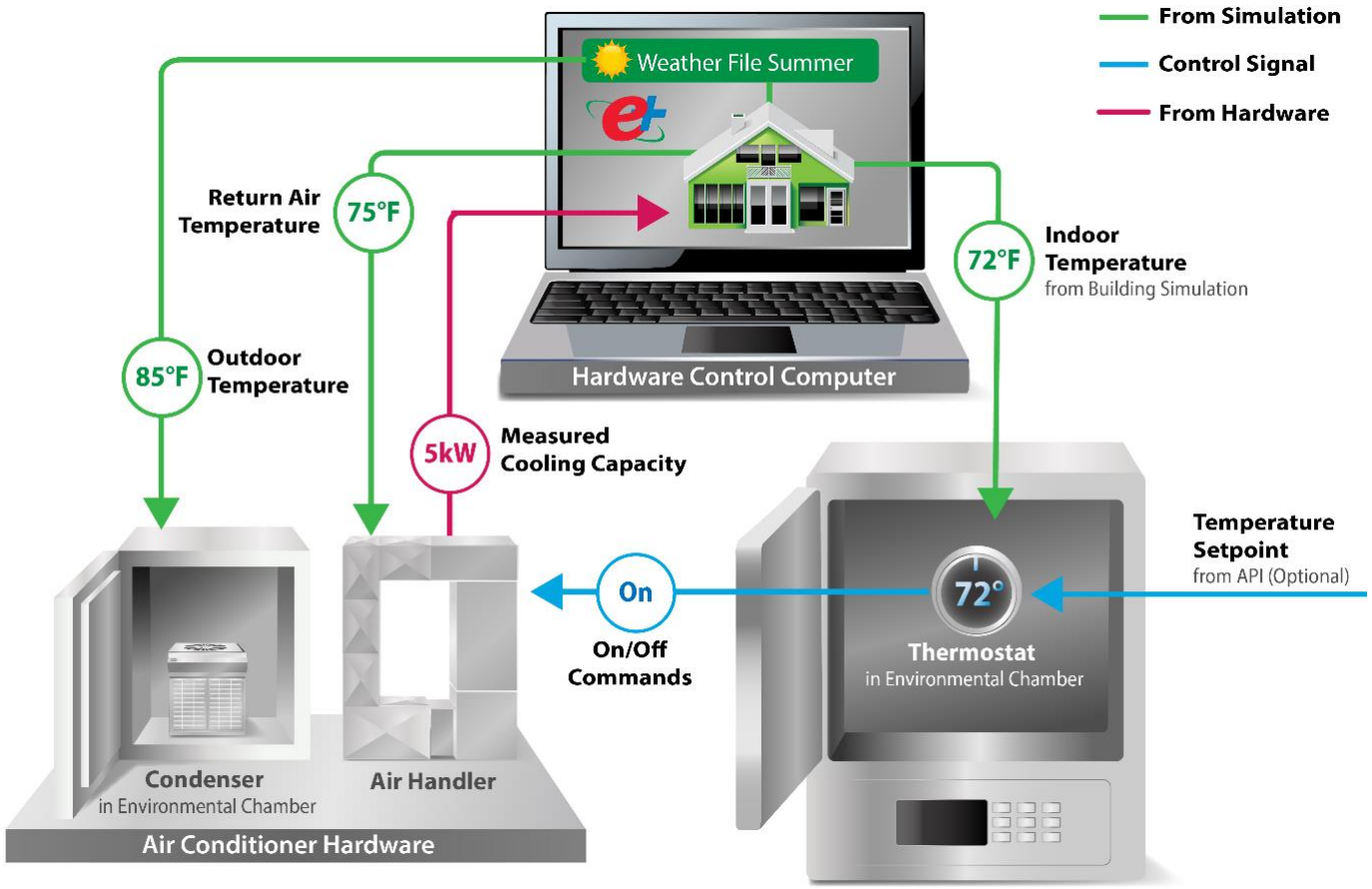
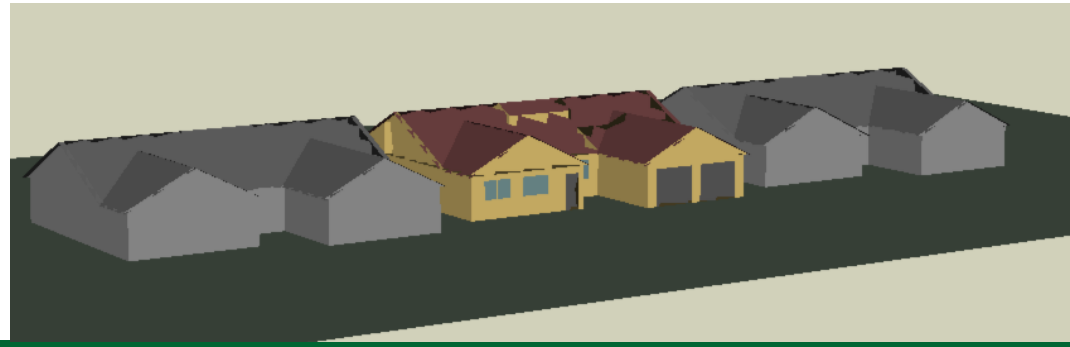


Fig. HVAC HIL Experiment Architecture

Fig. Hardware installed in SPL for HIL experiment

Approach: Hardware in the Loop 'Ground Truth'

- Greenbuilt retrofit laboratory house
  - Joint effort between Greenbuilt Construction and NREL (Sparn et al. 2014)
  - All-electric, 1980s era house in the eastern Sacramento suburb
  - Retrofitted with cost-effective energy efficiency measures
  - Heat pump and air distribution system, PV array
  - Control4 home control system
  - Small space heaters to simulate occupancy and sensible heat gains
- Field results from Greenbuilt retrofit test house (2010) are used for HIL validation



Sparn, B., et al. 2014. "Greenbuilt Retrofit Test House Final Report." Golden, CO: NREL. https://www.nrel.gov/docs/fy14osti/54009.pdf.

Approach: Commercialization Path

The HwHuIL Open Dataset

- NREL's laboratory HwIL data and field HuIL data from homes will be published openly on OpenEI, and likely other relevant data repositories
- The data will be disseminated and publicized, including among Annex 79 & ASHRAE MTG-OBB

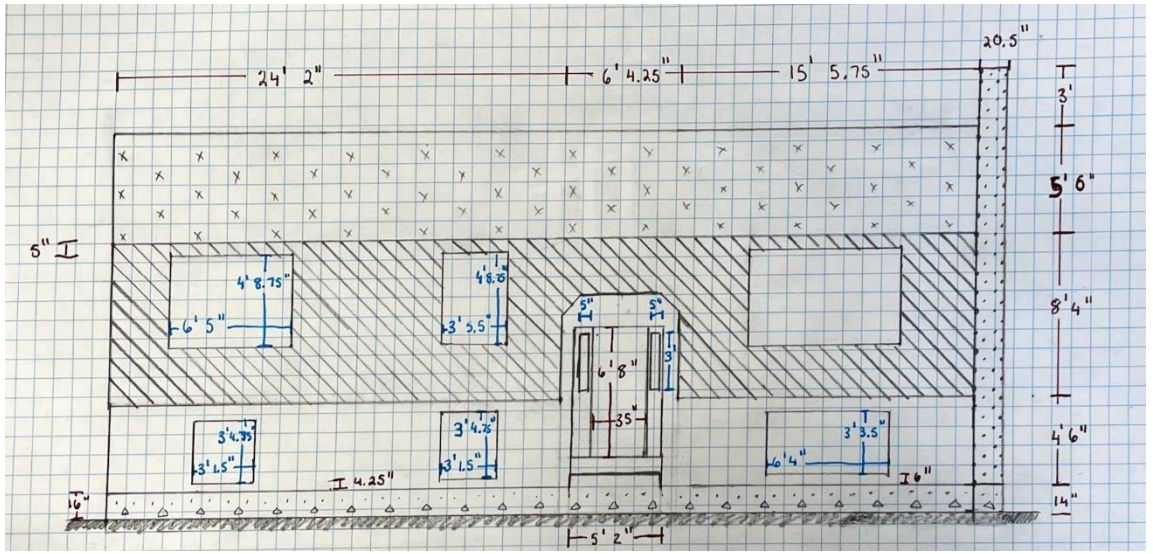
Heat-pump Models

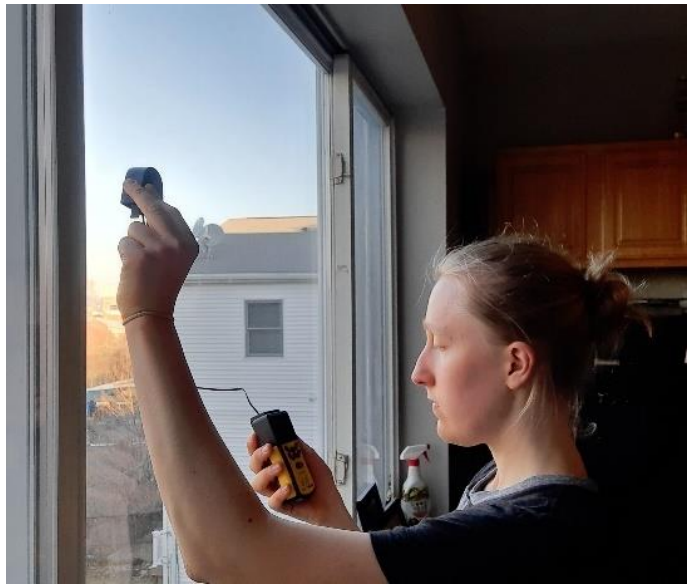
- NREL & NEU will engage with 3rd party heat-pump manufacturers to use methods developed in the project to characterize their device's abilities to provide grid services and improve controls
- ecobee will be engaged throughout the project, in design and advisory roles, with the goal of integrating the approaches into their technology and market plans.

Occupant Behavior Models

- The HuIL thermal AR approach may be scaled to a 500+ ppl as a follow-up with ecobee beta testing pop.
- ecobee will be engaged throughout the project, in design and advisory roles, with the goal of integrating the approaches into their technology and market plans.

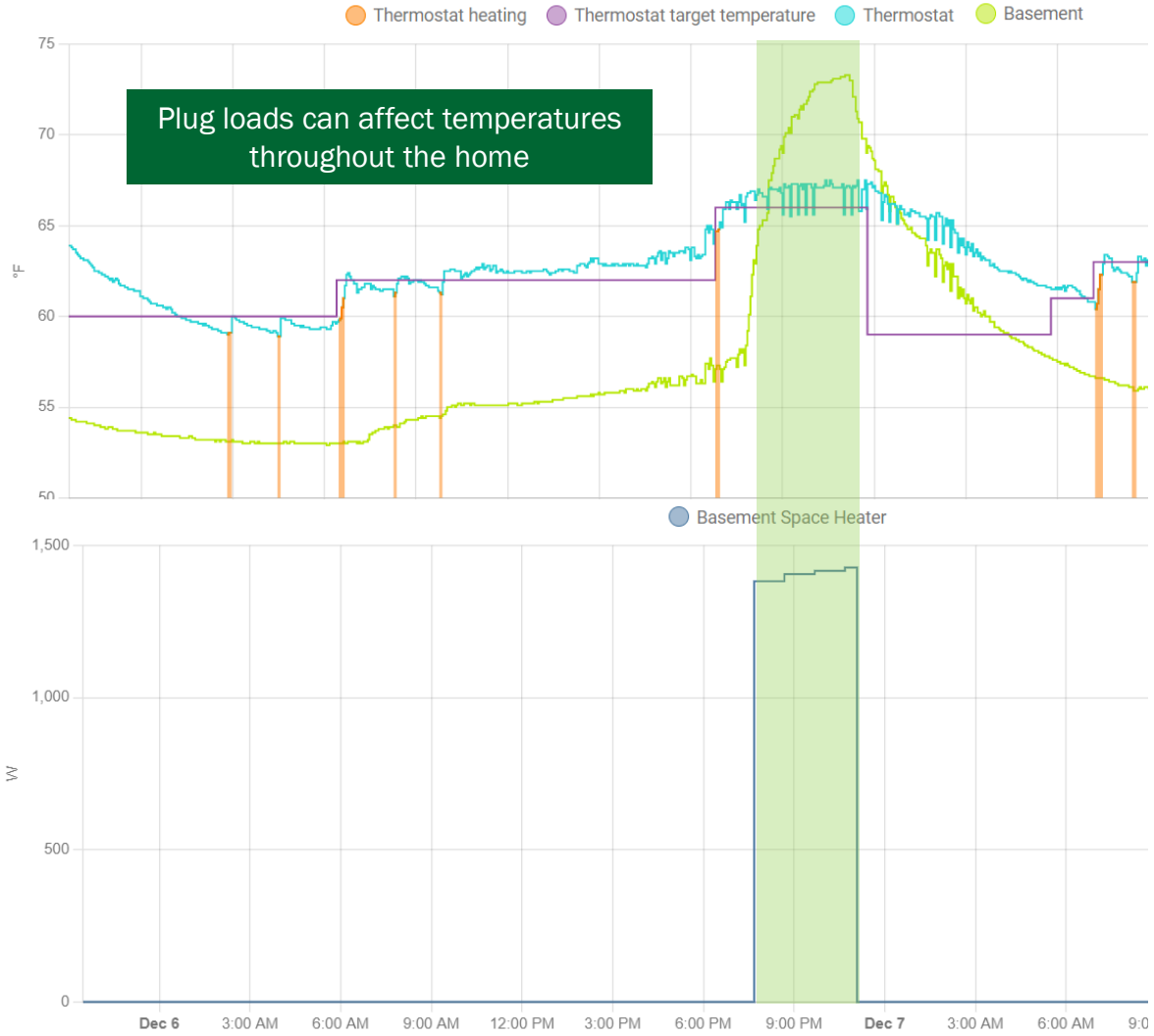
Progress: Installation, Documentation, & Energy Audit





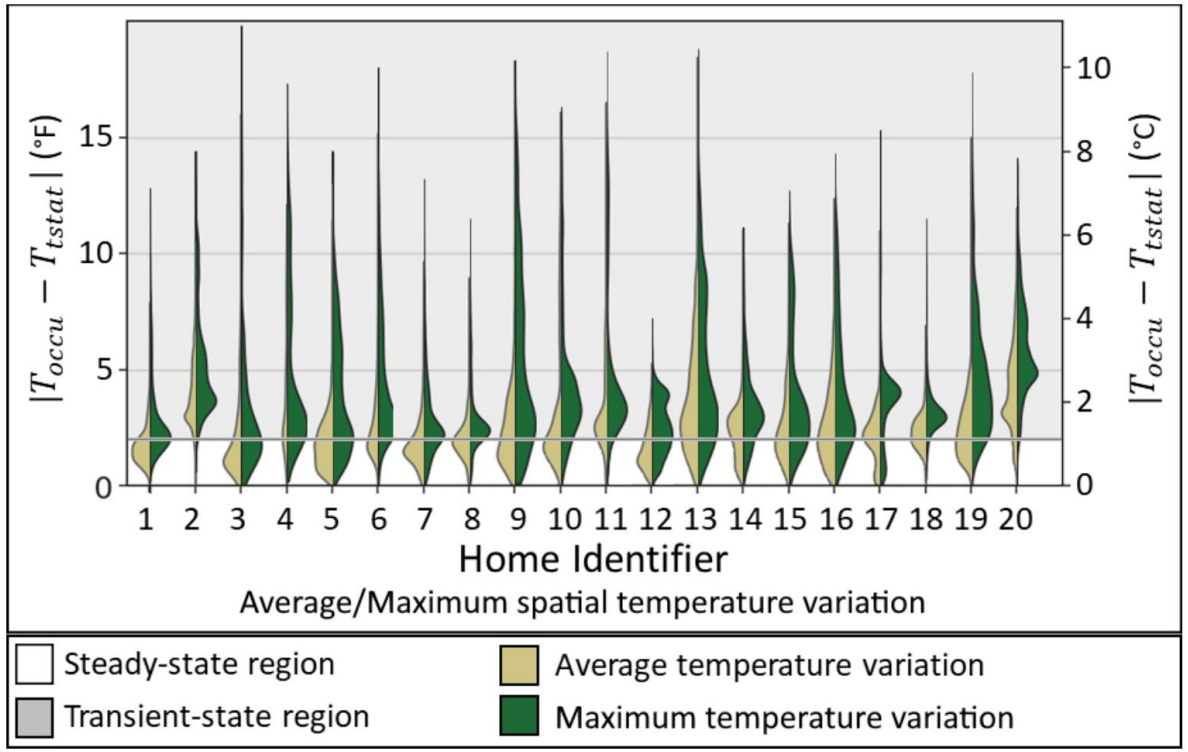
Progress: Temperature Variations & Plug Loads

Temperature & Plug Load Data



Spatial Temperature Variations in Homes

Remote sensors compared to thermostat temperature



The thermostat alone cannot predict occupant comfort depending on where they are in their home.

Progress: Occupant Comfort and Behavior

Responses Compared to ASHRAE 55 Prediction

Steady state ASHRAE 55 Adaptive Comfort Model

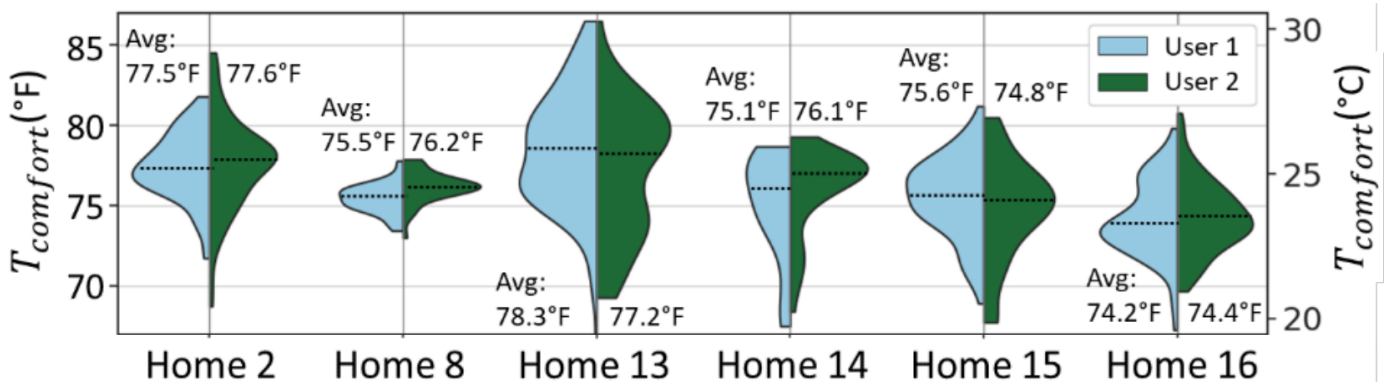
		Predicted: Within 80% Acceptability Limit (Negative)	Predicted: Outside 80% Acceptability Limit (Positive)	Total
Actual	**Satisfied Votes** (Negative)	71.78% N=1,071	15.35% N=229	87.13% N=1,300
Actual	**Dissatisfied Votes** (Positive)	10.12% N=151	2.75% N=41	12.87% N = 192
	Total Votes	81.90% N=1,222	18.10% N=270	100% N_{total}=1,492

Predicts comfort well (accuracy = 0.75), but poorly predicts discomfort (F1 = 0.18)

*For GEB controls, it is important to accurately predict **discomfort** that drives overrides*

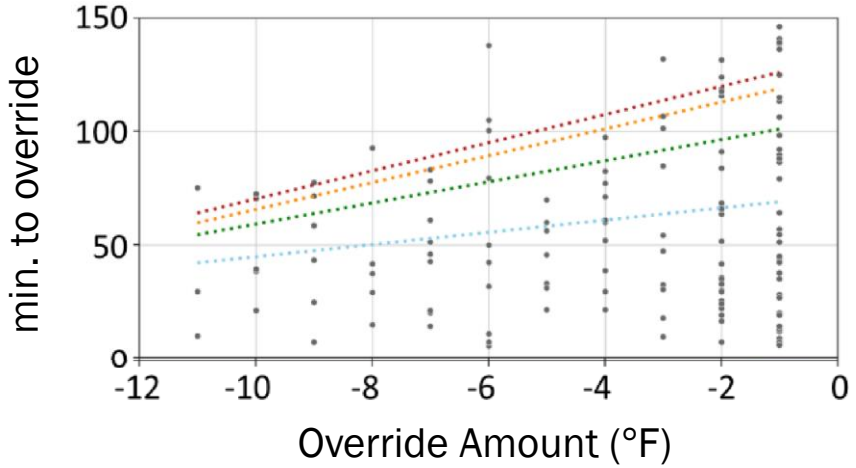
Just-in-time Survey Responses

Temperatures that respondents answered "just satisfied", "satisfied", or "extremely satisfied"



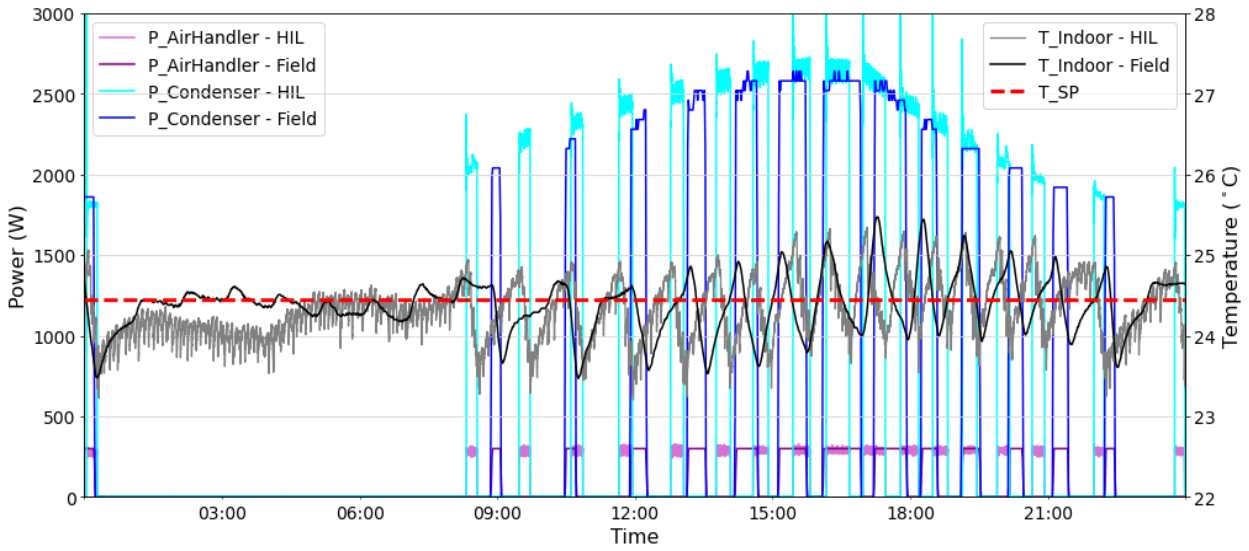
Occupants' comfort temps. are similar within homes, but very between homes

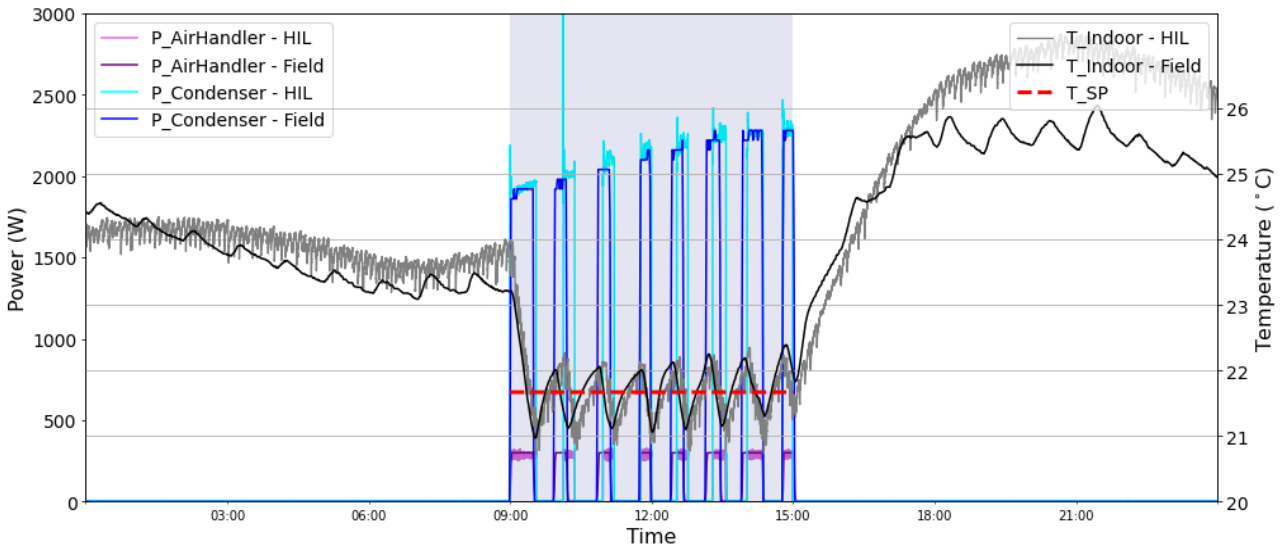
Thermostat Override Dynamics



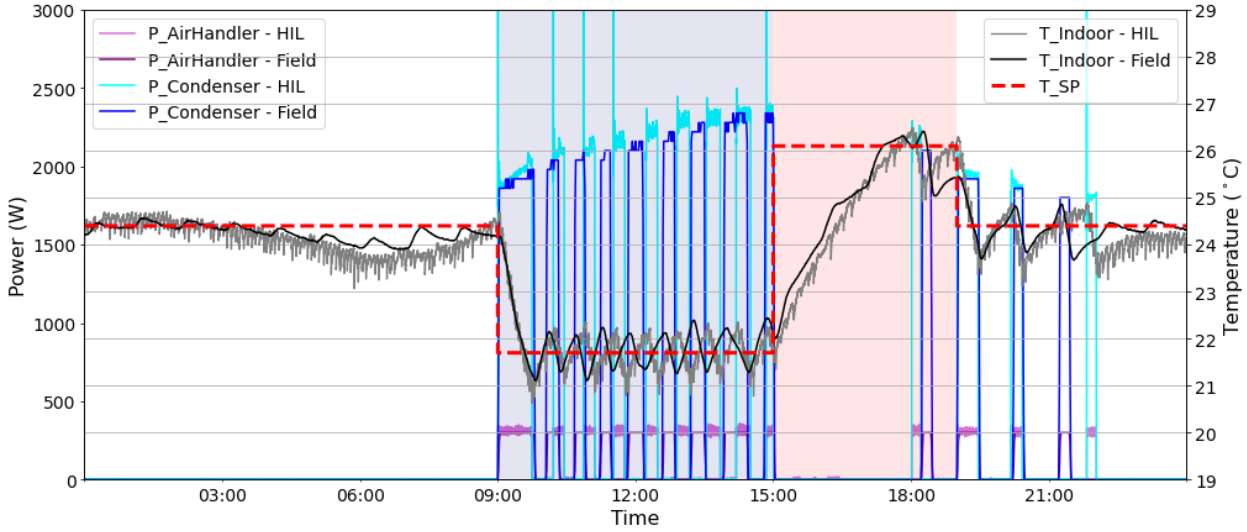
Larger automated setpoint changes are overridden faster

Progress: HwIL Benchmarking – HPs and GEB





HwIL testbed can accurately simulate HP energy under different conditions and different homes



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

Key Findings & Future Work

Human in the Loop

- **Key Findings & Results**
  - Spatial temp. variations in homes necessitate remote sensors for DR *(can't use only t-stat to model comfort)*
  - Occupant behavior is dynamic *(depends on history and rates)*
- **Future Work**
  - **May '23**: MA&CO start simulating DR in
  - **May '23**: FL deployments
  - **2024+**: Scale deployments and develop ML behavior models *(NSF CAREER award 2047317)*

Hardware in the Loop

- **Key Findings & Results**
  - HwIL platform can emulate real home HP hourly energy use within ~5%
  - t-stat algorithms drive HP energy time-of-use on 5-min. scales more than the HP
- **Future Work**
  - **Q3 '23**: NREL HwIL sys. cold climate upgrade
  - **Q4 '23**: NREL HwIL tests to inform NREL HP modeling team

Thank You

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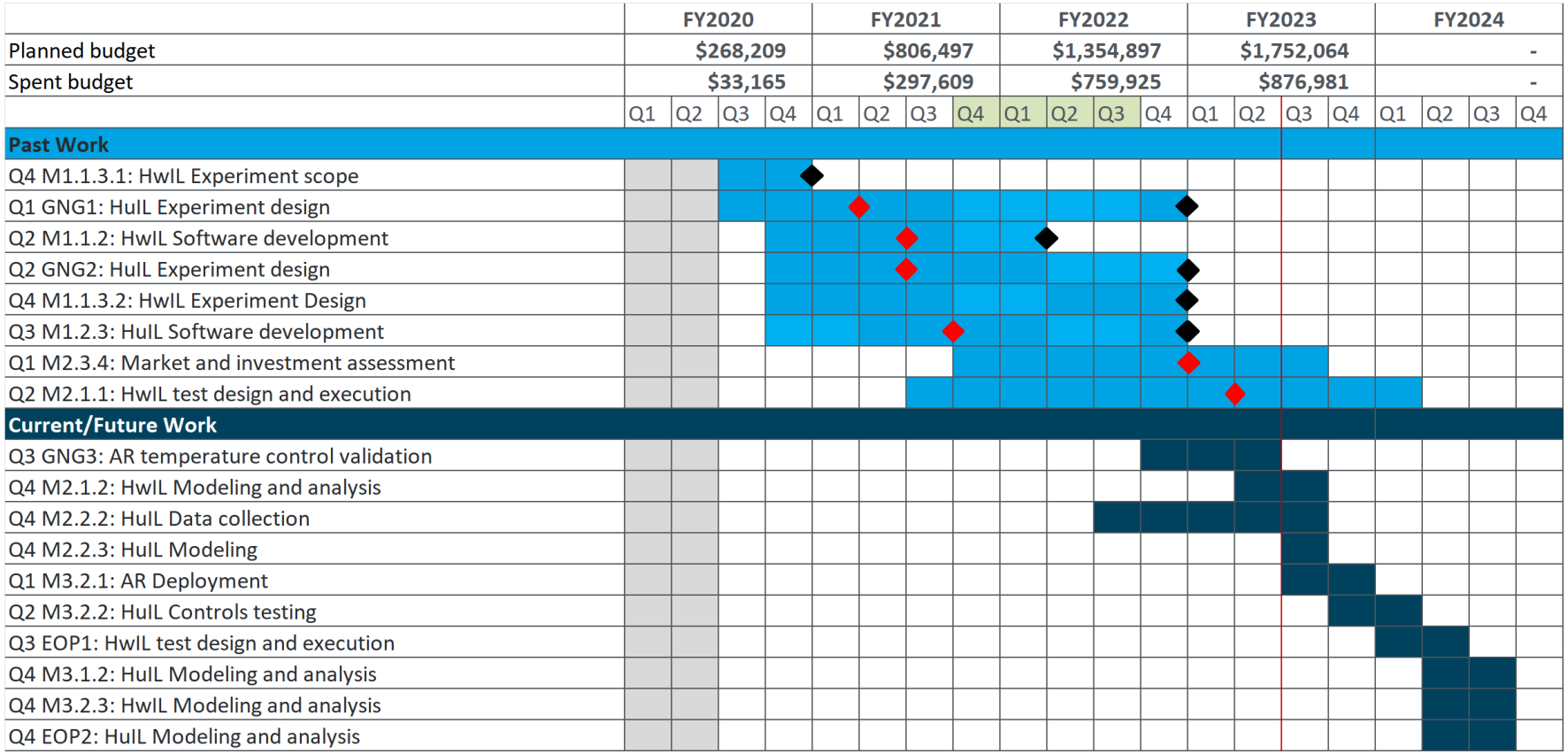
REFERENCE SLIDES

Project Execution



- NCTE received for delays in human subjects research due to COVID pandemic
- Florida not in sync. with MA & CO since it was a stretch goal (not in SOPO), partnering challenges
- Transitions for self-built co-simulation (occ. & GEB) to NREL's Alfalfa delayed simulation results
- NREL construction delays will push HwIL experiments to late 2023 (scheduled for spring 2023)

Team

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Industry Advisors

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kaiterra

15 lightyears
Energy Testing | Solar Power | Green Certification

Progress: Qualitative Analysis

Researcher:

All right, let's see. Typically, how do you think about balancing the goals of being comfortable, saving money, and saving energy in terms of the important factors in your heating and cooling use?

Participant A:

Yeah, I think we, like I said, we're happy to layer up instead of trying to heat the house wearing t-shirts and shorts. On days where it's not necessarily breaking 70 degrees, we will have windows open, especially in Participant B's office. She'll open up the windows to get that room to cool down a little bit. I don't know how much Participant COB really thinks about this, but [Utility] just gave us, I guess, tiers or time to use charges for electricity. As far as I know not gas. And then like I said, having an air conditioner is new to me from the sense that my last two houses didn't have air conditioning. Most recently we've had a swamp cooler and before that I didn't have anything. I used a window air conditioner. What was I going to say on that?

Personal Adaptation

Building Interaction

Time of Use

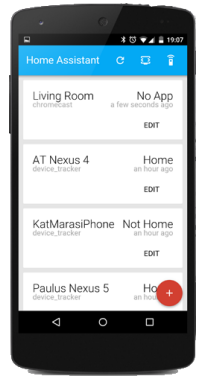
Progress: Occupancy Sensor Benchmarking

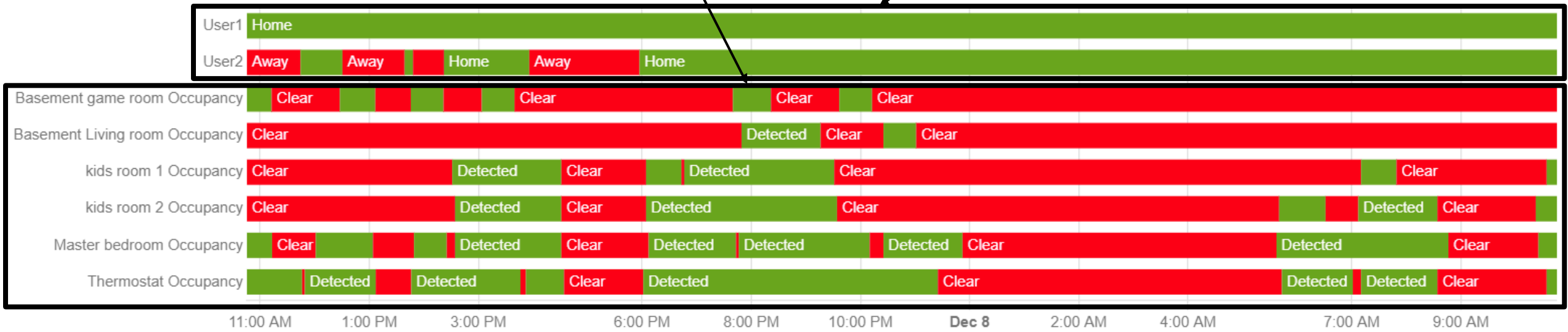
Occupancy sensors are known for have ‘unoccupied’ biases

Occupancy

Passive Infrared Sensor

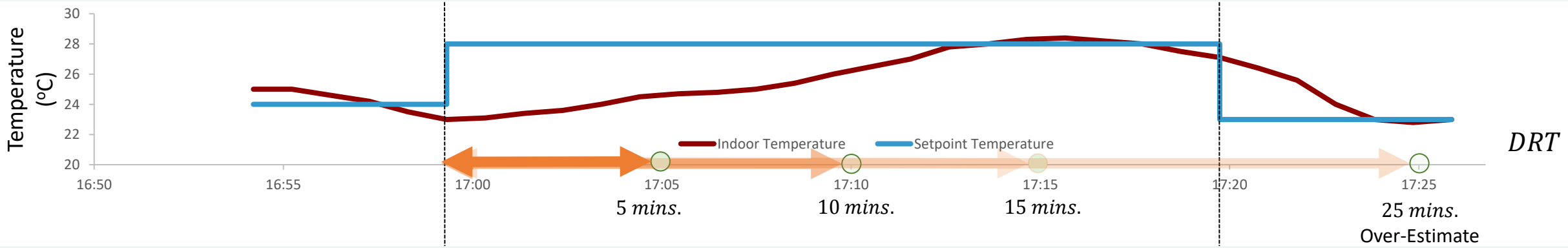
Cell Phone Geofence



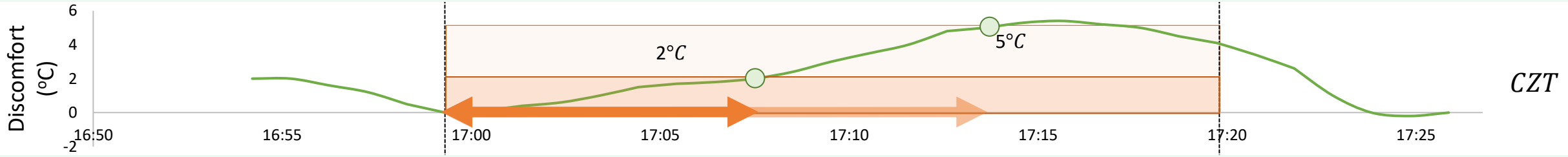


Progress: Occupant Thermostat Override Modeling

Delayed Response Theory (DRT) Overrides occur a **fixed time interval** from the initiating set-point change

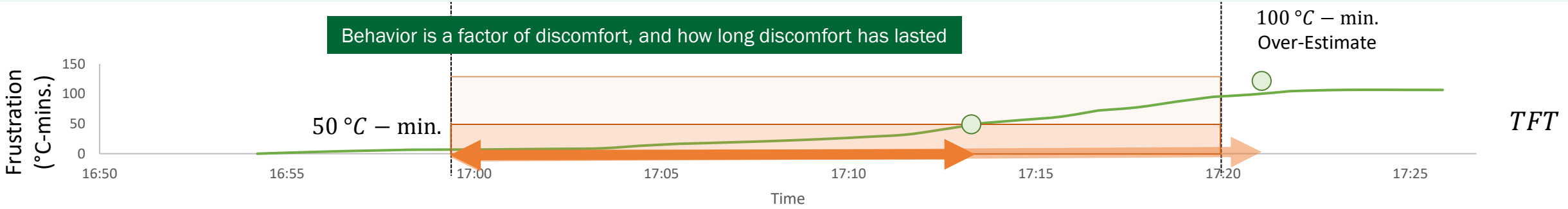


Comfort Zone Theory (CZT) Overrides occur when **temperature deviates** past a threshold from a nominal temperature

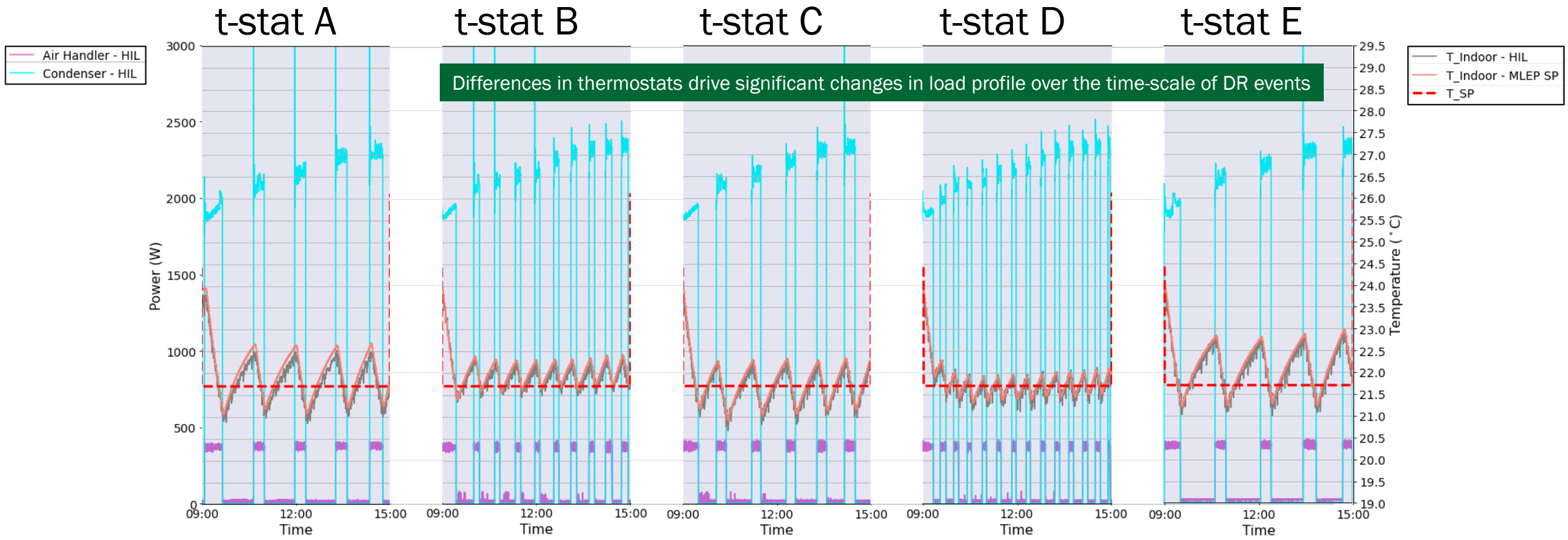


Thermal Frustration Theory (TFT) Overrides occur when **accumulated thermal discomfort** exceeds a threshold

Behavior is a factor of discomfort, and how long discomfort has lasted



Progress: HwIL Benchmarking – HPs and Thermostats



	Field	Baseline	t-stat A	t-stat B	t-stat C	t-stat D	t-stat E
Condenser Energy [kWh]	8.7	6.3	6.0	6.3	6.0	7.0	5.9
Condenser Energy Difference [%] with baseline	-	-	**4.8**	**0**	**4.8**	**11.1**	**6.4**
Runtime [mins]	266	185	174	182	173	200	168
Runtime Difference [%] with baseline	-	-	**6.0**	**1.6**	**6.5**	**8.1**	**9.2**