2024 PROJECT PEER REVIEW

U.S. DEPARTMENT OF ENERGY
BUILDING TECHNOLOGIES OFFICE

BTO Peer Review: Residential Heat Pump with Thermal Energy Storage to Enable Grid Decarbonization



Residential Heat Pump with Thermal Energy Storage to Enable Grid Decarbonization

Stor4Build
U.S. DEPARTMENT OF ENERGY

Oak Ridge National Laboratory
Kyle Gluesenkamp, Distinguished R&D Staff
gluesenkampk@ornl.gov
03.04.06.75

Prototype TES-ready heat pump



Retrofit-ready: air handling unit

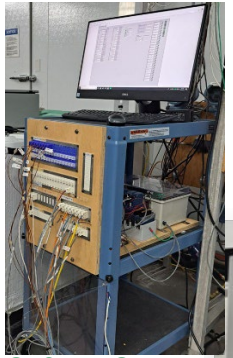


Refrigerant line set

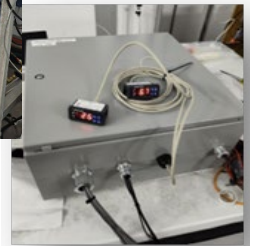
Hydronic connection (secondary loop)



TES – salt hydrate PCM



DAQ & TES-HP controller



EXV control box

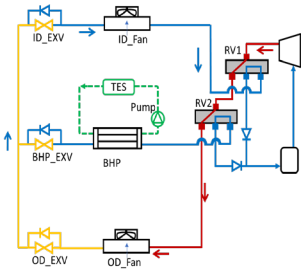
Project Summary

OBJECTIVE, OUTCOME, & IMPACT

- Develop a prototype TES-ready heat pump and controls for laboratory and field testing at ORNL.
- Design and fabricate a 3-ton TES-HP system.
- Achieve at least 20% peak electric demand reduction for 3 hours compared to a conventional air-source heat pump.







TEAM & PARTNERS

Oak Ridge National Laboratory (ORNL)

OAK RIDGE National Laboratory

Stor4Build
U.S. DEPARTMENT OF ENERGY

STATS

Performance Period: May 2022 – Sep 2026

DOE Budget: $603k, Cost Share: $0k

Milestone 1 (FY24): Build prototype TES-ready HP system and conduct laboratory shakedown testing. (1b milestone) (MET)✓

Milestone 2 (FY24): Evaluate TES-HP system in a laboratory environment. (MET)✓

Milestone 3 (FY25): Field testing during both summer and winter

Problem

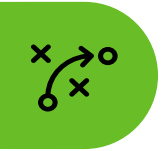
- Electrifying 57 million residential gas furnaces will require heat pumps with flexible electrical demand
  - Auxiliary backup for 57 million conventional heat pumps would be ~570 GW
- Market needs a heat pump product that can electrify heating and cooling, provide demand flexibility, and improve resilience.
- Barriers
  - Since the value of flexible demand not currently captured in the residential market, the installed cost must be competitive with alternative products
  - Additional complexity and cost of achieving 6 heat pump operating modes: refrigerant charge management with varying active system volume

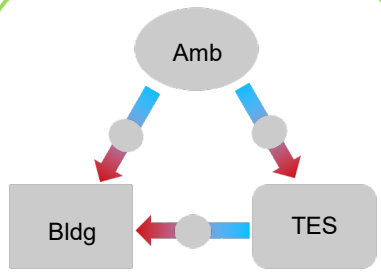
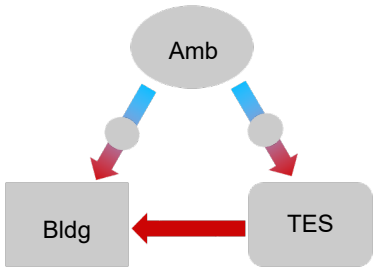
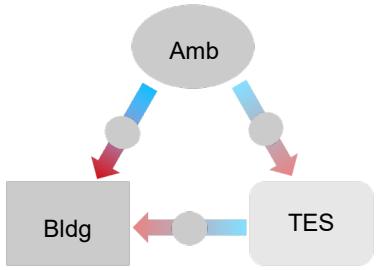
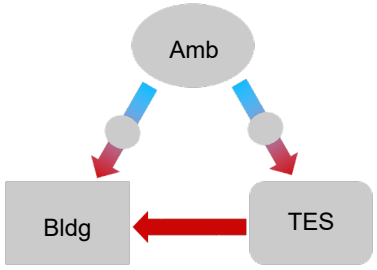
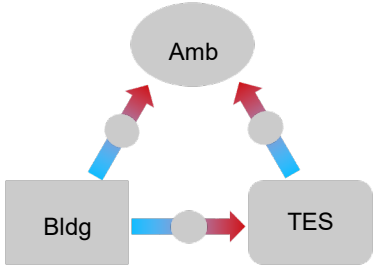
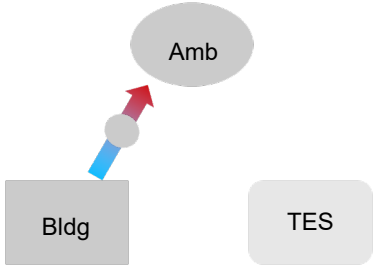
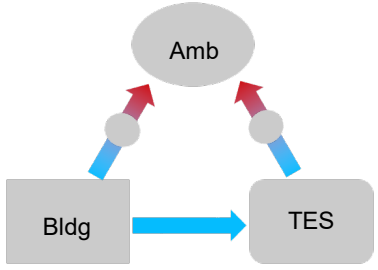
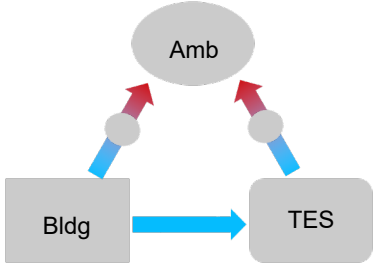
Alignment and Impact: TES-ready HP as Decarbonization Solution

Affordability and Equity	TES-ready heat pump reduces first and operating cost by “right-sizing” heat pumps and avoiding electrical service upgrade and operating the heat pumps at favorable COP during unfavorable rates and ambient conditions.
Resilience	On-site thermal storage can provide heating and cooling services during grid outages
Increase building energy efficiency	Pairing TES with HVAC systems boosts efficiency during peak hours, reducing the energy needed to maintain comfortable indoor temperatures.
Accelerate onsite emissions reductions	TES systems buffer renewable energy intermittency, reducing CO2 emissions. They also promote heat pump adoption in cold climates by lowering costs and grid demand, making them an alternative to fuel-fired furnaces.
Transform the grid edge at buildings	TES-ready heat pump enables load shifting, helping stabilize the grid and lower infrastructure costs.
Minimize building life cycle emissions	Load shifting with TES-ready heat pump improves smart building operations and indirectly reduces lifecycle GHG emissions from building materials and construction.

Deliverables to DOE: A TES-Ready HP prototype and a deliciated control strategy that can achieve these goals!

Approach – thermodynamic options



	Fully HP-mediated	Hot TES	Cold TES	Variable-temperature TES
Heating season				
Cooling season				

Most compatible with central ducted systems. Initial focus of analysis and prototype

Useful winter and summer, but least demand reduction potential

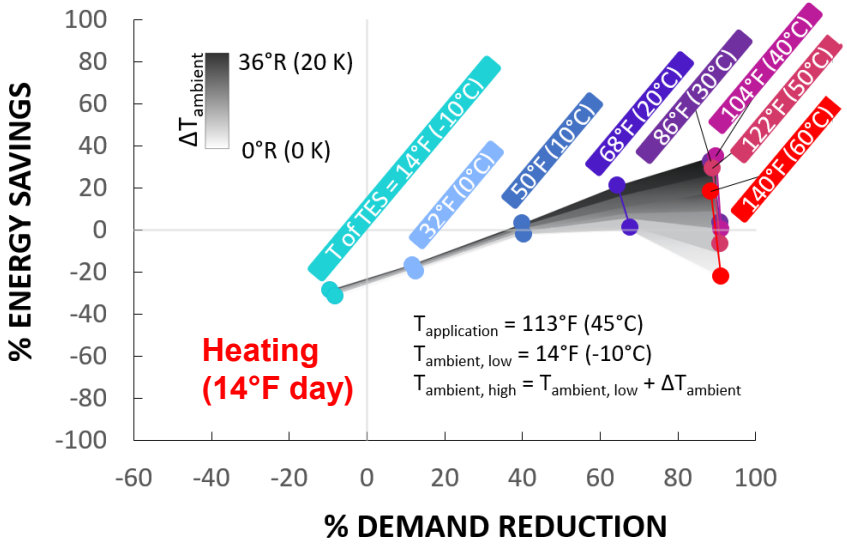
Best winter demand reduction, but not useful in summer

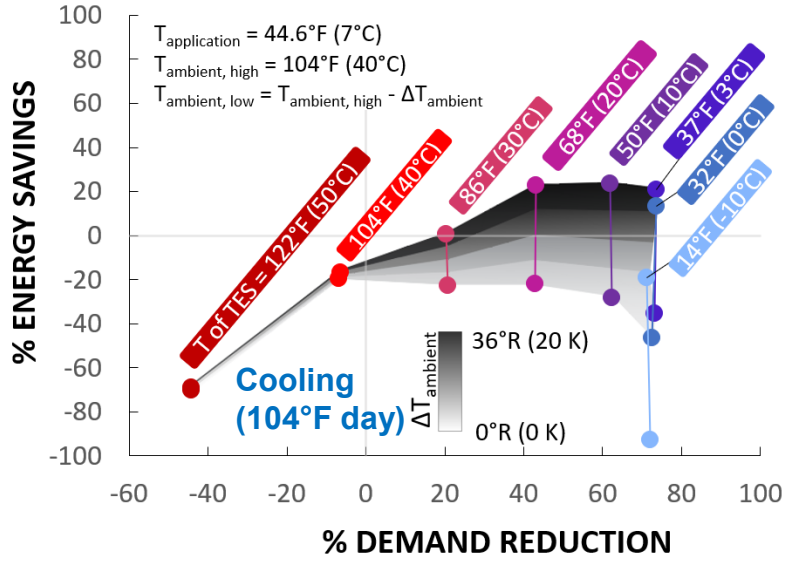
Best summer demand reduction, but less useful in winter

Can be accomplished with sensible storage or two PCMs

Approach – technology potential analysis

- **Novelty and solution:**
  - Save cost by using a single TES unit for both heating and cooling operation.
  - Simulation is based on a realistic model of vapor compression cycle in DOE/ORNL HPDM.



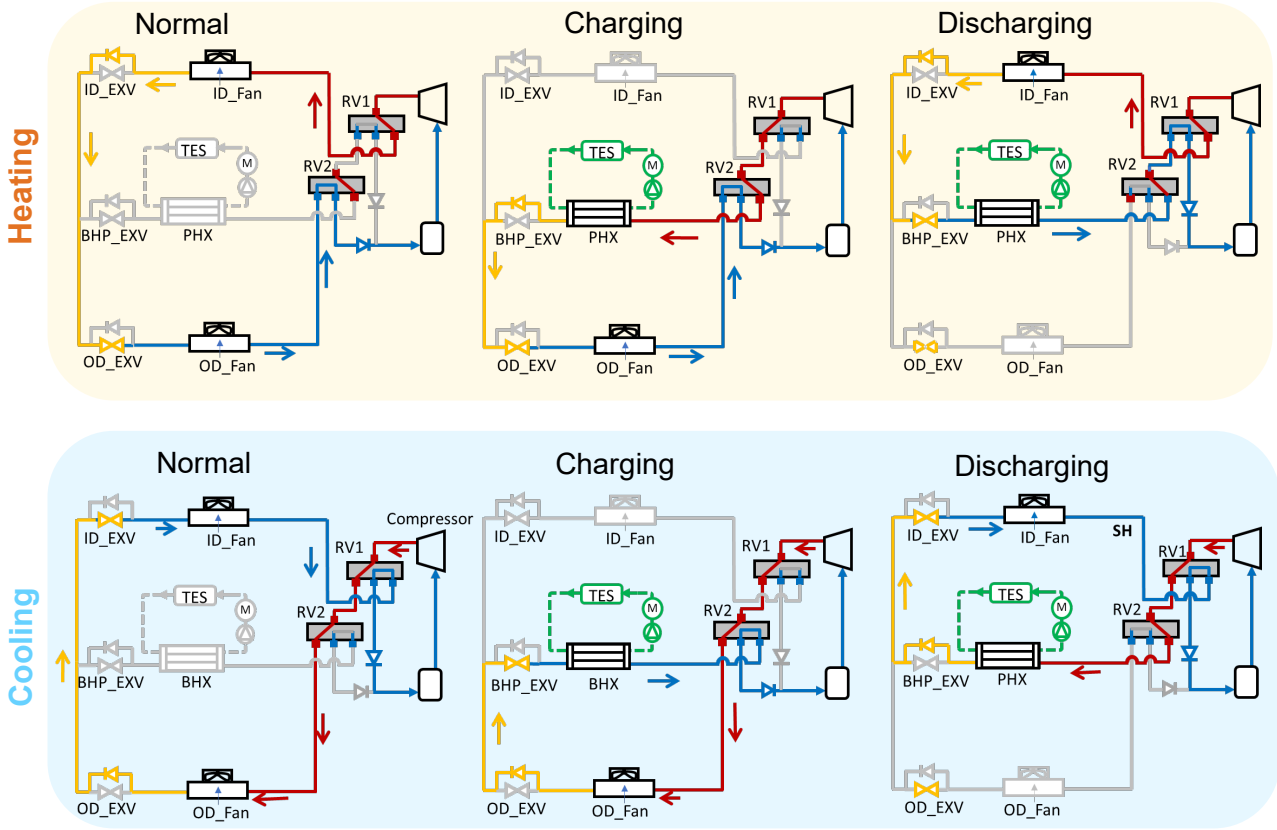


Figures generated using DOE/ORNL HPDM using the methodology described in: Jason Hirschey, Zhenning Li, Kyle R. Gluesenkamp, Tim J. LaClair, Samuel Graham (2023) "Demand Reduction and Energy Saving Potential of Thermal Energy Storage Integrated Heat Pumps" *International Journal of Refrigeration* https://doi.org/10.1016/j.ijrefrig.2023.01.026

Approach – TES-ready HP P&ID Design

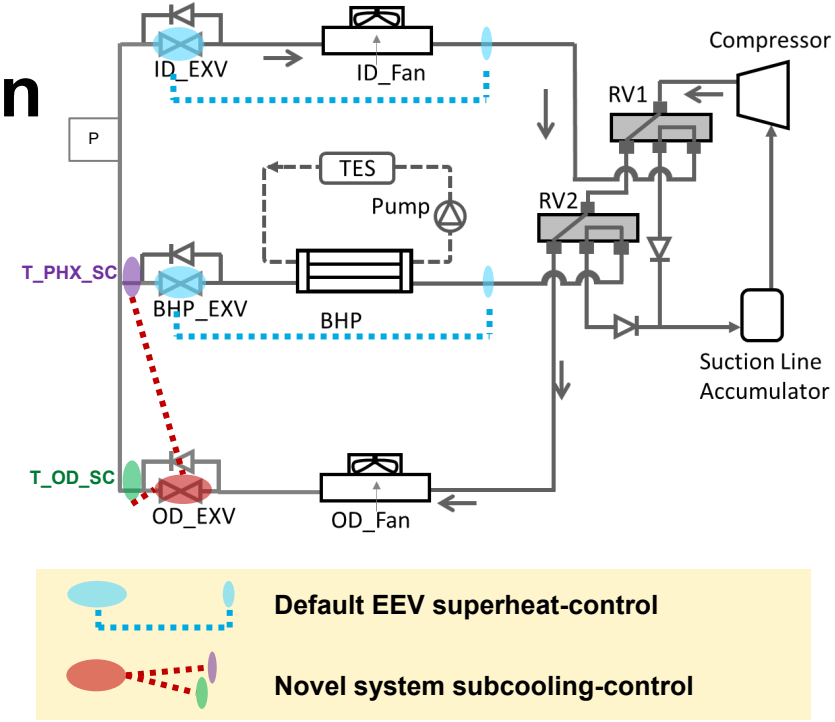
- **Novelty and solution:**
  - Accomplish all mode switching within the refrigerant circuit of the heat pump using commoditized components. Six modes enable load shifting year-around.
  - Six mode operations can enable the TES-ready HP operation year-around.

	Mode	Heat Source	Heat Sink
Heating	Normal	Air	Building
	charging	Air	TES
	discharging	TES	Building
Cooling	Normal	Building	Air
	Charging	TES	Air
	Discharging	Building	TES



Approach – Control Design

- A new control strategy was needed to obtain adequate refrigerant charge management.
- **Novelty and solution:**
  - A **novel system subcooling-control strategy** using the OD EEV has been proposed.
  - Lab tests have been conducted to **tune PID parameters and validate the feasibility** of this subcooling control.
  - Achieved **high COP and appropriate subcooling** across all six modes.



Mode	EXV	Target
Heating Normal	OD_EXV	T_OD_SC = 10°R
Heating Charge	OD_EXV	T_OD_SC = 10°R
Heating Discharge	OD_EXV	T_BHX_SC = 15°R (T_OD_SC = 15°F for Heating Discharge pre-action)
Cooling Discharge	OD_EXV	T_BHX_SC = 15°R

In order to evaluate all the modes, PID control parameters were tuned for each case

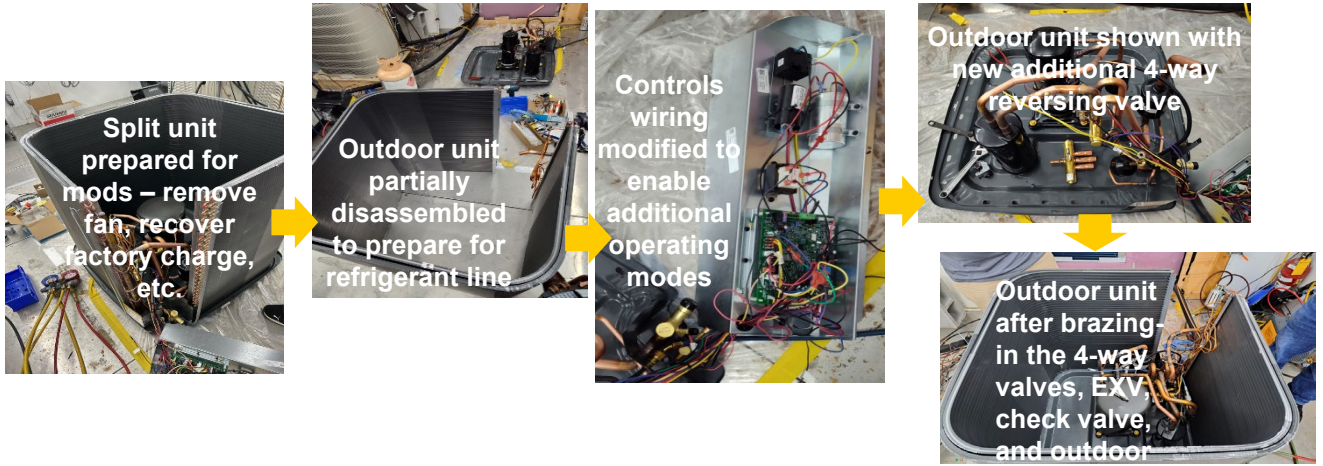
Approach – Prototype Development

Barrier: Lack of performance data for a TES-ready HP prototype using a single TES unit for both cooling and heating.

Novelty and solution:

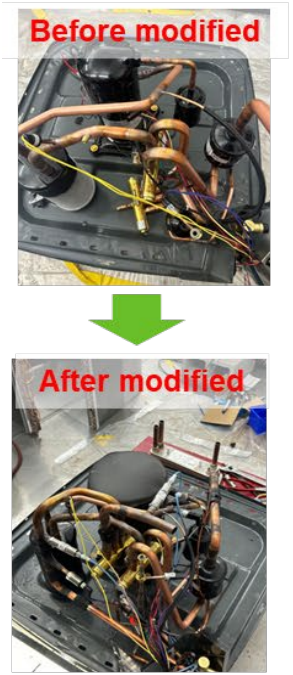
- ORNL has fabricated and evaluated the proposed TES-ready HP system in the lab.
- Laboratory evaluation: evaluate **all 6 modes** under various standard psychrometric conditions
- Field evaluation: operate using supervisory controls to confirm field performance

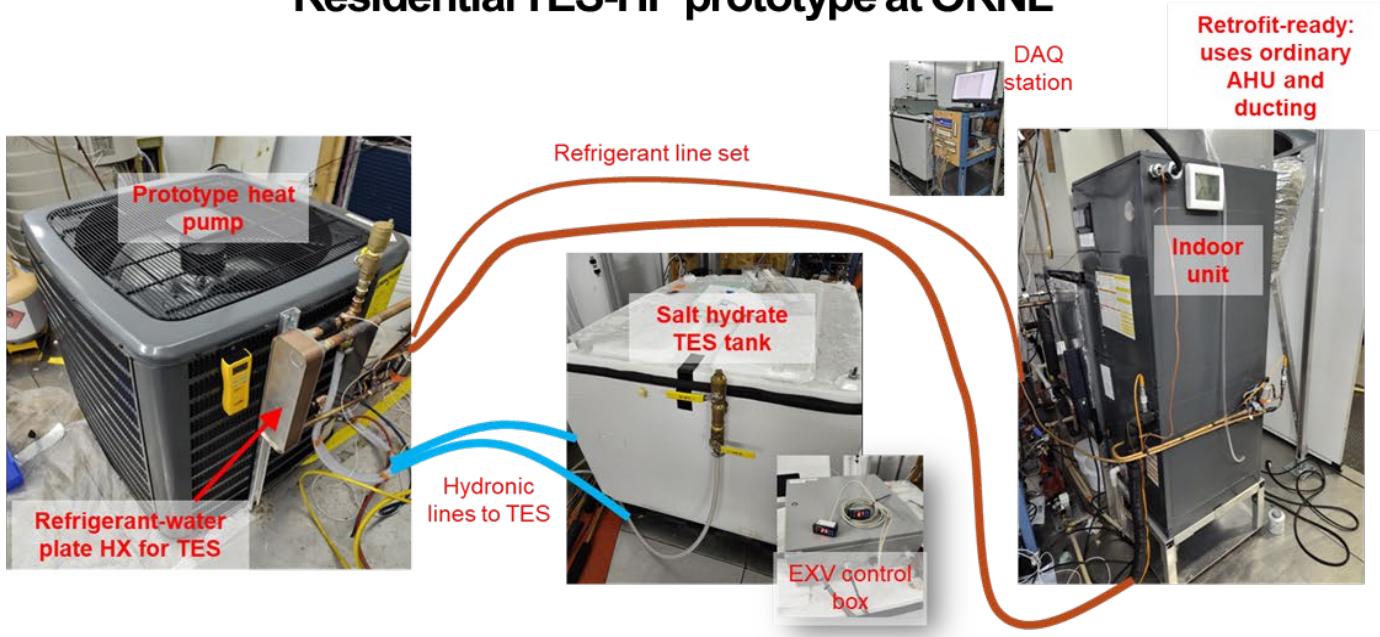
Residential split system prototype development starting with commercially-available system



Progress – Prototype Development

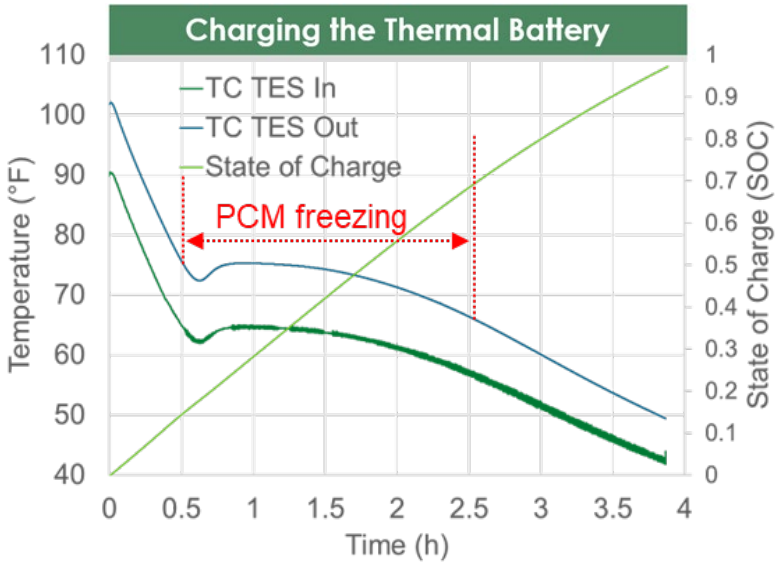
- The heat pump was modified and integrated with salt hydrate TES
- Shakedown tests were successfully completed with proper controls

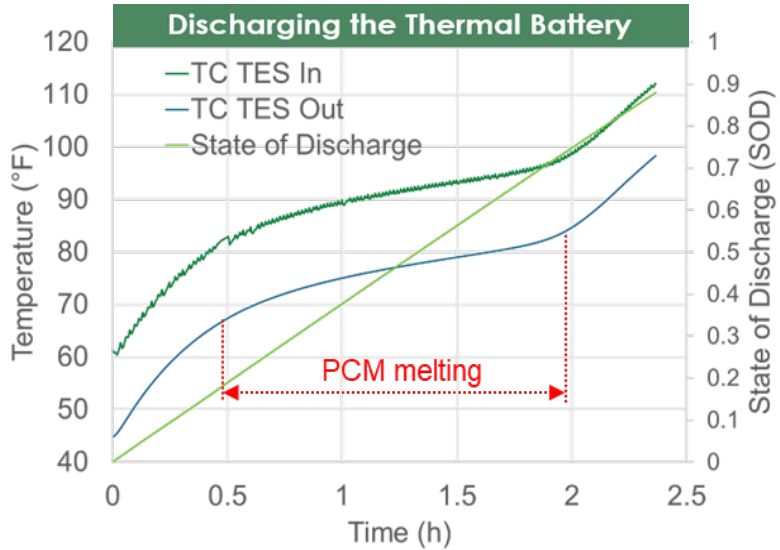




Progress – Experimental Tests in Six Modes

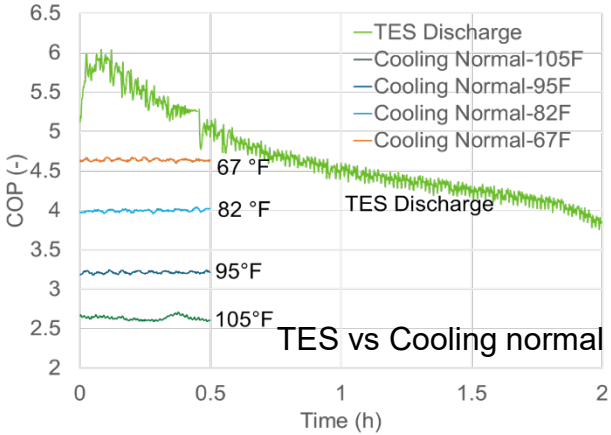
- All six operation modes have been tested in the lab for both heating and cooling under AHRI Standard 210/240-2023
- TES achieved expected charging and discharging performance

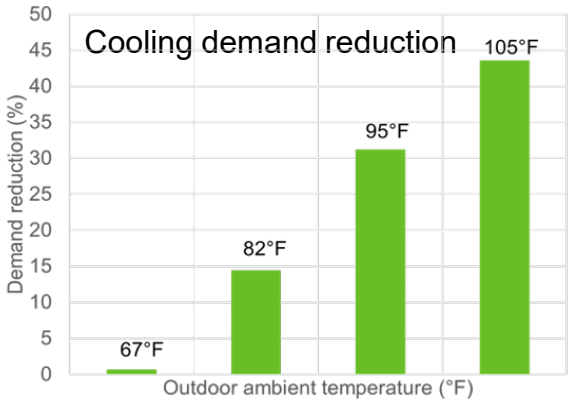


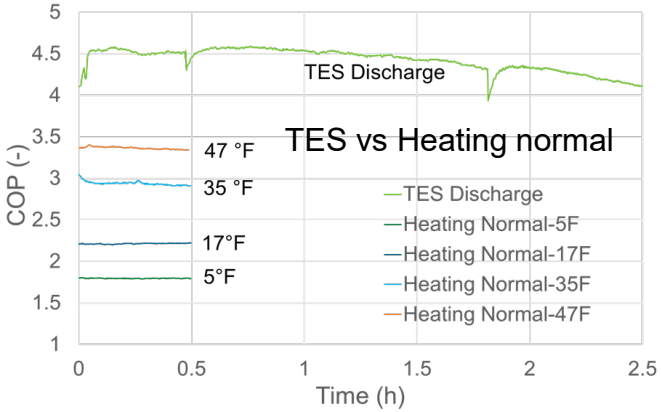


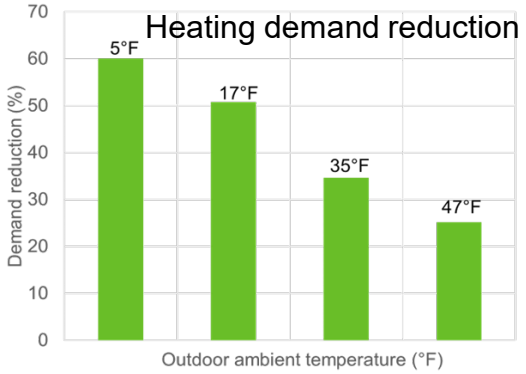
Progress – Load Shifting for Cooling and Heating

- TES-mediated HP reduces electricity consumption for both heating and cooling compared with conventional ASHP at rating conditions
- Energy demand for cooling at 95°F and 105°F was reduced by 31% and 44%, respectively
- Energy demand for heating at 17°F and 5°F was reduced by 51% and 60%, respectively



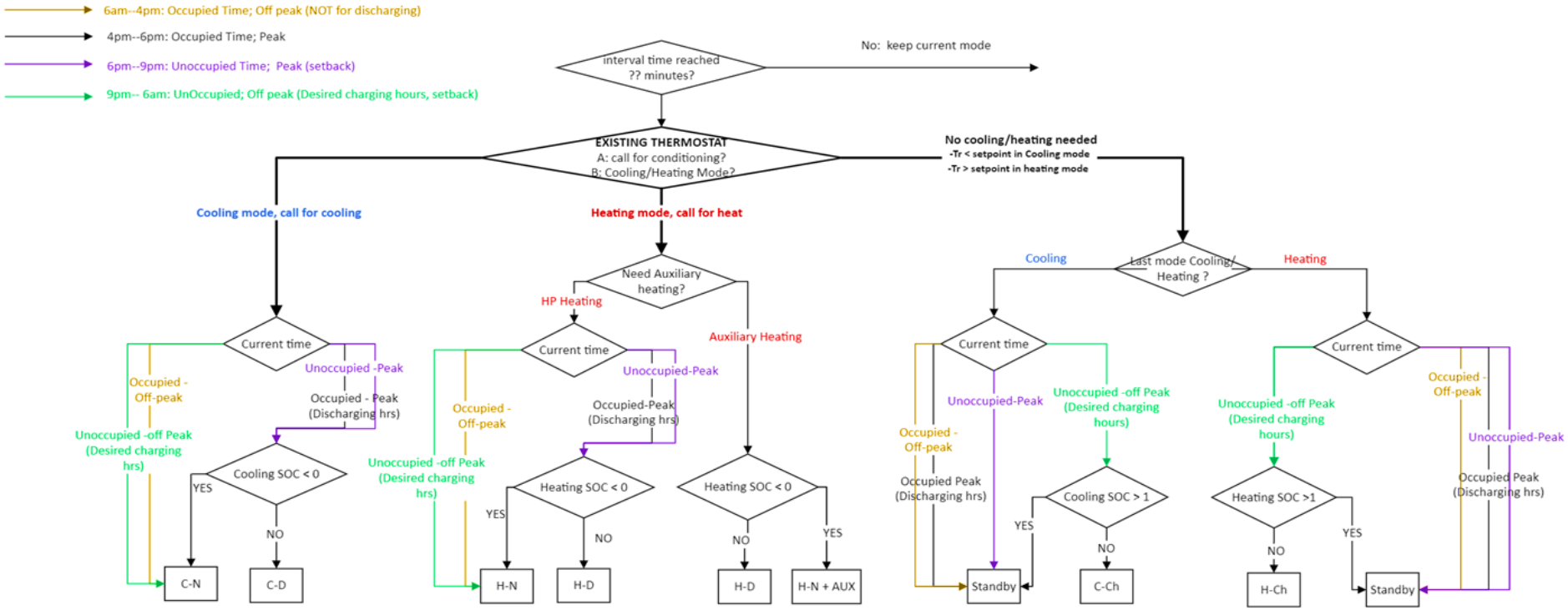






Progress – Supervisory Control for Field Test

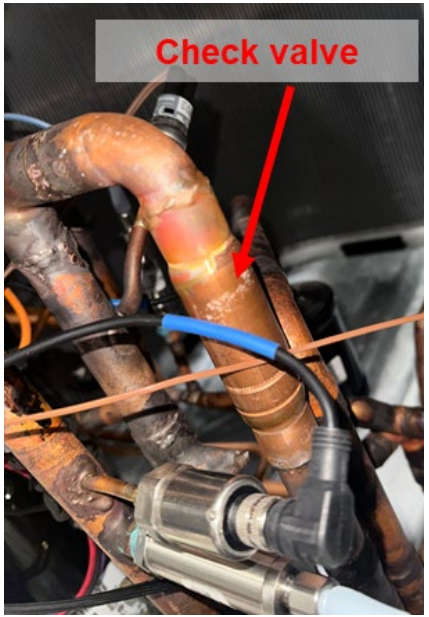
Rule-Based Control (RBC) Decision Tree



Progress – Problem Encountered and Solution

- Problem:
  - When outdoor temperature is low (below 35°F) during heating modes, refrigerant was found to have condensed and accumulated in the outdoor unit, causing performance degradation due to reduced refrigerant charge during heating discharge modes

- Solution:
  - Add a check valve between the reversing valve and suction line to prevent backflow
  - Adjust mode control sequence by switching modes between heating normal and heating discharge to maintain proper refrigerant charge in the loop



Future Work

1) Advanced controls to improve performance

- Lab tests on the prototype TES-ready heat pump showed promising results. The next step is to develop and evaluate a rule-base control (RBC) strategy for automatic mode selection for load shifting and building decarbonization.
- Demonstrate improved comfort during defrost using TES unit

2) Deploy and evaluate prototype in field to demonstrate system performance

- The field test will take place at ONRL's Yarnell research house using a 3-ton air-source heat pump with low-GWP refrigerant (R454B, GWP 466).
- The prototype TES-ready heat pump system is designed to reduce peak electricity demand by 20% for 3 hours compared to a conventional air-source heat pump.



ORNL's Yarnell research house, Knoxville, TN

End Vision

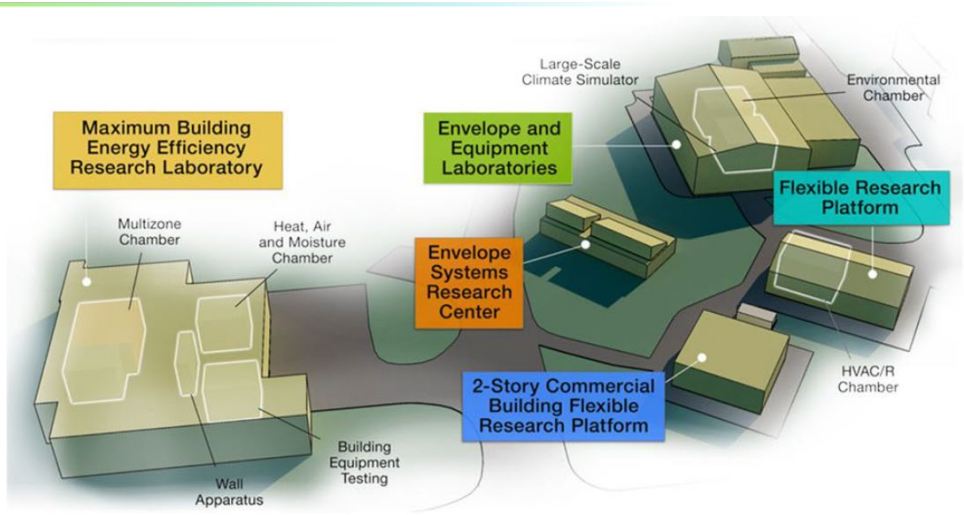
A new affordable modular TES-ready heat pump product for the U.S market

- Demonstrate the TES-ready heat pump prototype in real-world conditions to highlight its benefits in shifting demand load and improving seasonal efficiency
- Showcase the use of modular TES configuration for defrosting to boost performance and comfort
- Implement OpenADR 3.0 communication for improved grid-enabled data exchange and interoperability
- Transfer advanced control strategies to industry
- Develop product-to-market commercialization strategy with original equipment manufacturer (OEMs)

Thank you

Oak Ridge National Laboratory ||
Kyle Gluesenkamp, Distinguished R&D Scientist
gluesenkampk@ornl.gov
BTO WBS 03.04.06.75

Stor4Build
U.S. DEPARTMENT OF ENERGY



The **Building Technologies Research and Integration Center (BTRIC)** at ORNL has supported DOE BTO since 1993. BTRIC is comprised of more than 60,000 square feet of lab facilities conducting RD&D to develop affordable, efficient, and resilient buildings while reducing their greenhouse gas emissions 65% by 2035 and 90% by 2050.

Scientific and Economic Results
139 publications in FY24
140+ industry partners
60+ university partners
16 R&D 100 awards
64 active CRADAs

BTRIC is a DOE-Designated National User Facility

Project Execution

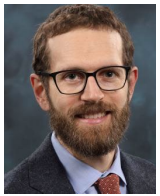
	FY2024				FY2025				FY2026			
Planned budget	$538,183				$648,000				$500,000			
Spent budget	$414,340											
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Milestone: Laboratory shakedown testing of prototype HP-TES system												
Milestone: Laboratory Evaluation of prototype HP-TES system												
Current/Future Work												
Milestone: Develop of RBC Controller												
Milestone: Evaluate in Laboratory (FRP2) Test Bed												
Milestone: Instrumentation, Installation and Shake-down of Low-GWP TES-HP in Field (Yarnell House)												
Milestone: Heating Season Field Evaluation of Low-GWP TES-HP (Yarnell House)												
Milestone: Cooling Season Field Evaluation of Low GWP TES-HP (Yarnell House)												

◆ Target

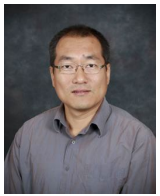
◆ Completed

Team

System Design, Experimental, and Modeling



Kyle Gluesenkamp
Distinguished R&D Staff



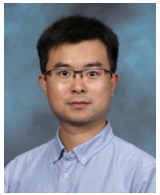
Bo Shen
Senior R&D Staff



Navin Kumar
Technical Staff



Zhenning Li
Associate R&D Staff



Lingshi Wang
Associate R&D Staff



Yifeng Hu
Associate R&D Staff

System Design, and Controls



Xiaobing Liu
Senior R&D Staff



Yiyuan Qiao
Postdoctoral Researcher

Thermal Energy Storage Materials



Tugba Turnaoglu
Associate R&D Staff



Vera Bocharova
Research Staff



Damilola Akamo
Postdoctoral Researcher