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Session 7 – Advanced Thermal Energy Storage Solutions for Water Heating Systems

Session Chair: Navin Kumar

Presenter: Peter Grant

Stor4Build Annual Meeting
August 26–27, 2024
Oak Ridge National Laboratory

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Existing Storage is Inexpensive Storage - Maximizing Use of TES in Heat Pump Water Heaters

S4B Annual Meeting - Integration Thrust Area

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Presenter: Peter Grant (PI)

Contributors: Peter Grant, Weiping Huang, Tao Yang, Aditya Kanteti

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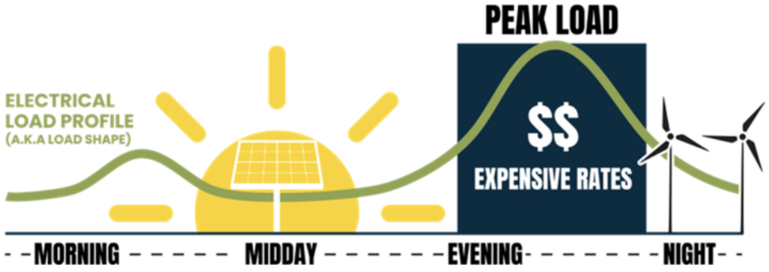
CalFlexHub

- Identify, evaluate, develop, and demonstrate pre-commercial, load flexible technologies
- **Standardize the signals** used to communicate dynamic price and GHG information to devices



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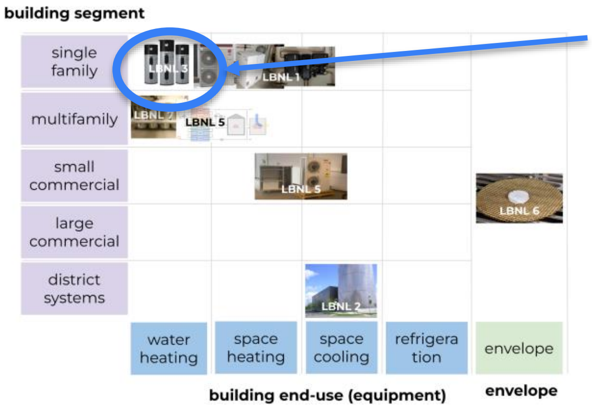
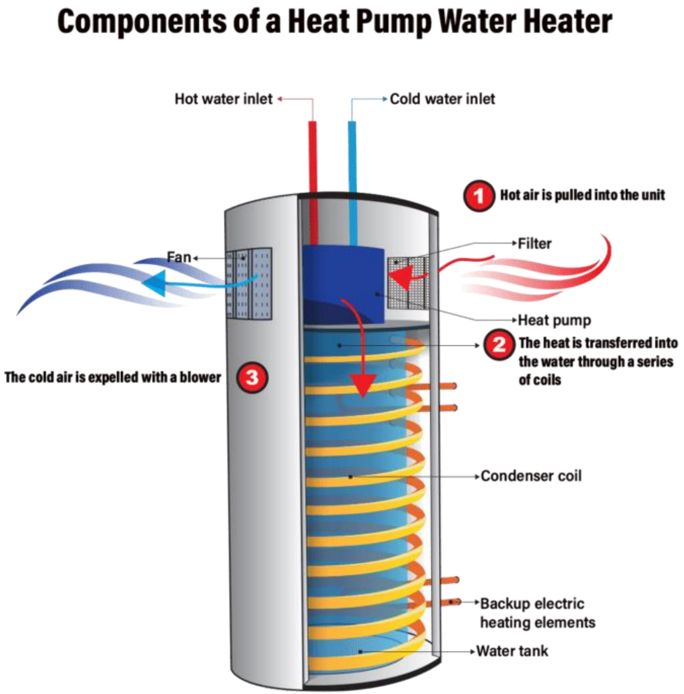


Large-scale load shifting with commercially available HPWHs

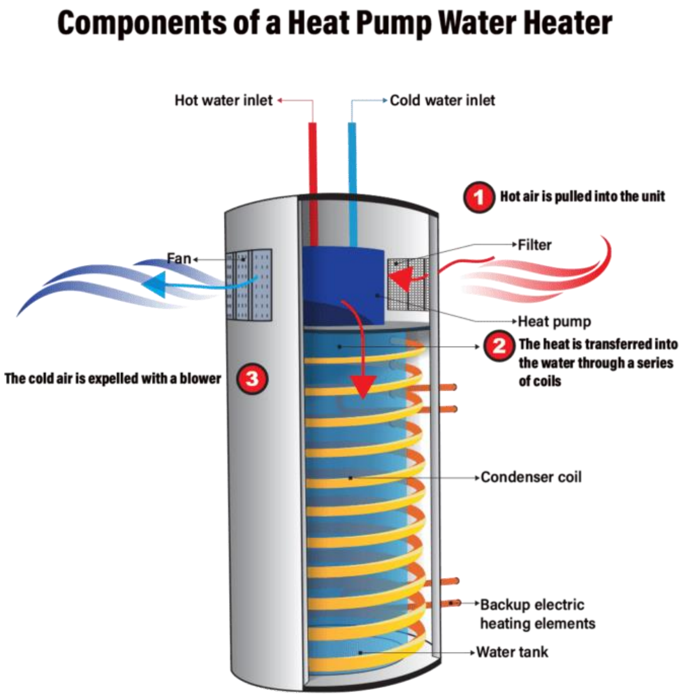
Heat pump water heater (HPWH) load shifting



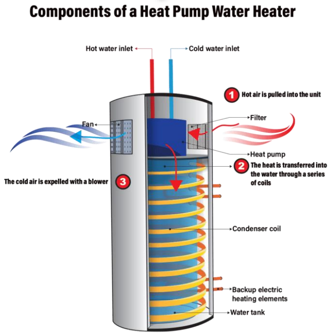
- Characteristics
  - ~1.2 kW-th heat pump
  - Condenser wrapped around tank
  - 2x ~4kW-el resistance elements
  - **CTA-2045 and API communication**
  - **190-303 L storage tank**

Thermal energy storage (TES) is available!
We need to how use it intelligently

Heat pump water heater (HPWH) load shifting



- **Key benefits**:
  - **Energy efficiency**: Reduces energy consumption by ~75% (compared to gas)
  - **Grid edge**: Demand flexibility minimizes utility bills, electrical upgrades and carbon emissions while integrating distributed resources
  - **Emission Reduction**: HPWHs emit 58% less CO2 (compared to gas). Flexible demand can shift from fossil fuels to renewable electricity
  - **Fast, interactive DER**: Able to activate/deactivate heat pumps as needed

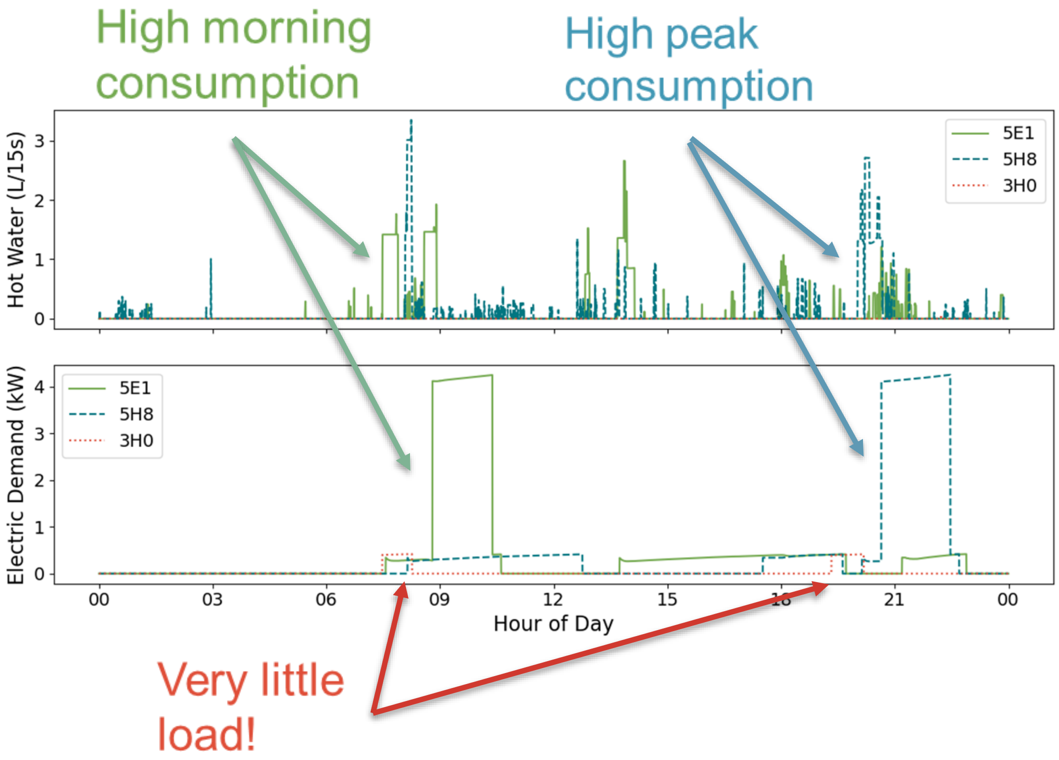


CTA-2045 Communication Standard

- **Enables demand flexibility**
    - Both **hardware and software**
- Can **increase/decrease electric load**
    - Increase:
        - **Load Up**: Bring water **to set temperature**
        - **Advanced Load Up** (CTA-2045-**B**): **Increase set temperature**, bring water to set temperature
    - Decrease:
        - **Shed**: **Delay heating** longer than normal
        - **Critical Peak Emergency**: **Delay heating even more**

State of the Art

- Decarbonization requires matching consumption to renewable production
- **Status quo:** Apply identical load shifting to all HPWHs in a fleet
    - Not optimized for occupant behavior
- **Status quo:** Not sensitive to tank conditions
    - Can cause resistance element use
    - Can increase operating costs by 49-63%



Proposed Solution

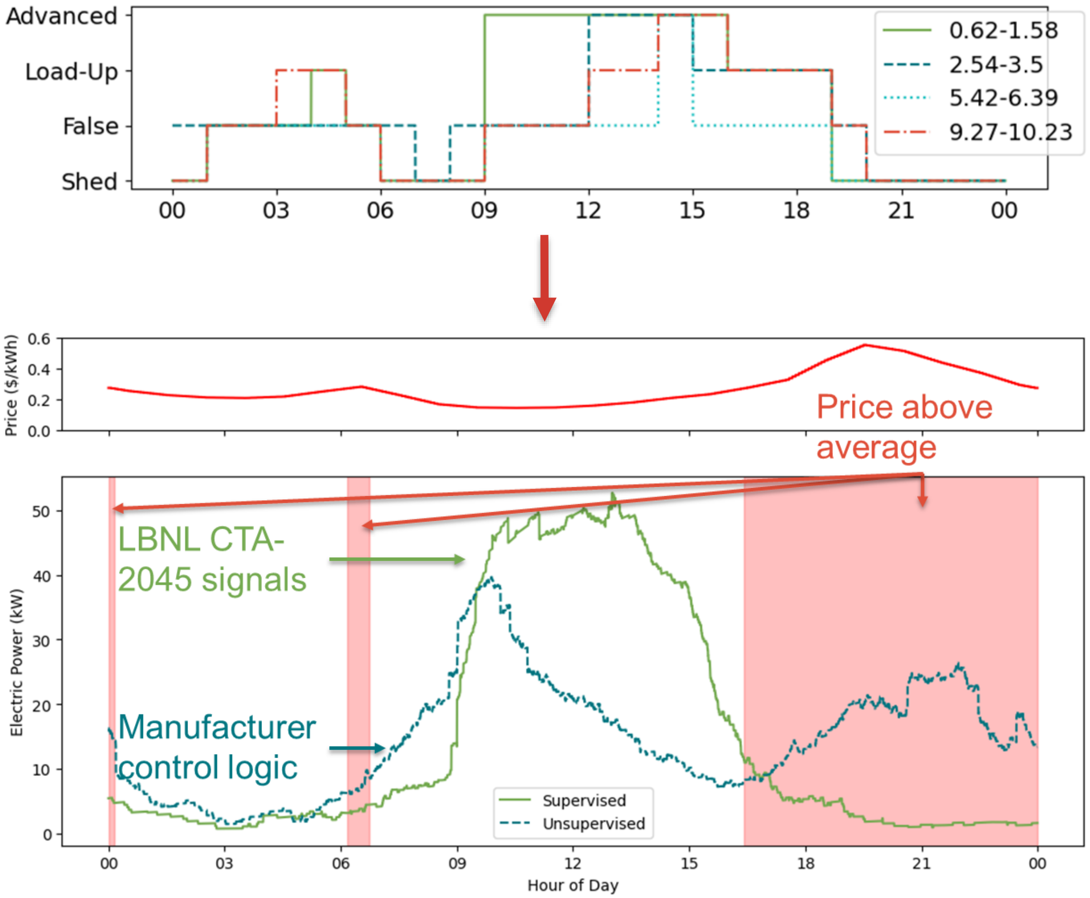
Methods

- Leverage **only existing capabilities**
- **Precomputed** schedule response to different price and load curves
- **Manufacturers** can include on CTA-2045 module or product
- **Aggregators** can host on the cloud
- **Daily use** to match price curve

Impacts

- Optimize use of **existing storage**
- **Shift 77% peak load** to low price times of day
- **Reduce** operating cost by 29%

Customized CTA-2045-B Signal Schedules



Research Questions

Temperature control

•How can controls **avoid triggering resistance element** usage?

CTA-2045 control

•How important is the **Advanced Load Up** command (only available in CTA-2045-**B**)?

Field monitoring

•What **operational cost and load shifting benefits** can be achieved in real homes?

•How are the results impacted by **different price schedules**?

Technology transfer

•How do we create a **toolchain for utility programs**?

Your concerns

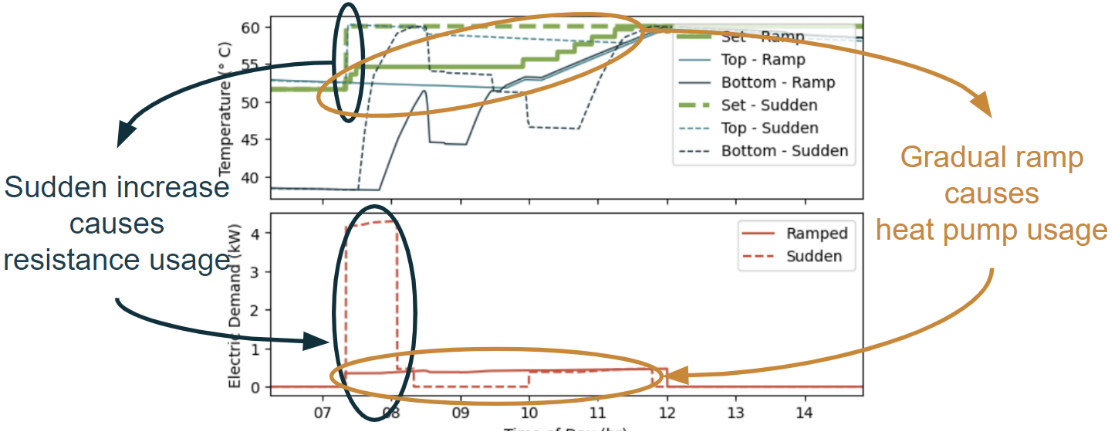
•What questions should we add **to this list?**

Temperature Control: Avoiding Resistance Element Use

Problem
- HPWHs activate resistance elements when far below setpoint
- **Increasing setpoint too rapidly increases operating costs**

Solution
- **Gradually increase setpoint**
- Compare water temp to setpoint
  - If close: set + 1 °F
  - If not close: no change

Impact
- **Cost: -52.5%**
- **Max demand: -88%**



CTA-2045: Advanced Load Up Is Important

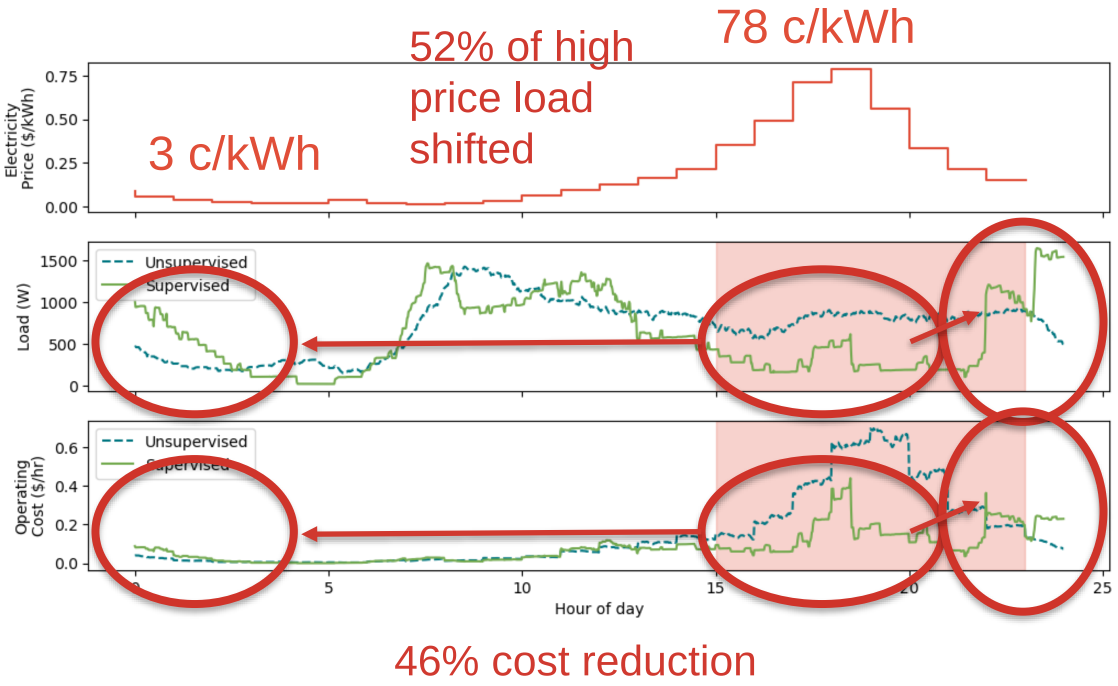
Impact

	Operating Cost (%)	Peak kWh (%)	Mid-Day kWh (%)
Without ALU	-32%	-29%	+14%
With ALU	-53%	-60%	+65%

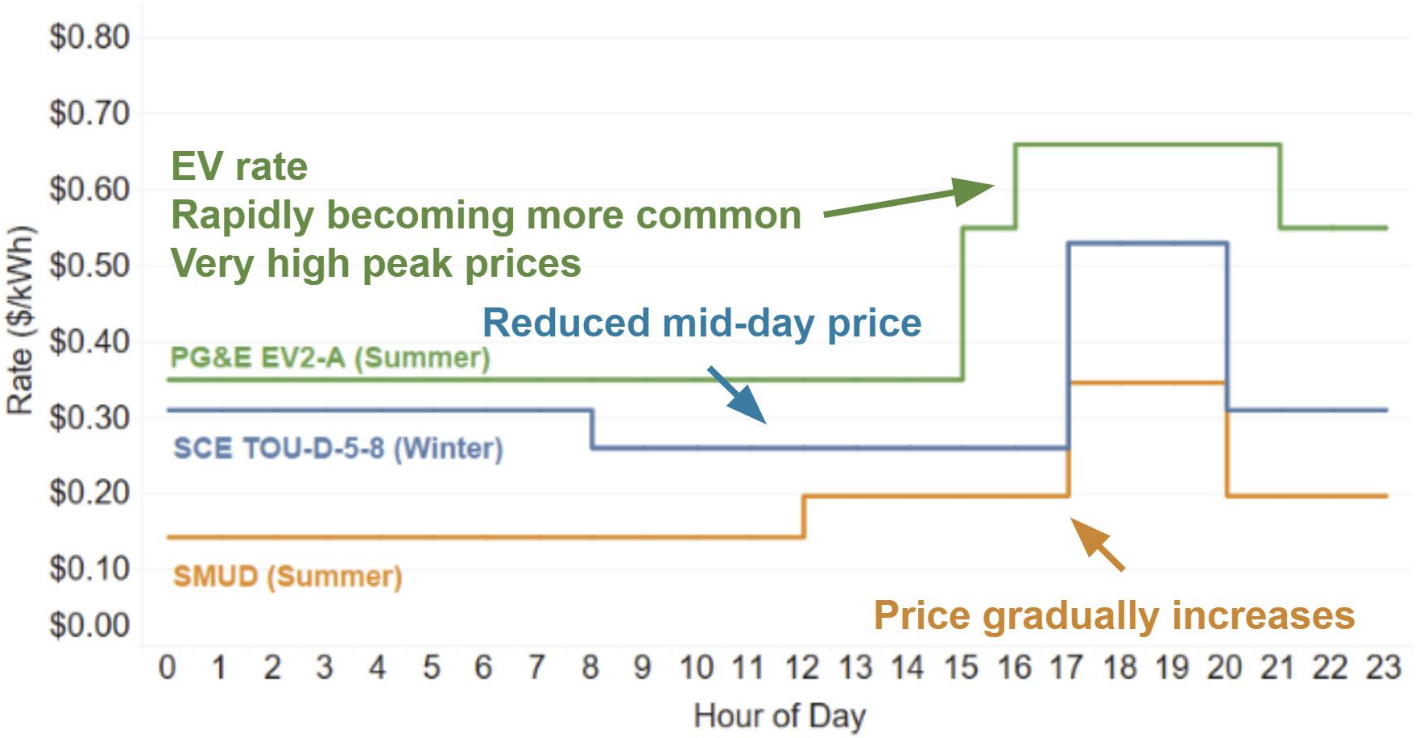
Field Results: CalFlexHub Summer Highly Dynamic Price

Fleet details

- **10 HPWHs**
- 120V product
- California
- Single family
- CTA-2045 (**not B**)



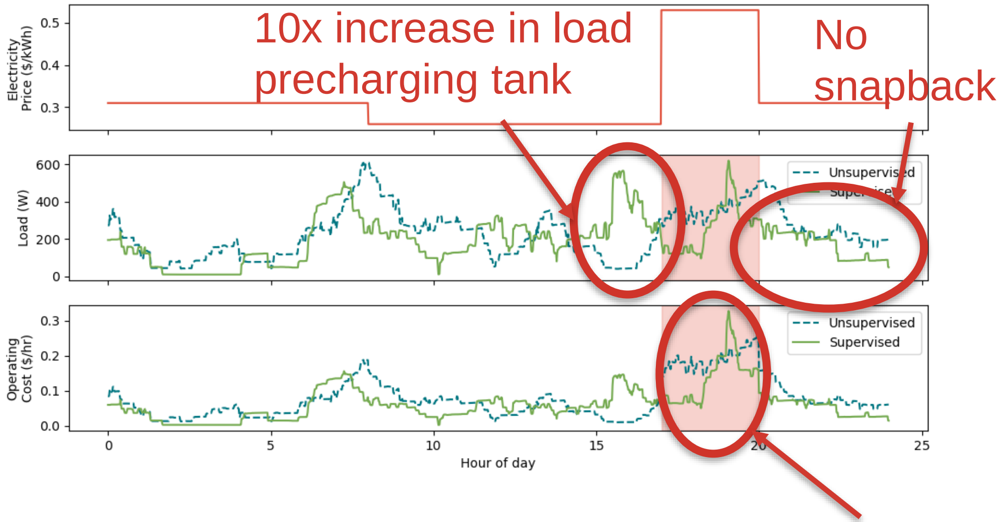
Field Results: Studied Time of Use Rates



Field Results: Reduced Mid-Day Rate

Fleet details

- **4 HPWHs**
- 120V product
- California
- Single family
- CTA-2045 (**not B**)



Peak kWh: -29%
Electricity cost: -19%

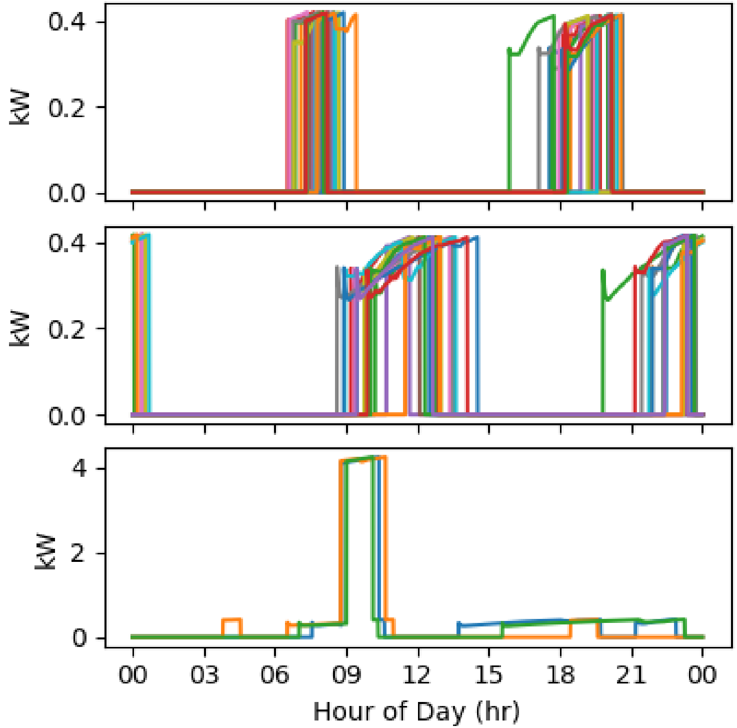
Result Comparison

Electricity Price Profile	Peak kWh Reduction (%)	Solar Peak kWh Increase (%)	Operating Cost Decrease (%)
CFH, WinterHDP	41.49	-14.15	30.42
CFH, SummerHDP	52.38	-12.71	46.37
EV	54.20	12.72	8.45
Reduced Mid-Day	29.02	9.42	19.29

Transitioning to Utility Programs

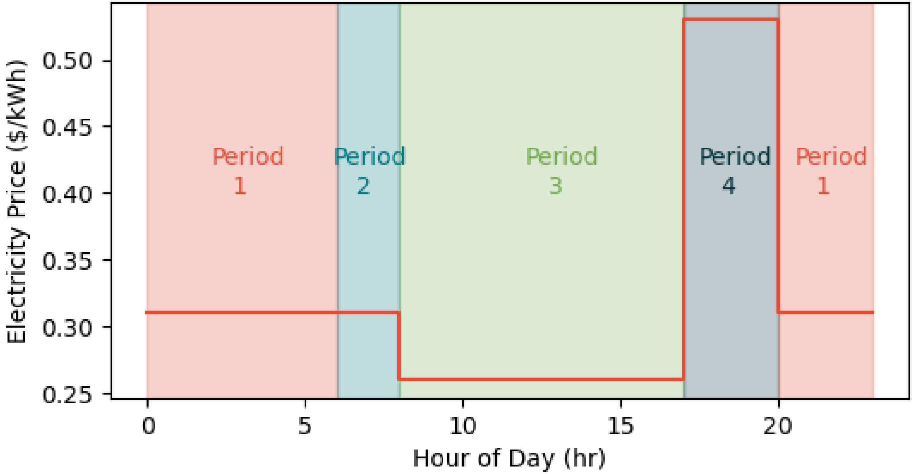
Current method:

- 148 HPWHs into **groups with similar baseline electricity consumption**
- Grouped by **RMSE with 15s timestep**

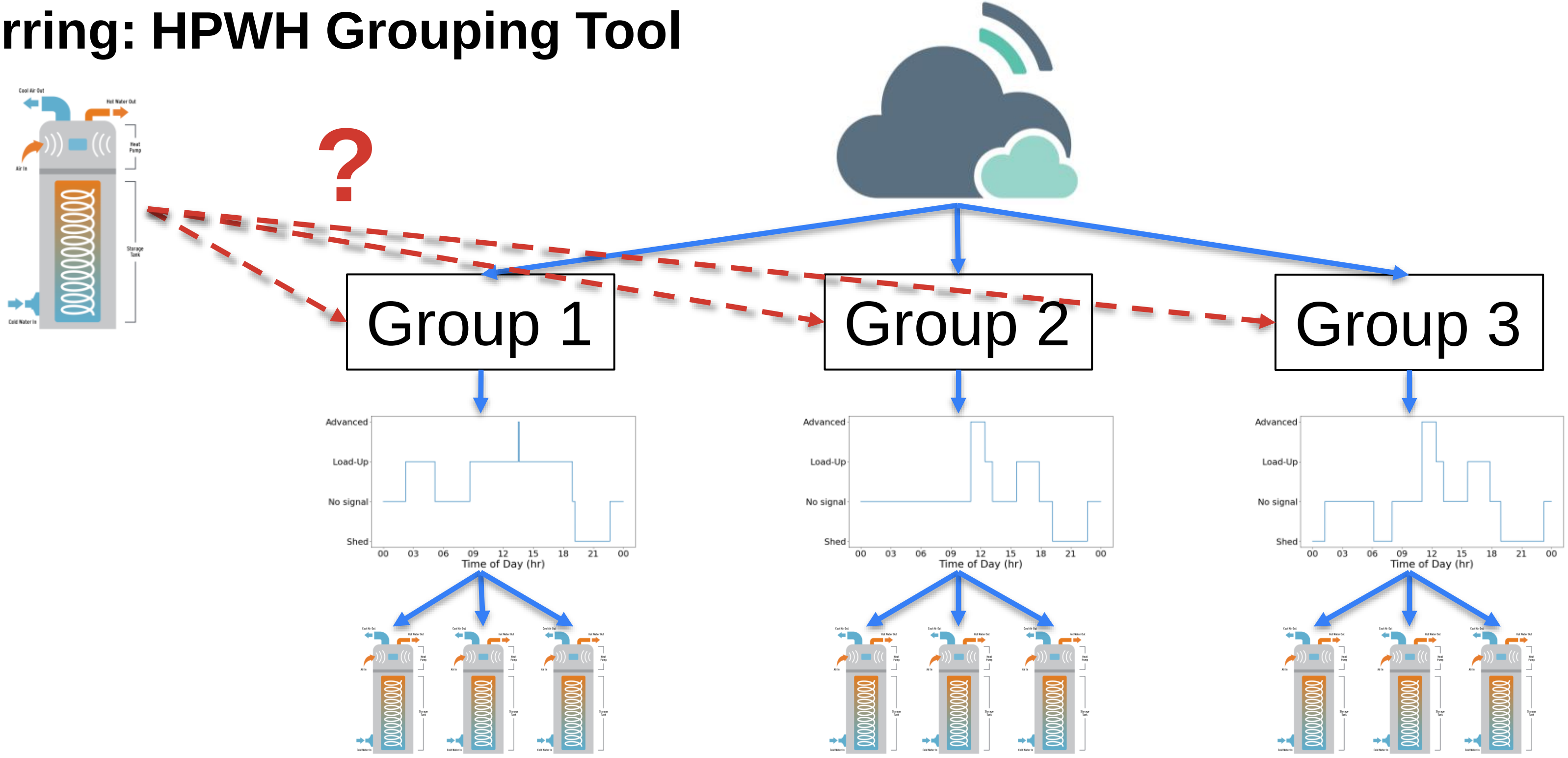


Underway updates

- Group based on **kWh during price period**
  - Enables groups customized to time of use rates
- Add a **"morning shower rush"** period
  - Enables controls to **minimize resistance**



Transferring: HPWH Grouping Tool



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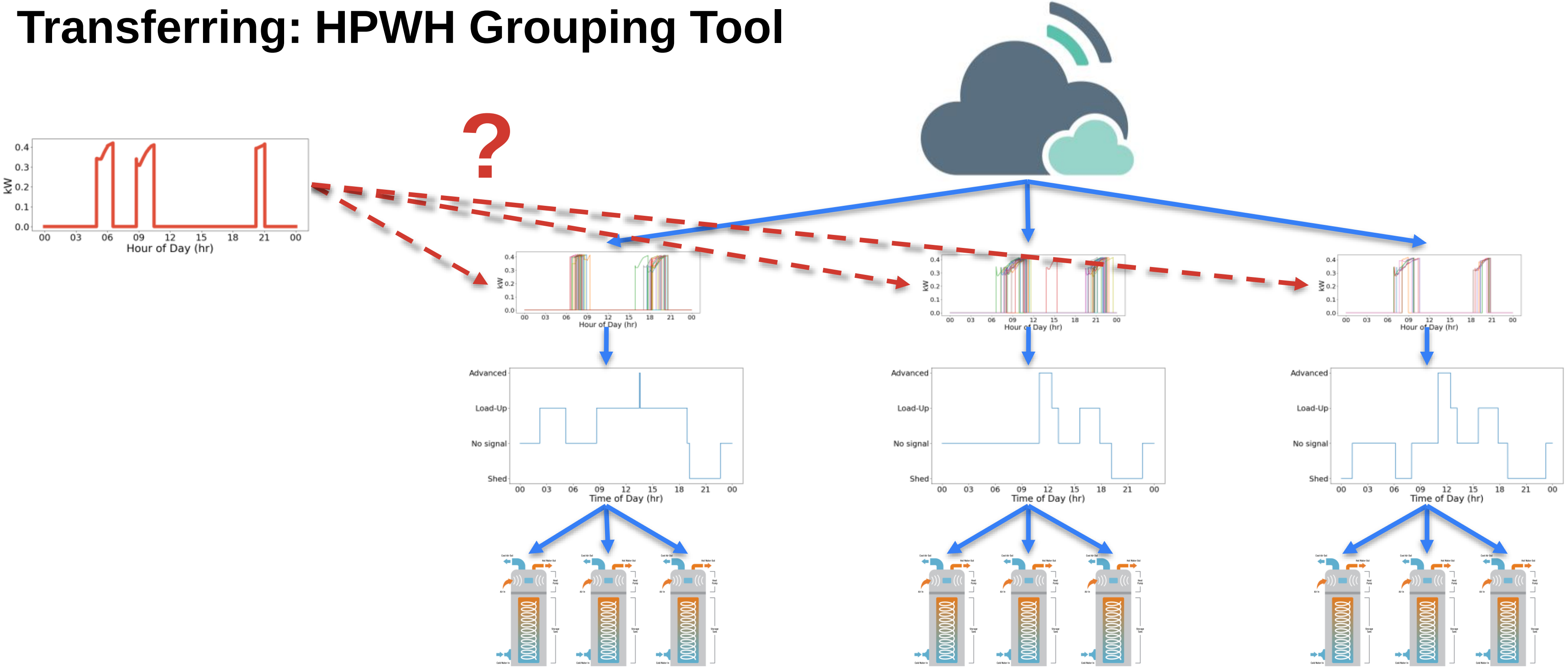

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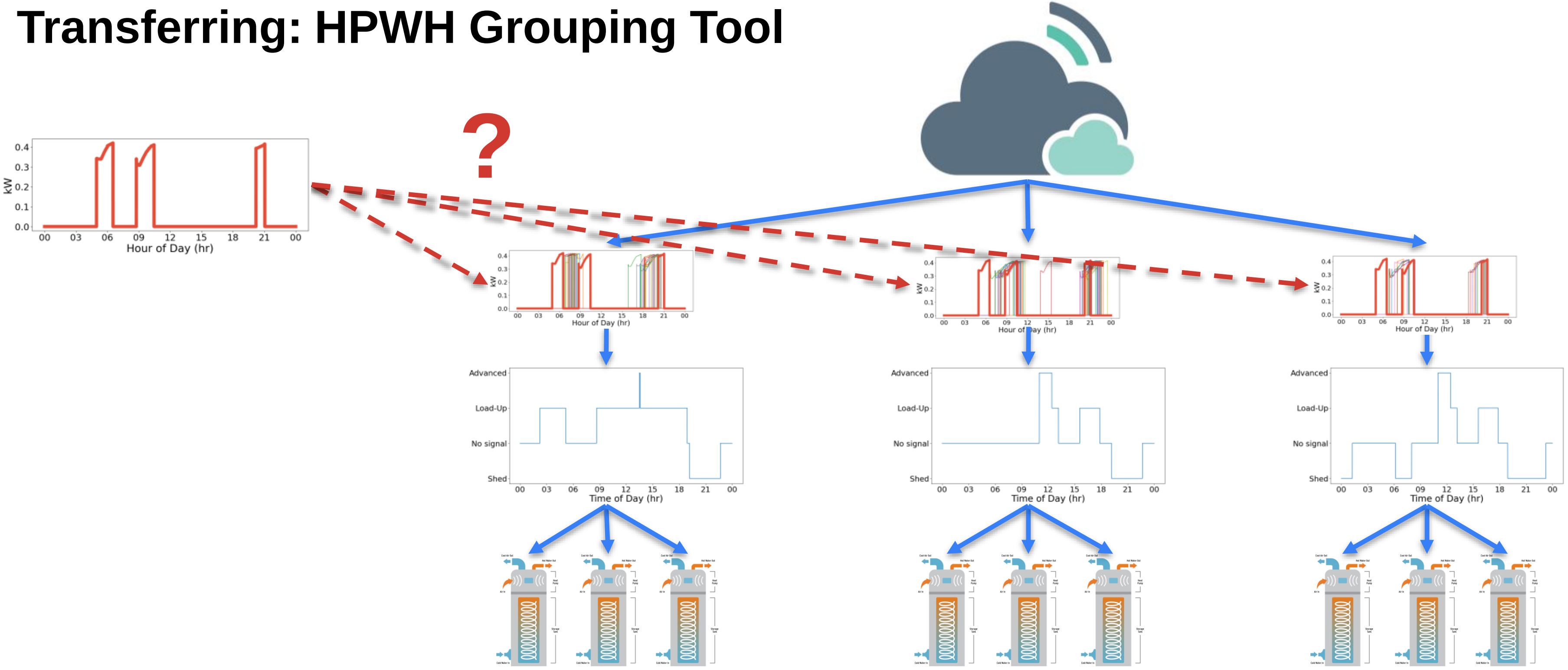

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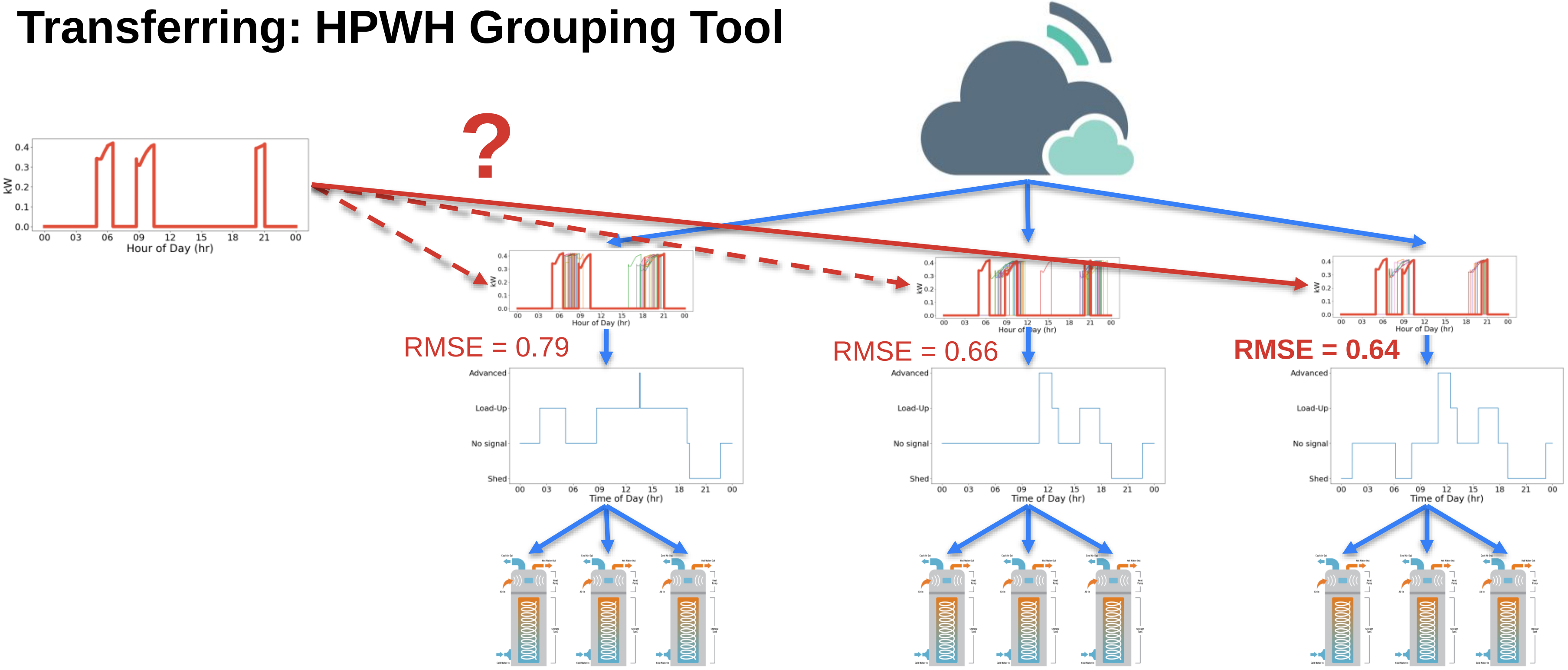
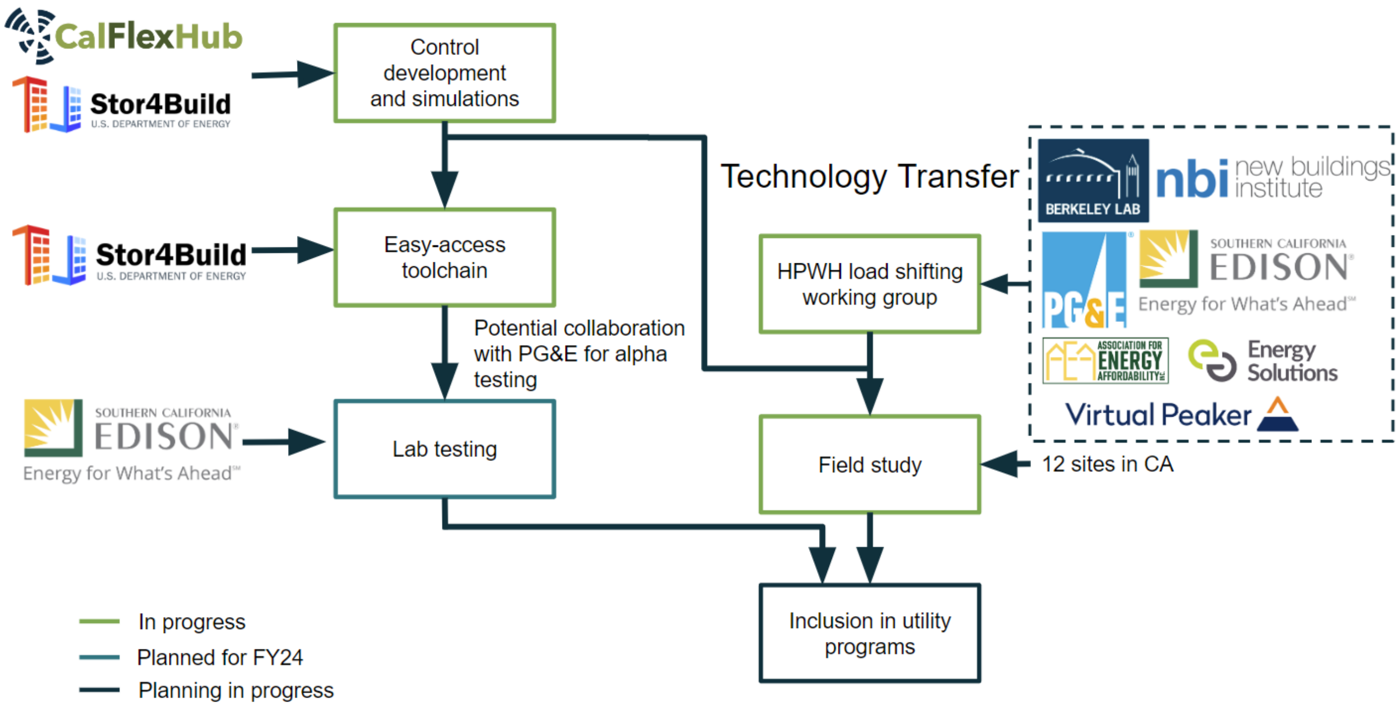


Technology Development and Transition Pathway



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Expanding Heat Pump Water Heater Range: Adding TES to Serve Small Multifamily buildings

S4B Annual Meeting – Integration Thrust Area

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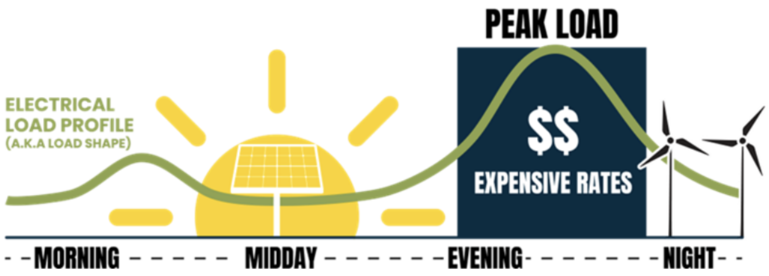

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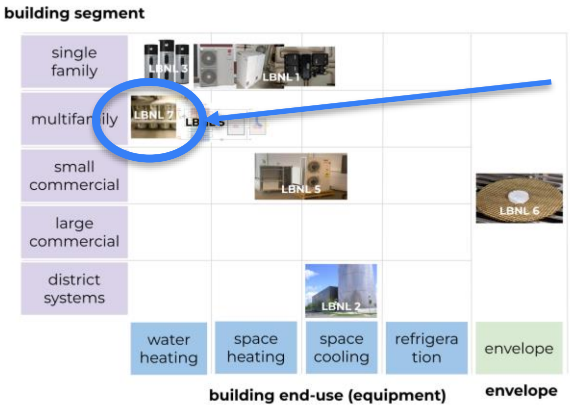
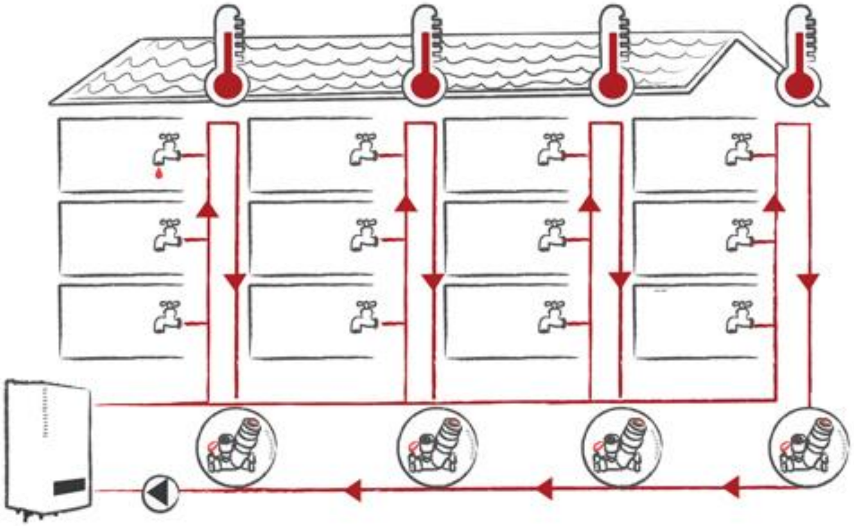


Adding TES to HPWH to serve small multifamily buildings

TES in MF DHW

Key Benefits of TES integrated DHW system:

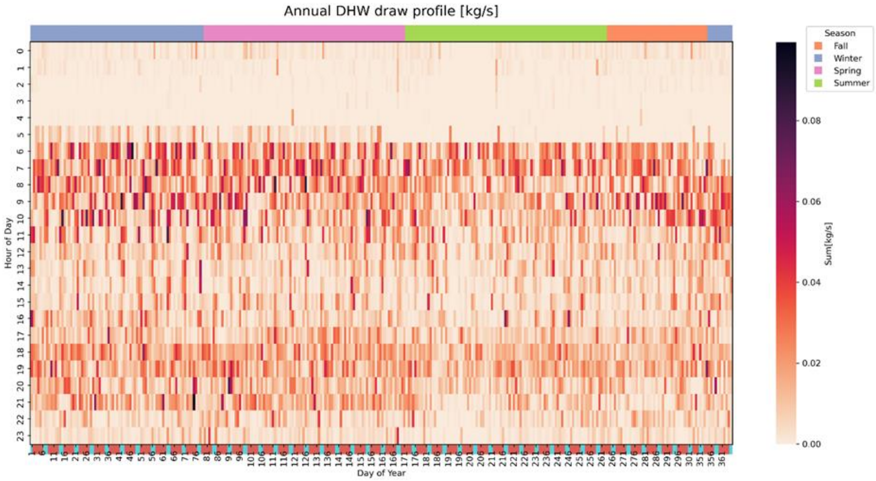
- **Energy Efficiency and Equity**: Reduces costs for lower income communities by sharing cost of highly efficient heat pump water heater (HPWH) system
- **Grid edge**: Demand flexibility minimizes utility bills, electrical upgrades and carbon emissions while integrating distributed resources
- **Resilience**: Smaller phase change material TES increases access to hot water during power outages
- **Emission Reduction:** Reduced installation and operation costs support converting gas water heaters to CO_2 heat pumps

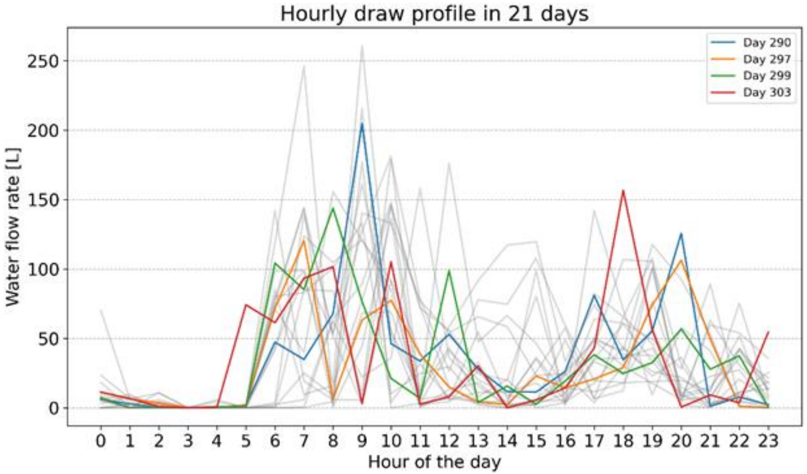


Challenges

- SanCO2 HPWH is **not designed to work with additional thermal energy storage** (TES). Integrated controls are needed
- Automated load shifting controls for these devices are **preliminary**
- Predicting domestic hot water (DHW) usage is inherently challenging due **random and uncertain human behavior**
    - **Industry uses historical average consumption**

- **How do you optimize control when you can’t predict demand?**





Research Questions

Integrated control

•What control algorithm can integrate the HPWH + TES?

•How do we develop an **easily adopted** algorithm?

DHW Forecasts

•How can we **handle the high uncertainty** in DHW consumption forecasts?

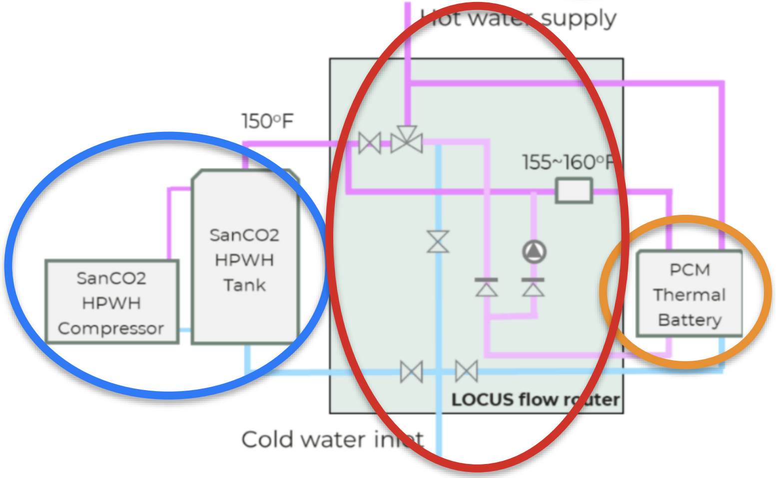
•How accurate does the forecast need to be to be **useful for control**?

Your concerns

•What questions should we add **to this list?**

Studied System

- Manufactured by **private industry partner**
- Central system for **small multifamily buildings**
- SanCO2 CO2 air-to-water heat pump
- Additional storage to handle larger loads of multifamily buildings
- PCM: Smaller form factor than water tanks
- Transfers heat between water tank and PCM
- Plug-and-play decarbonization solution
- TES enables 1) reduced heat pump size, 2) avoided panel upgrades, 3) controllable grid resource



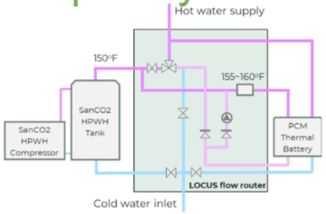
Integrated Control: Semi-Optimal Simple Predictive Controls HP + TES

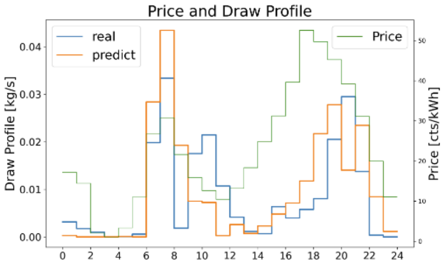
DHW load

Obtained load data from field site

Script to obtain weather forecasts

Developed system model

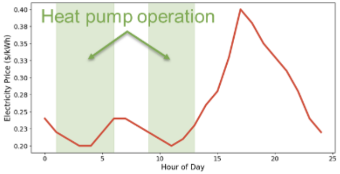




DHW consumption forecasting tools

HP operation commands

Calculate lowest cost operation timing



Load forecast

Integrated Control: Semi-Optimal Simple Predictive Controls HP + TES

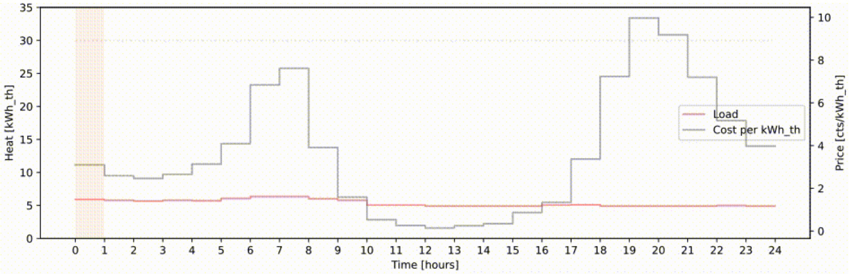
Predictive Control Customer Discovery

Limited adoption
Complex
•Expensive
•Unproven
•***Necessary***

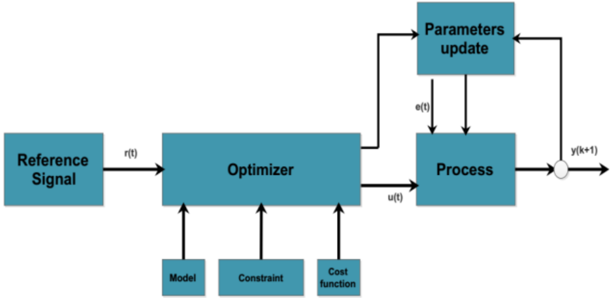
Research Question

What if we made a generic, simple, predictive control?

Proposed Control:



Model Predictive Control (MPC):



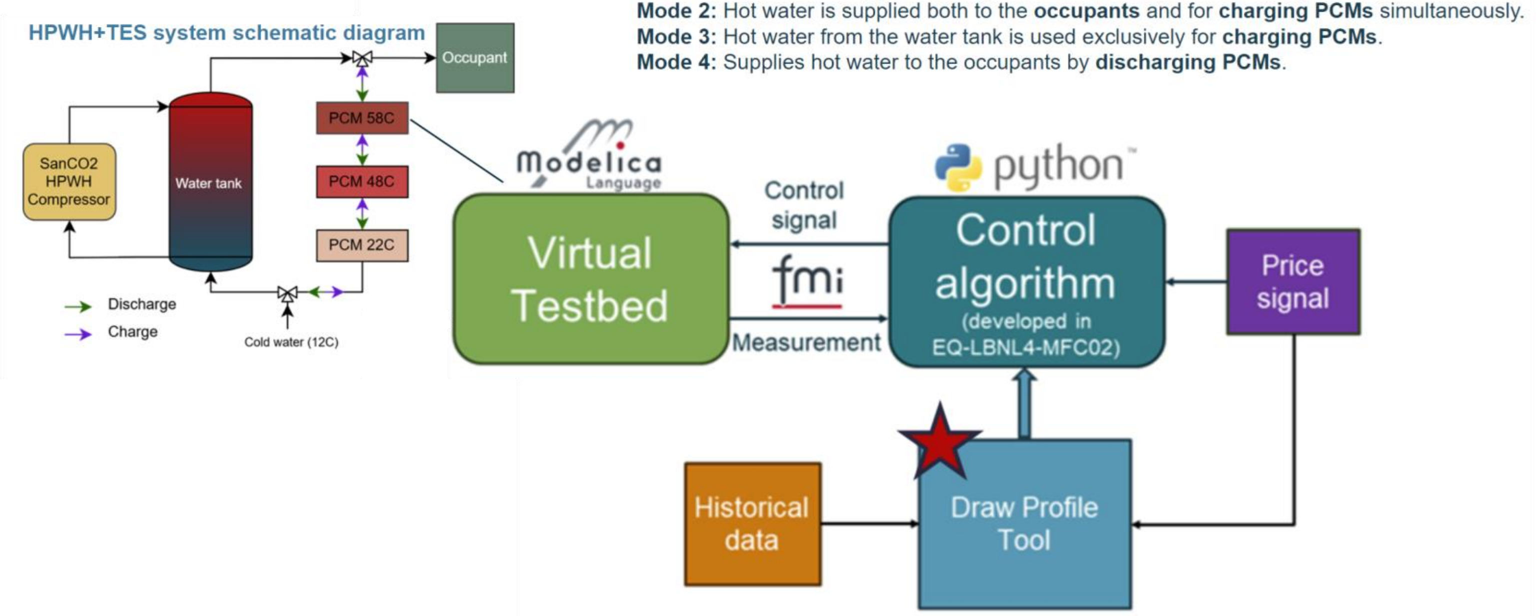
•**Data driven performance map**
•Calculate cost/kWh-th each hour
•**Forecast when TES SOC <=0**
•Operate AWHP at **cheapest prior time**
•If cheaper soon: heat minimum
•Else: Charge tank

•**Custom calibrated simulation models** for each building
•**Opaque rationale** behind control decisions
•**Not easily understood** by industry
•**Excellent performance**

Virtual Platform

Controllable variables
water flow rates in the supply loop

Control modes
Mode 1: Hot water is supplied directly from the water tank to the **occupants**.
Mode 2: Hot water is supplied both to the **occupants** and for **charging PCMs** simultaneously.
Mode 3: Hot water from the water tank is used exclusively for **charging PCMs**.
Mode 4: Supplies hot water to the occupants by **discharging PCMs**.



DHW Forecasts: Novel Tools

Hypothesis: Can generate a DHW forecast which is useful for control
May not need to be accurate

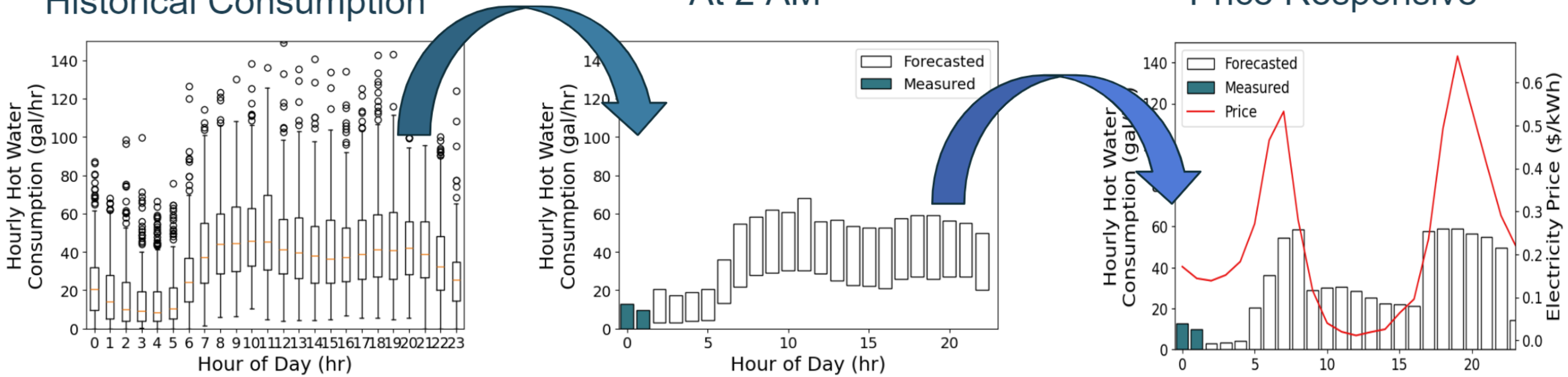
Identifies 25th & 75th percentiles
Updates based on prior consumption that day

Assumes low consumption at low price times
Assumes high consumption at high price times

Historical Consumption

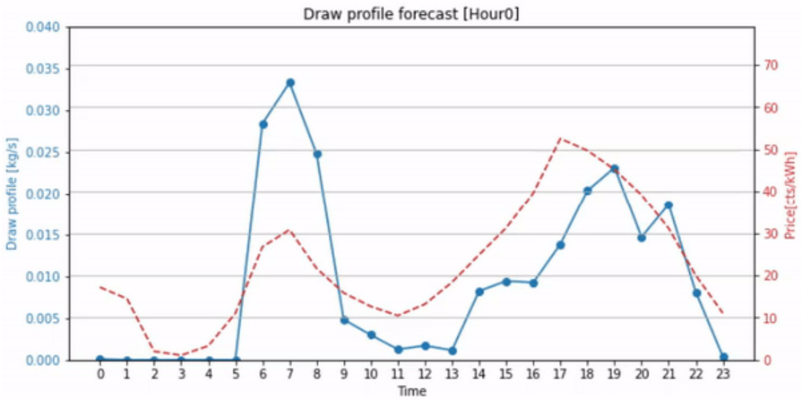
At 2 AM

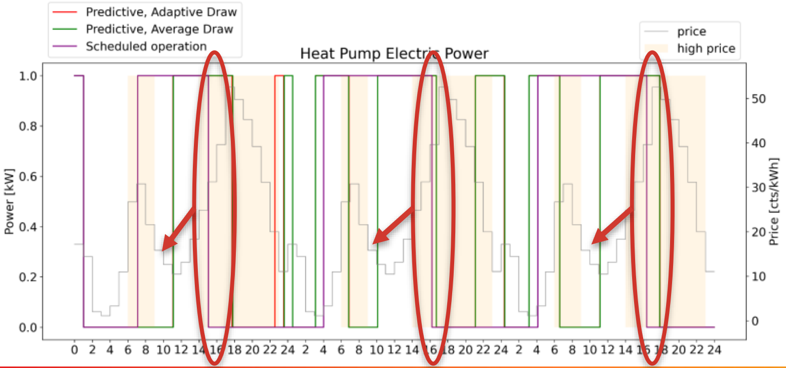
Price Responsive



Sample Results

- DHW forecast **updates each hour based on past behavior**
- Biases system to **pre-charge TES** before high price times
- **Avoids overpredicting** consumption

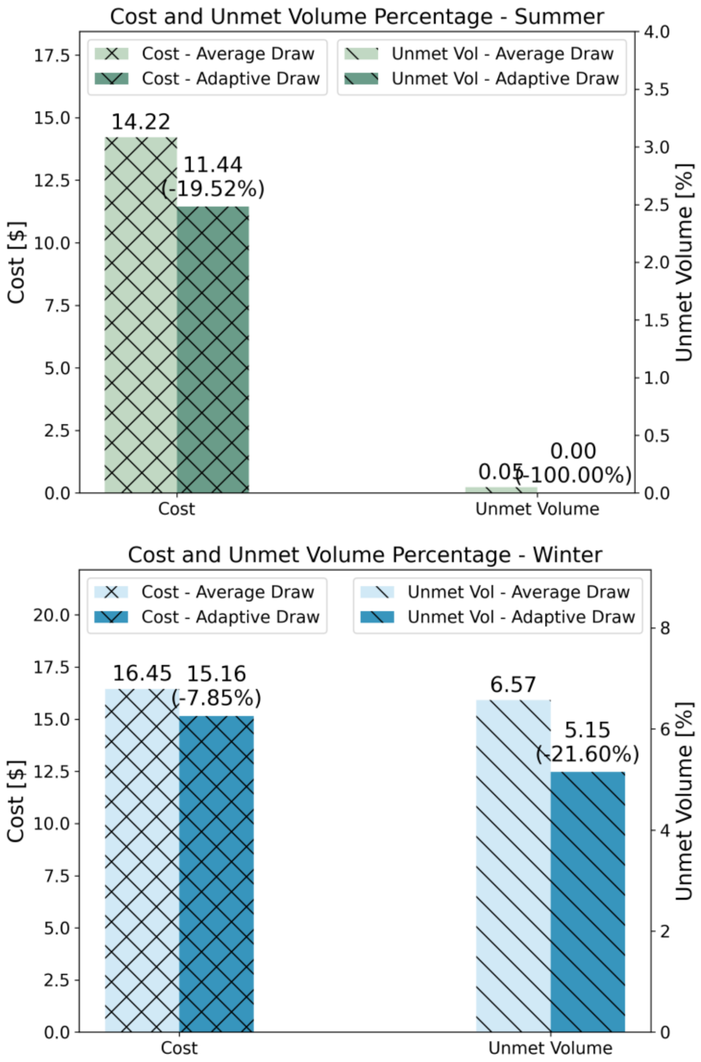




- Shifts load to low-use times of day
- **Reduces unmet load by 91%**
- **Reduces operating costs by up to 24%**
  - **Remaining room for improvement**

Seasonal Results

- Impacts on operating cost and unmet load from using draw profile tool
- Adaptive tool reduces:
  - Operating cost:
    - Summer: **19.52%**
    - Winter: **7.85%**
  - Unmet load:
    - Summer: **100%**
    - Winter: **21.60%**



Conclusions

- Created **simple, price-responsive control algorithm**
  - Can be adopted for other systems
- Developed draw profile tool sensitive to **typical behavior, daily behavior, and prices**
- **Created virtual platform** for evaluation of controls and draw profile tool

Expected Impacts

- Reduced operating costs by:
  - **Control algorithm: 16%** (compared to scheduled control)
  - **Draw profile tool: 8%** (compared to average profile)
- Reduced **cold water events by 91%**

Next Steps

- Develop a **metric for identifying high performance** draw profile tools
- Perform **laboratory testing, receive feedback** from industry partner
- Modify tool to **better identify multiple price peaks**

Acknowledgements

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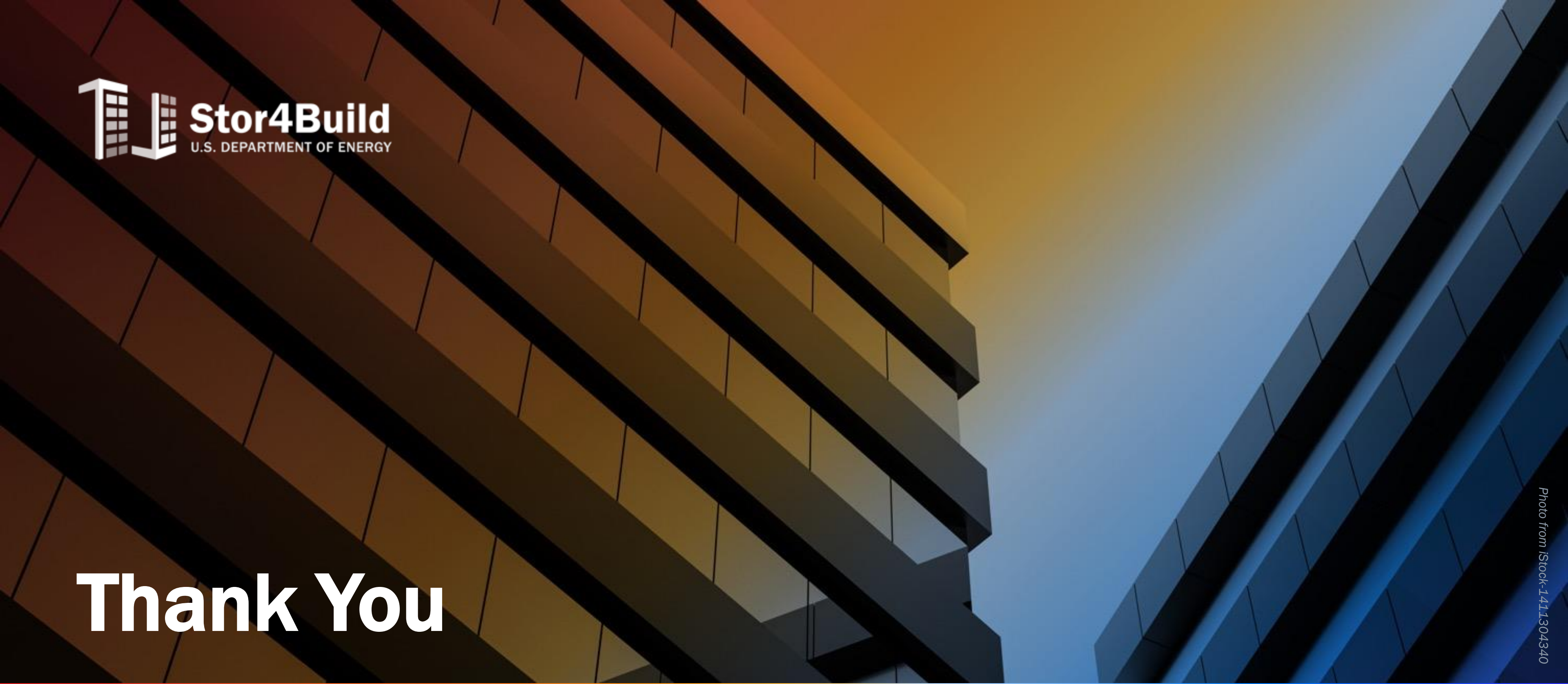

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