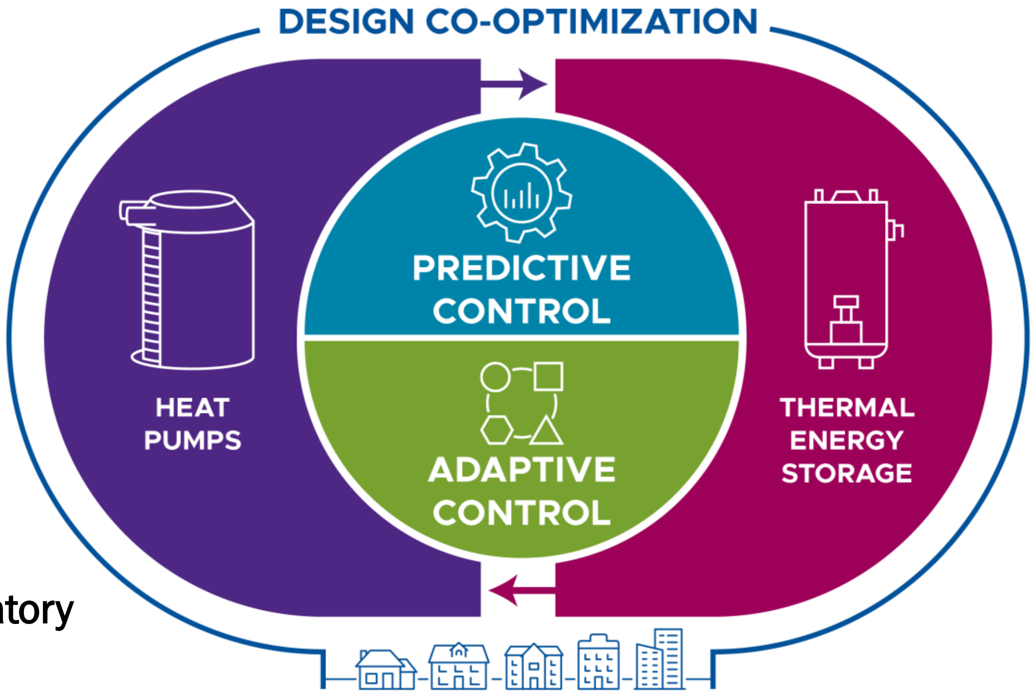
Predictive Device-level Control and Optimal Sizing of Integrated Heat Pump Systems for Deep Decarbonization and Energy Resilience

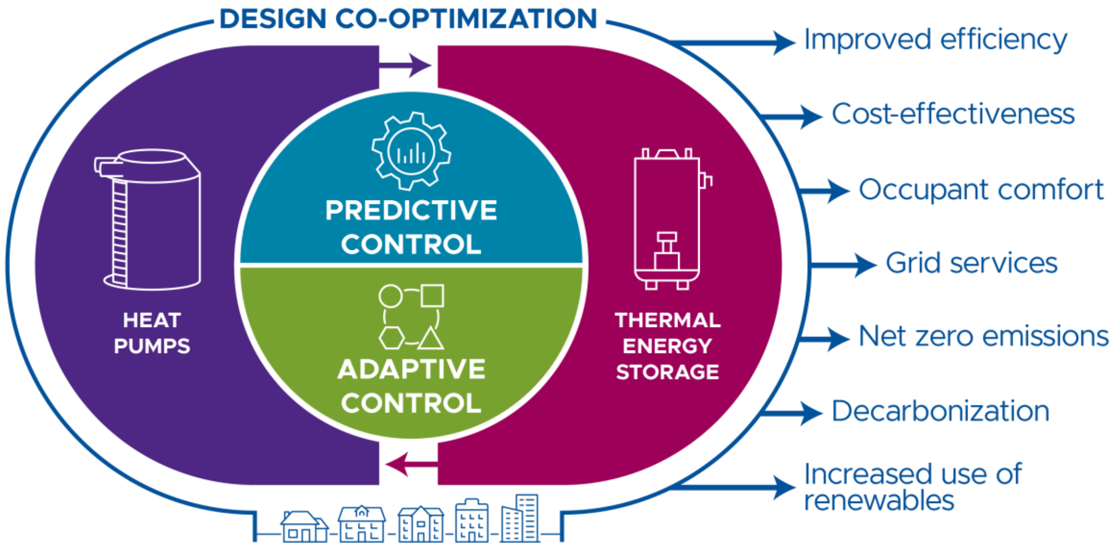


Pacific Northwest National Laboratory
Veronica Adetola
509 371-6996; Veronica.Adetola@pnnl.gov
Project #: 3.2.2.57

Project Summary

Objective: Create and demonstrate predictive and adaptive device-level control solutions, co-optimization sizing tools, and optimized heat pump (HP) systems, with or without thermal energy storage (TES), enabling affordable, cold climate energy-efficient, and grid-responsive integrated HP systems.

Outcome: HP-TES optimal sizing tool and advanced rule-based control software prototypes validated with superior performances on two *residential* HP test cases – multi-purpose HP (MHP) that utilizes domestic hot water tank as thermal storage and variable speed water source HP (WSHP) for multifamily buildings – in a hardware-in-the-loop environment and a Lab Home.



Team and Partners

Pacific Northwest National Laboratory (PNNL)

Texas A & M University (TAMU) – a minority serving institution

Trane Technologies

LG Electronics US (LGEUS)

Stats (New Start)

Performance Period: 10/1/2022 – 09/30/2025

DOE budget: $1,900k, Cost Share: $120k

Key Milestones

1. Component and system models of integrated MHP and WSHP use cases are developed and validated, achieving with >85% accuracy.
2. Device-level control for WSHP is implemented in digital simulation environment to achieve 30% peak load reduction and >10% energy savings through fan and compressor speed coordination.
3. Improved MHP controls deployed on Lab equipment result in reduced energy consumption by ≥ 10%, energy cost by ≥ 15%, and peak load by >30% while maintaining occupants' comfort.

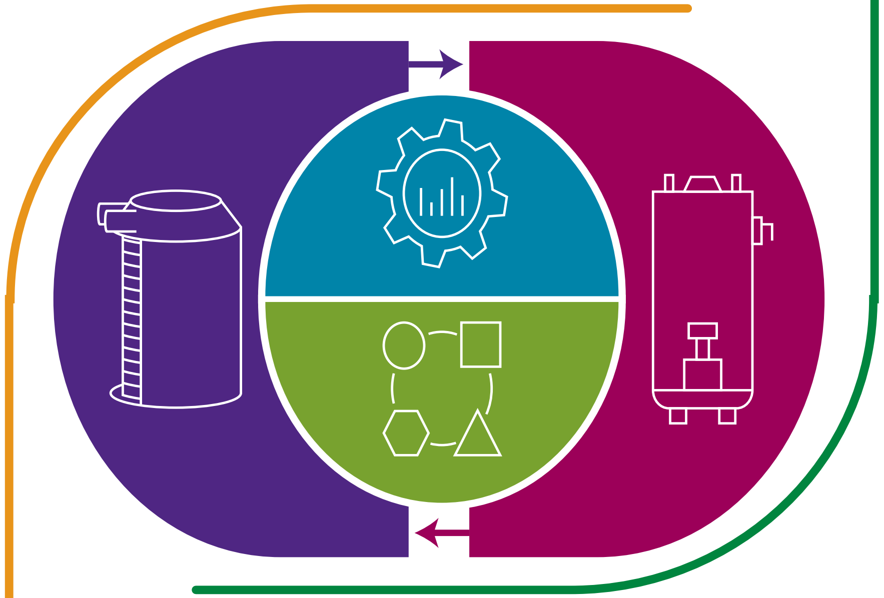
Problem

CHALLENGES

Homeowners and tenants need affordable and reliable alternatives to fossil fuel-based systems for space conditioning and domestic hot water.

Electric heat pumps are the most viable alternative, but most HP capacity and efficiency decline during cold temperatures.

Integrated HP systems lack optimized controls to extract maximum flexibility and benefits.



Innovations such as design co-optimization and advanced control that systematically integrate thermal energy storage with heat pumps to provide cost-effective, reliable, energy efficient grid-responsive solutions offer compelling clean options.

OPPORTUNITIES

BTO Alignment and Impact

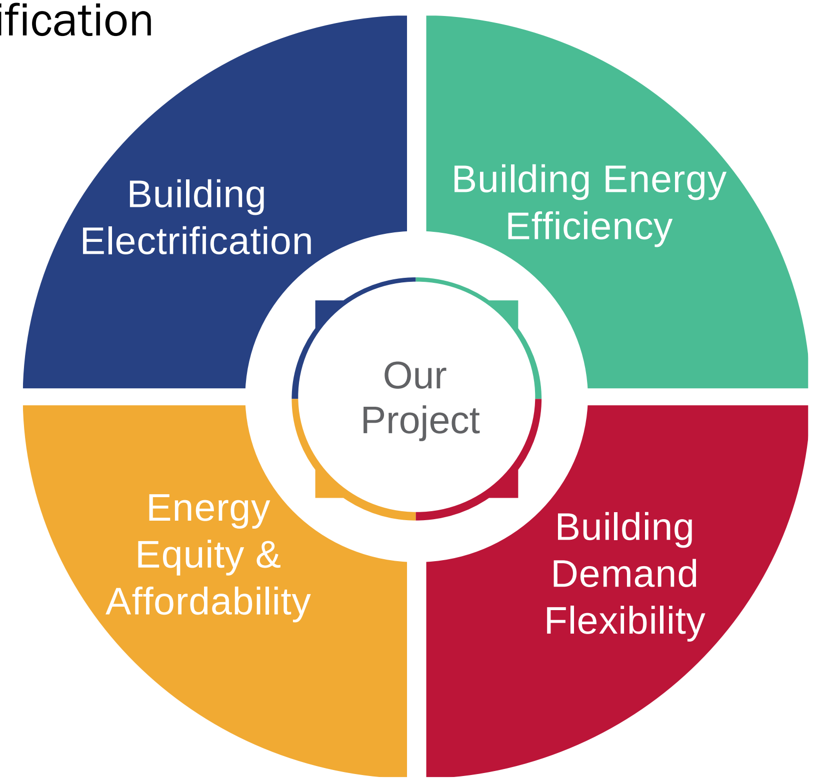
Advanced rule-based control with predictive and adaptive capabilities plus co-optimization-based equipment sizing and control tuning for affordable, high-performing HP integration

- Reduce lifecycle cost of HVAC electrification by enabling HP-TES optimal system configuration, sizing, and operation

Reduce upfront capital cost by ≥ 10%

Reduce energy cost by ≥15%

- Enable affordable building electrification in multi-family homes
- Train students and researchers from groups underrepresented in STEM



- Maximize the inherent flexibility of HP-TES through improved controls and coordination strategies

Reduce energy consumption by ≥ 10%

Increase cold temperature operational capacity by ≥ 15%

- Enable greater demand flexibility to off-peak periods or periods when renewable electricity is available

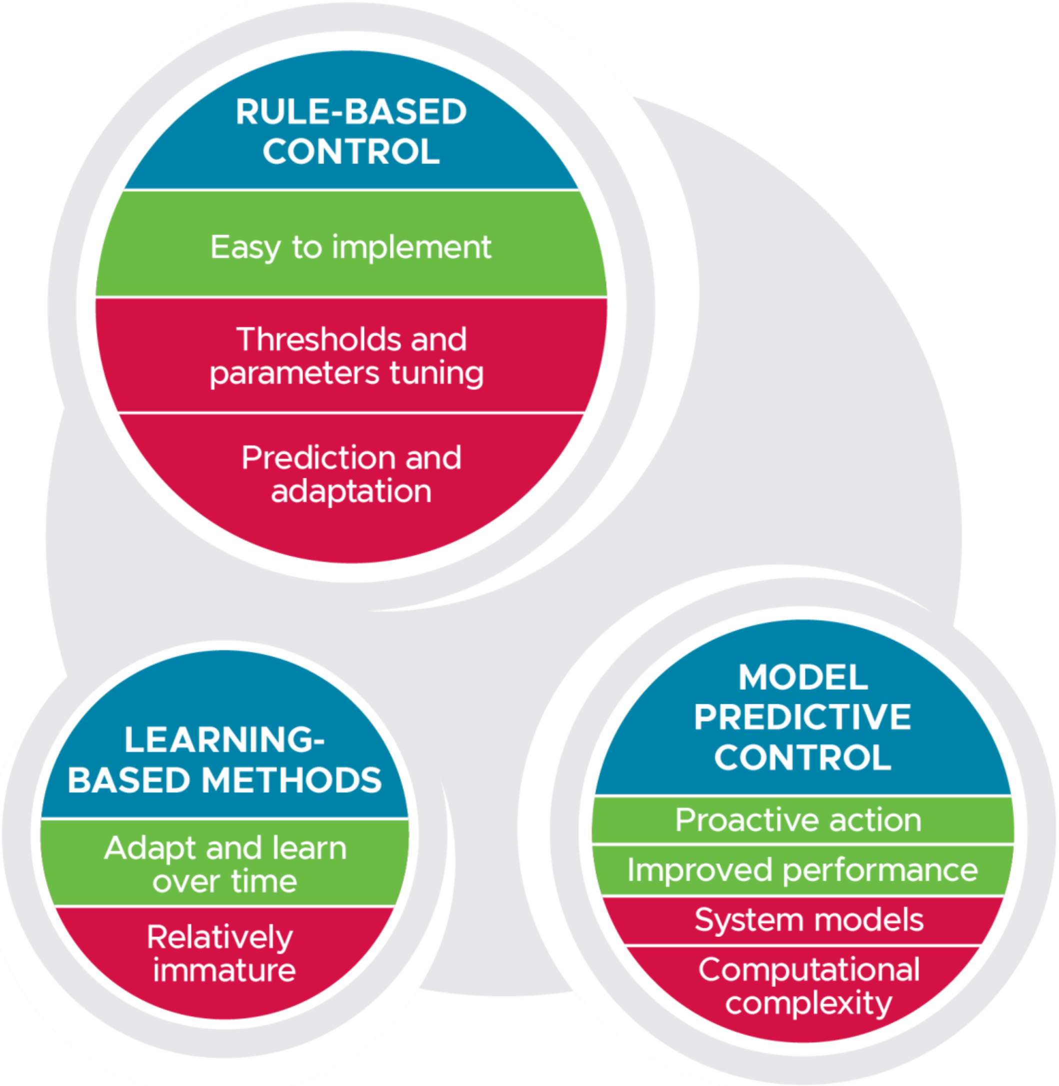
Reduce peak load by >30%

North America residential heat pump market size is valued at >14 billion USD with projected annual growth rate of over 8% from 2022-2028.

Approach: State-of-the-Art

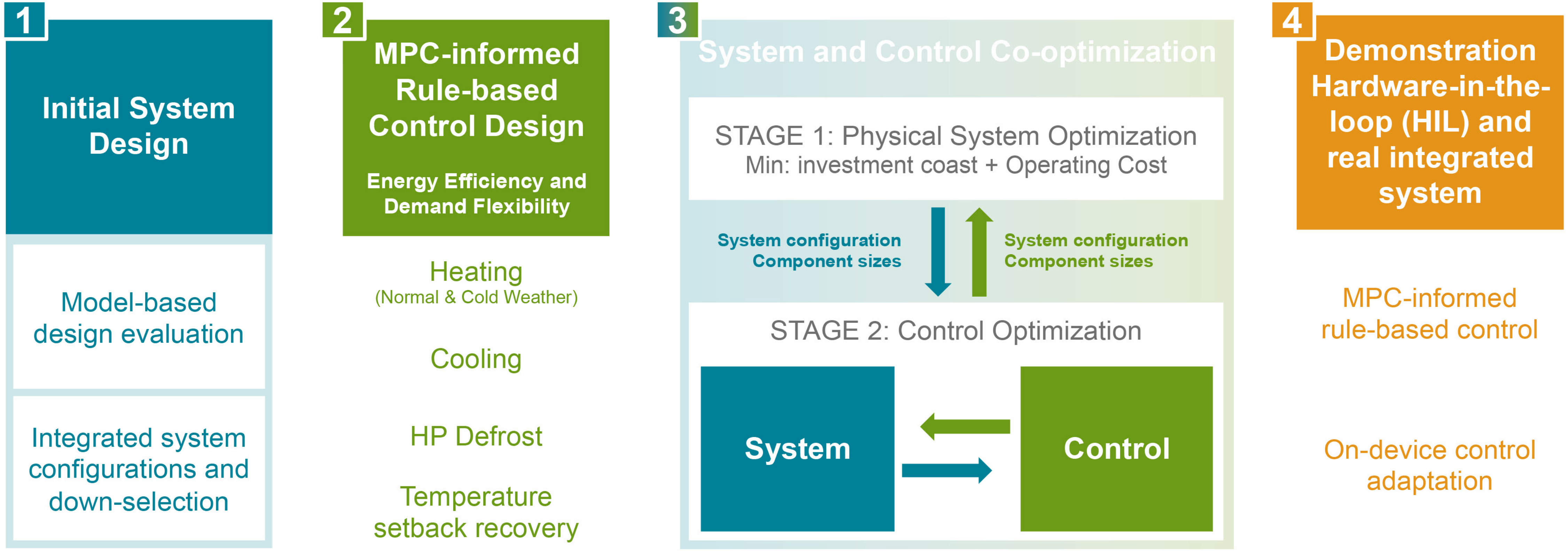
- Existing TES in the form of domestic hot water storage (or others) is rarely integrated with HP
- Best-in-class systems offer hardware capabilities but lack intelligence and controls to extract maximum flexibility and benefits
- TES sizing tools do not explicitly consider interaction with other building systems nor how the TES will be operationalized (control strategies)

HVAC and Energy Storage Control



Approach – Key Technical Elements

- Unified device-level control approach that agglomerates the advantages of model predictive control (MPC) and learning-based techniques with the relative implementation ease of rule-based control (RBC)
- Co-optimization-based sizing tool to deliver optimized system configuration and sizing decisions
- Two distinct testcases confirm benefits and amplifies impact

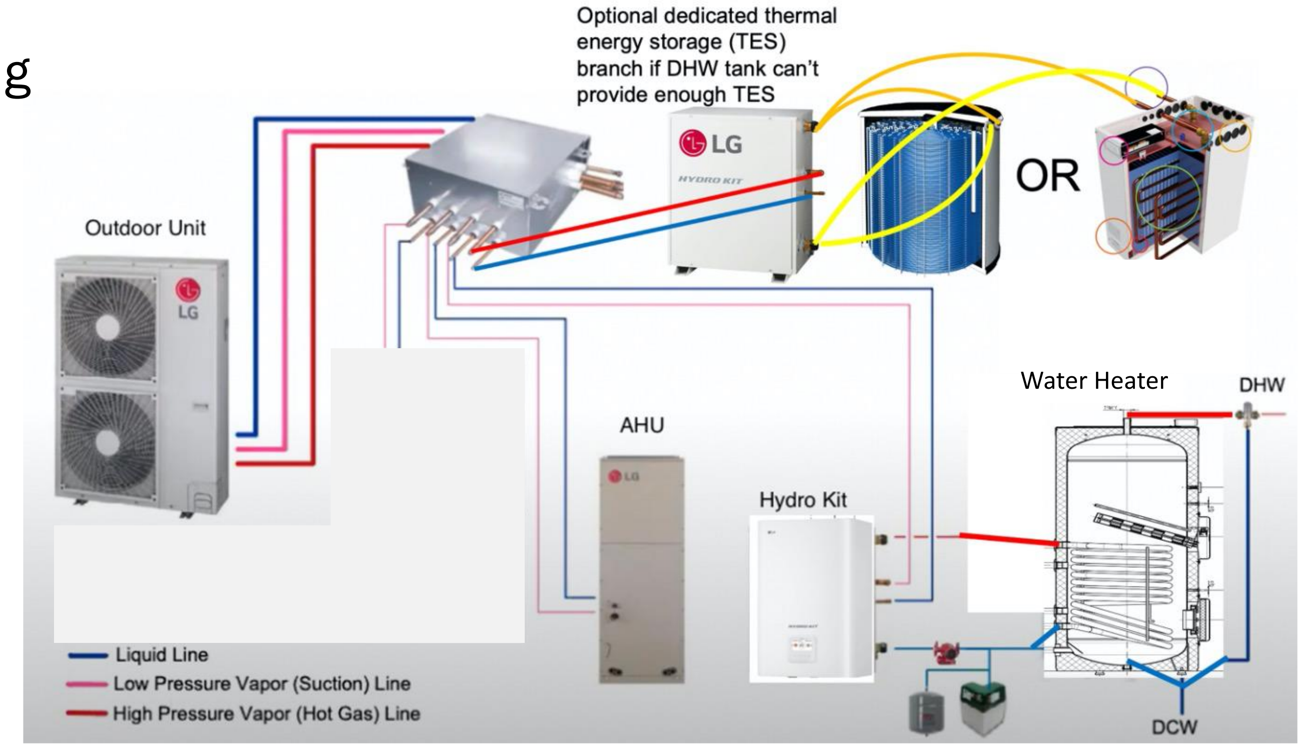


Leverage PNNL's developed ML-enabled scalable control co-optimization framework and tools for integrated building energy systems

Approach: Test Case 1 - Multi-purpose Heat Pump (MHP)

Air-sourced MHP system for single family residential homes

- Variable refrigerant flow system (VRF) with heat recovery (HR)
- Connects space conditioning and water heating to provide simultaneous heating and cooling
- Potential to
  - access heat from the water heater for space heating
  - reject air conditioning waste heat to heat water (free hot water in the summer)
  - use heat from the water heater for HP defrost
- Utilizes domestic hot water as TES
- Can be configured with a variety of TES solutions
- Testing in PNNL Lab Homes



Residential heat pump with VRF heat recovery system setup that provides space conditioning, domestic hot water, and the option of dedicated thermal energy storage

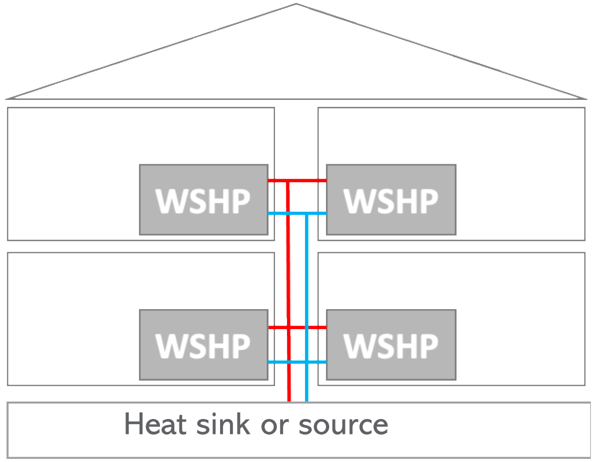
Approach: Test Case 2- Water Source Heat Pump (WSHP) System

WSHP system for multifamily buildings

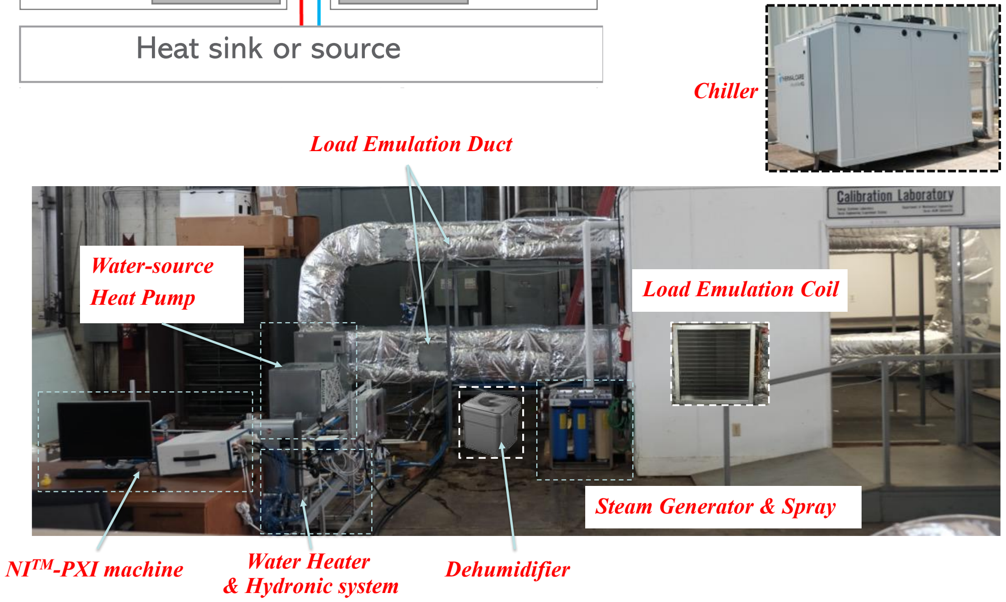
- Higher efficiency in cold winter because of relatively constant temperature of heat source/sink (water body/ground)

- Distributed heat pump system provides simultaneous heating and cooling loads to meet diverse requests from individual WSHP in each apartment

- Testing in Texas A&M HP test facility



TRANE TECHNOLOGIES™



Trane Axiom™ WSHP

Advanced Rule-based Control: MPC-Informed Design

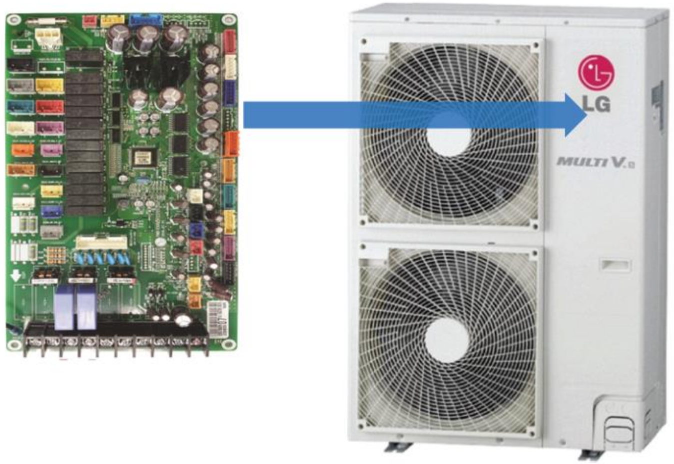
- **Offline:** Principled, offline, data-driven approach to learn simplified strategies for HP-TES operations
- **Online:** Light weight adaptation scheme (e.g., Fuzzy-logic-based) enabling RBC self-tuning and control adaptation to new data and operational scenarios

Remote Controllers
(interface for users to control comfort)

Central Controller (Monitor and control entire system)

Mode Switch Controller

- Outdoor Unit → Compressor pressure, four-way valve, fan speed, EEV
- Indoor Unit → Fan speed EEV
- Hydrokit → EEV



Advanced Rule-based Control : Example Strategies

MHP System

Coordinated space cooling and TES charging to maximize heat recovery (free hot water in the summer)

Proactive TES control that minimizes HP operation during the coldest hours of the day (typically at night) when efficiency is low

MHP defrost strategy that draws heat from the lower half of the stratified DHW tank without impacting the occupants' hot water demands

Distributed WSHP System

Optimized coordination of compressor and fan operation for improved variable-speed HP performance (baseline is synchronized)

Optimize common water loop temperatures by coordinating the operations of individual WSHP units and the central heat sinks/sources

MHP and WSHP Systems

Demand side (space cooling/heating) load management

Target metrics*

Increase cold temperature operational capacity by ≥ 15%

Reduce energy consumption by ≥ 10%

Reduce energy cost by ≥15%

Reduce peak load by >30%

* *Compared to best-in-class high-efficient HP systems under diverse conditions (climatic, electricity pricing, etc.)*

Risks, Stakeholder Engagement and Technology Transfer

Key technical risks –Advanced RBC robustness, system integration and testing

- Utilize a balanced set of operational scenarios, ambient conditions, operating modes, and building loads for control design and validation.
- Phased testing (simulation to lab) produces holistic assessment and confirms performance.
- Work closely with Trane and LG to resolve any hardware/software's related issues. Install additional sensors for observability if needed.

Key market barriers - cost and reliability, awareness and training.

- Integrate market-available HP and TES components, reduce overall system cost while maintaining occupant's thermal comfort.
- Reduce software engineering cost through automation and delivery of lightweight controls, deployable on existing onboard control platforms.
- Reach a large percentage of end users through industrial partner's existing sales network.

Communications/Outreach Strategy

- Engage diverse advisory board, promote work and solicit feedback at conferences and trade shows attended by target audiences.
- Publish underlying core capabilities, algorithms, and codes for broader use.

Technology Transfer and Commercialization

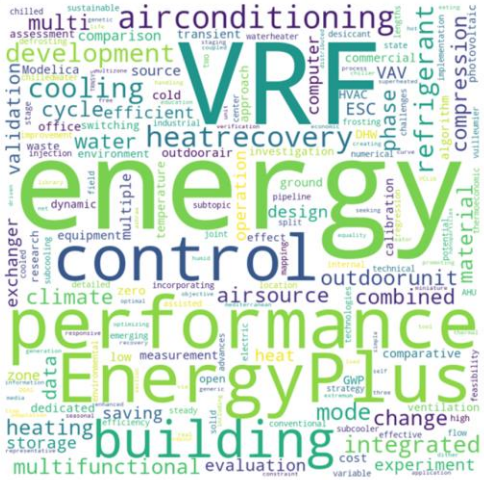
- Identify market size, potential market penetration for MHP & WSHP systems with advanced controls.
- Identify missing products (if any) to address market.
- Add new capabilities to product development roadmap, determine best timing.

Progress: Towards Model-based System Evaluation | MHP

Rigorous literature review (66 papers) on variable refrigerant flow (VRF) system with heat recovery

Word: Frequency

'energy': 19
'VRF': 16
'performance': 14
'EnergyPlus': 13
'control': 11
'building': 9
'air-conditioning': 9
'heat recovery': 8
'cooling': 7
'multi': 7
'development': 6
'refrigerant': 6
'integrated': 5
'mode': 5
'outdoor unit': 4
'air-source': 4
'multi-functional': 4
'cycle': 4
'climate': 4
'heating': 4



Main Take-away

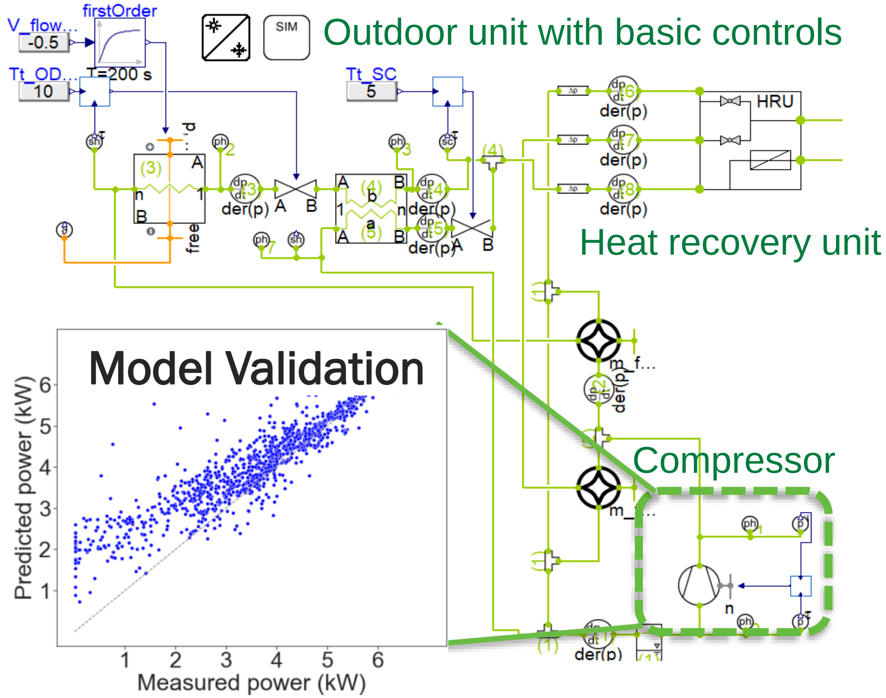
- **EnergyPlus** - Limited dynamic performance verification. Lacks flexible control support. No support for water-to-refrigerant heat exchanger.
- **Modelica** – No existing models for VRF with HR. Limited support for mode switching.

Shared findings and gaps with BTO Building Energy Modeling TM to inform new efforts

MHP component models and baseline controls implemented in Modelica. Ongoing validation using data from installed LG system.

Installed MHP system

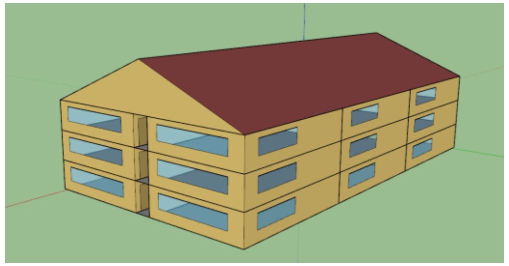
System model



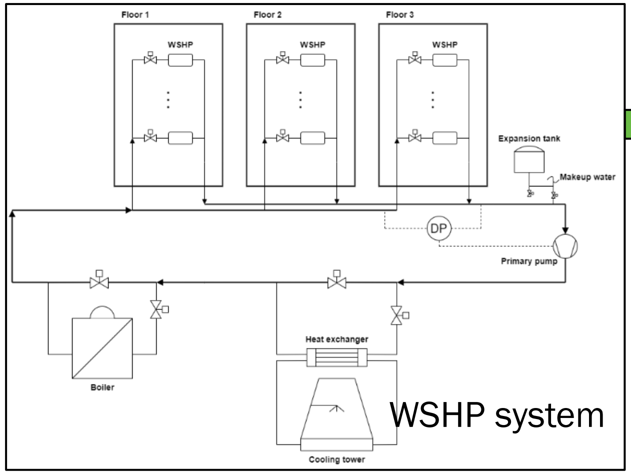
Progress: Towards Model-based System Evaluation | WSHP

Establish baseline configuration based on common industrial practice and created a virtual testbed

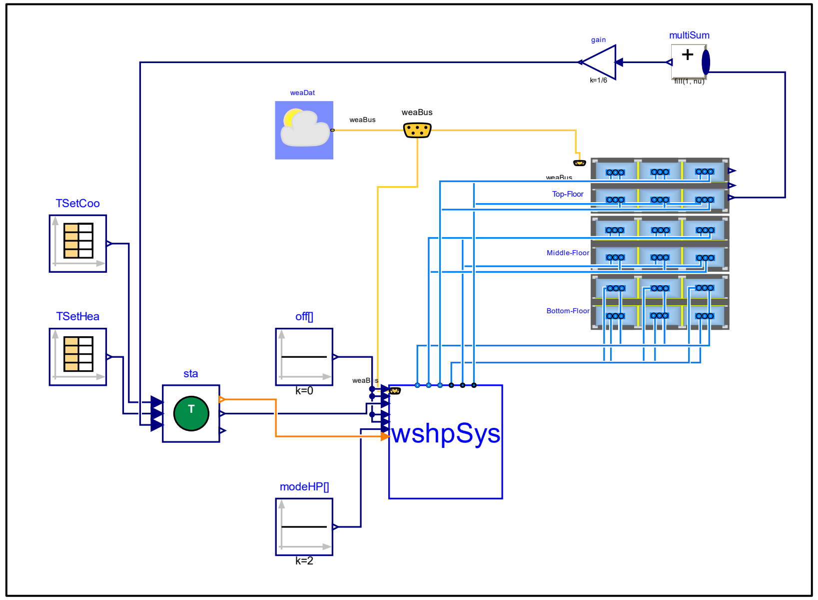
Source side	Ventilation system	Heat transport / pumping	Piping system	Load side
Condensing Natural Gas Boiler; Cooling Tower	Supply-side ventilation fan (for low rise building)	Variable flow – differential pressure control	Reverse return	Distributed WSHP



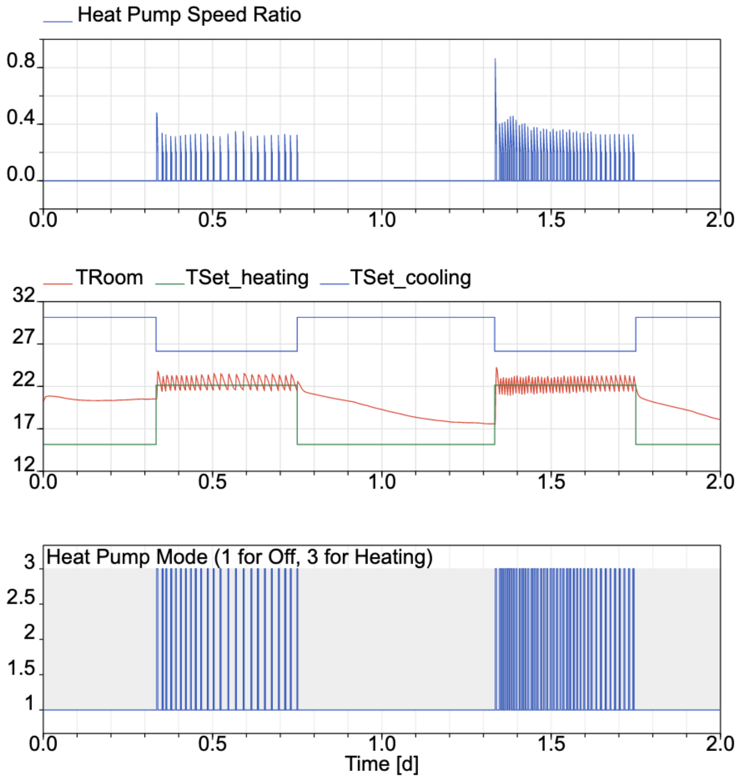
DOE prototype multifamily low-rise building (3 floors, 18 apartments)



WSHP system



Established whole system model using spawn of EnergyPlus



Simulation result of WSHP heating operation

Progress: Strategic Advisory Group

Established strategic advisory board

Name	Affiliation	Group
Rohini Brahme	Senior Manager, Lennox International	HVAC OEM
Russ Taylor	System Engineer, Carrier AdvanTEC Solutions	
Paul Ehrlich	President, Buildings Intelligence Group	Consultants – Energy efficiency and building to grid integration
Sonya Pouncy	Partner Building Vitals	
Katelynn Essig	Director of Sustainability Foundation Communities	Underserved communities affordable housing interest
Genaro Bugarin	Director of Energy Innovation, The Energy Coalition	
Joe Raasch	Director, Projects and Applications. Thule Energy Storage	TES Manufacturer

Q1 Milestone: Project advisory board is established

- First meeting held on March 17, 2023
- Discussed project overview and down-selected system configurations*

Feedback:

- Control architecture
- Prioritizing control objectives
- Maintainability of control software

**Q2 Milestone: System configurations and evaluation metrics*

Future Work

1 **Initial System Design**
HP-TES modeling, configuration down-selection & evaluation.

2 **Control Design**
Baseline control specifications and implementation.
Develop, implement, and validate advanced RBC in simulation.

3 **System & Control Co-optimization**
Customize and apply existing method.
Address uncertainties.

4 **Control Integration, Validation, and Demonstration**
Test plan, control and communication architecture.
Advanced RBC control implementation and testing.

5 **Technology Transfer and Outreach**

Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12

Concluding Remarks

- Right-sized equipment combined with improved control systems to increase HP capacity and efficiency at lower temperatures and provide satisfactory grid response offers cost-effective and high-performing solutions.
- Advanced RBC method and co-optimization-based sizing apply to different HP and TES integrated systems.
- Project will
  - Deliver improved control strategies, equipment sizing tools, and guidelines for broader community use.
  - Transition validated control prototypes to LG and Trane for further testing and product integration.

Pacific Northwest NATIONAL LABORATORY
TEXAS A&M UNIVERSITY
TRANE TECHNOLOGIES
LG Life's Good

Thank You

Pacific Northwest national Laboratory (PNNL)
Texas A & M University (TAMU)
Trane Technologies
LG Electronics US (LGEUS)

Veronica Adetola (PNNL)
(509) 371-6996; Veronica.Adetola@pnnl.gov
Project #: 3.2.2.57

REFERENCE SLIDES

Project Execution

	FY2023				FY2024				FY2025			
Planned budget												
Spent budget												
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Q1 Milestone: Project advisory board is established												
Current/Future Work												
Q2 Milestone: System configurations and evaluation metrics												
Q3 Milestone: WSHP unit model is validated												
Q4 Milestone: MHP component and integrated models are validated												
Q4 Milestone: Preliminary system design completed												
Q1 Milestone: Preliminary device-level control for WSHP unit												
Q2 Milestone: Data generation and control test plan completed												
Q3 Milestone: Advanced RBC control for WSHP is validated												
Q4 Milestone: Co-design framework, equipment sizing and controls co-optimization												
Q1 Milestone: Co-optimization tool completed												
Q2 Milestone: MHP controls V1 completed												
Q3 Milestone: WSHP Control implemented and verified												
Q4 Milestone: MHP controls V2 implemented and verified												
Q4 Milestone: Commercialization plan												

Milestone planned date

Go/no-go decision points

Team

PNNL

Control design, System co-optimization. MHP modeling, controls implementation and testing

Veronica Adetola

Edward Louie

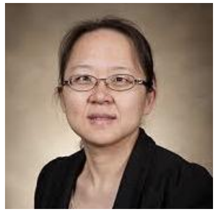
Xing Lu

Saptarshi Bhattacharya

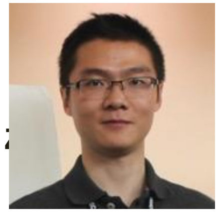
Junke Wang

TAMU

WSHP system: system modeling, control design and implementation, system integration and testing

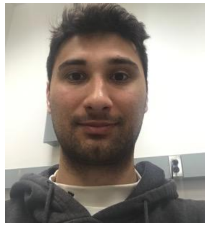


Zheng O’Neill



Ziyao Yang

Mingzhe Liu



Caleb Calfa

Trane Technologies

WSHP system: system modeling, baseline control specifications, control architecture, integration and testing

Scott Munns

Kaustubh Phalak

Venkatesh Mantalwad

LG

MHP system support: baseline control specifications, control architecture, integration and testing

Aushutosh Suri

Sangok Kweon