Low-cost PCM Integration into Heat Pumps

Oak Ridge National Laboratory
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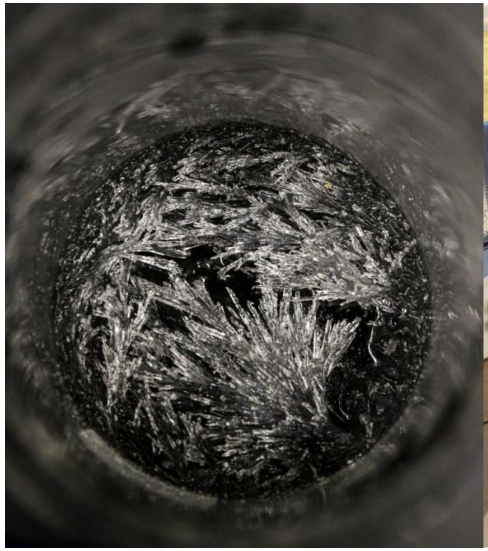
BTO WBS 3.4.6.75

Project Summary

Objective and Outcome

- ☐ The goal is to develop PCM integrated heat pump
- ☐ Outcomes
  - ○ Develop full-scale salt hydrate-based PCM HX integrated with a heat pump
  - ○ Demonstrate 1 ton (3.5 kW) usable discharge power and at least 2 hours storage capacity



Team and Partners

Oak Ridge National Laboratory (ORNL)

University of Tennessee, Knoxville

Georgia Institute of Technology

Melink Corporation

Stats

Performance Period: FY22-FY23 | DOE Budget: $800k/yr

Key Milestones:

Milestone 1 (FY22): Integrate ORNL salt hydrate-based PCM HX with a novel ORNL heat pump configuration (MET)

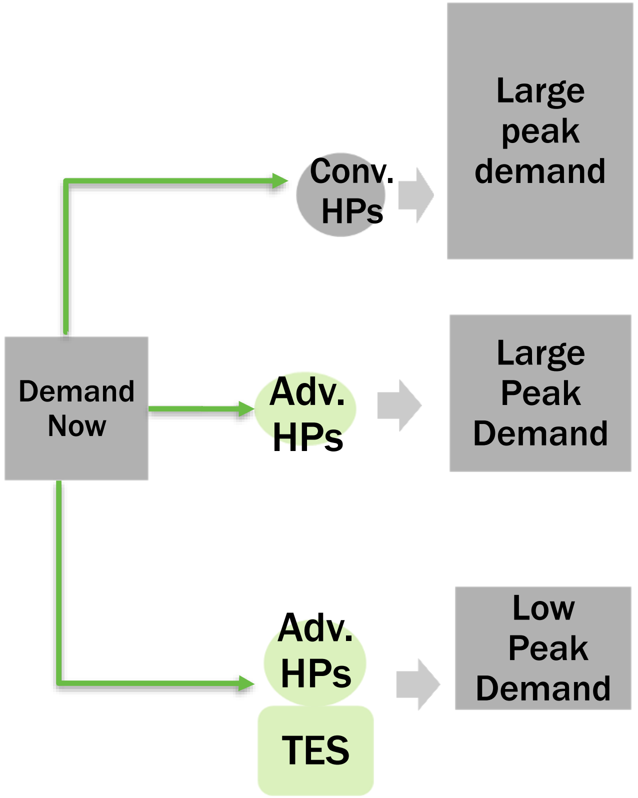
Milestone 2 (FY23): Develop salt hydrate-based PCMs with reduced phase change temperature

Milestone 3 (FY24): Performance evaluation of ORNL PCM integrated with novel heat pump config. and field demonstration

Problem

- **Urgent need to mitigate the impacts of climate change: Electrification for Decarbonization**
- **If we replaces all furnaces with conventional heat pumps:**

  Conventional heat pumps (HPs) use supplemental electric resistance heat, which will result in high electric demand in winter, which could overstress the existing grid and leading to blackouts



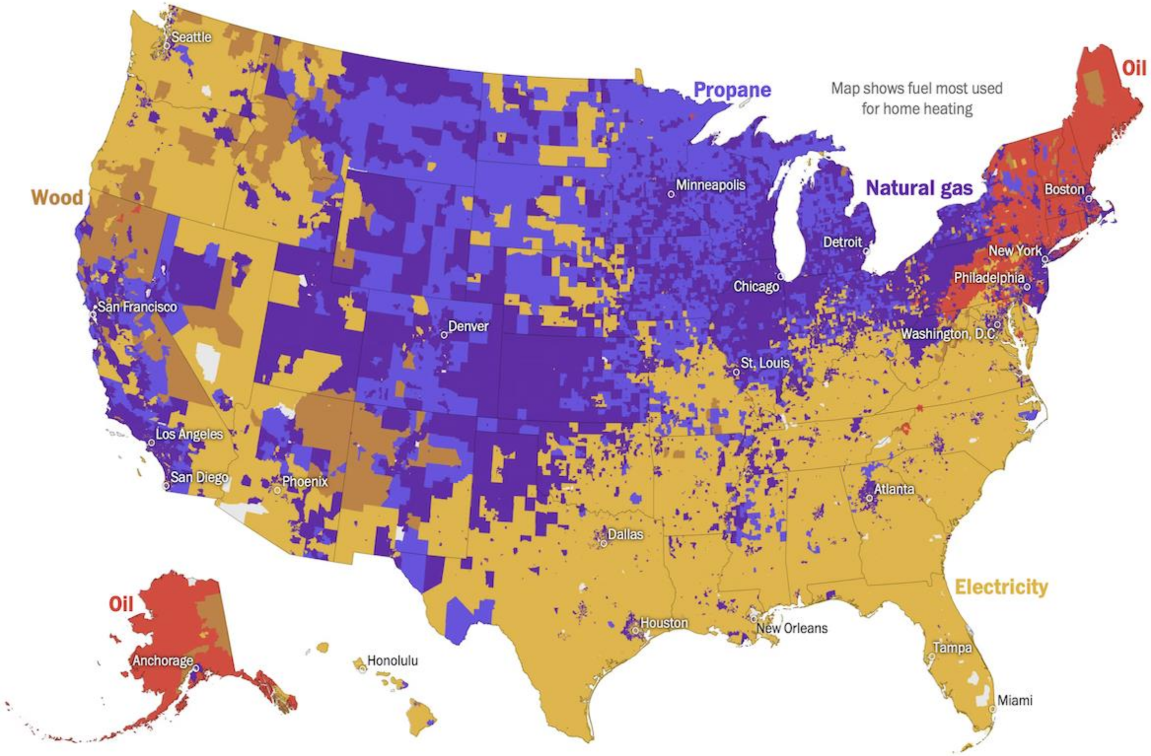


Figure: https://datainnovation.org/2023/03/visualizing-home-heating-sources/

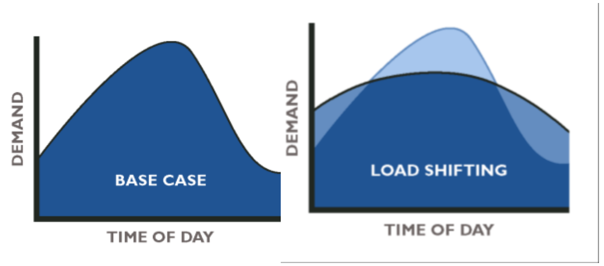
More info: Busby, J. W., More info: Baker, K., ... and Webber, M. E. 2021. “Cascading risks: Understanding the 2021 winter blackout in Texas.” *Energy Research & Social Science*, 77, 102106.

Alignment and Impact: HP-TES as Decarbonization Solution

Thermal Energy Storage integration in HPs can:

1. Provide Load Balancing, Flexibility

- System operation (store energy during off-peak hours and use it during peak hours)



- Improve grid resilience
- Might prolong the life of the HP system and reduce maintenance costs

Energy Justice

2. Reduce Energy Demand

- Reduce electricity demand in the grid
- May reduce HP size and cost

3. Enable Renewables Generation

- Overcome the mismatch between intermittent energy and varying demand

Greenhouse gas emissions reductions

Alignment and Impact: HP-TES as Decarbonization Solution

- Heat Pump Integrated Thermal Energy Storage (HP-TES): Simulations have shown strong advantages of using TES-integrated heat pumps. However, there is a gap:
  - Standardization (design and operation)
  - Optimization (configurations, sizing, and control strategies)
  - Durability (long-term performance)
  - Real-world performance (field studies)

- Key barriers to market success for TES in buildings:
  1. Lack of a commercially available PCM within BTO targets
  2. Low-cost HP-TES system integration and configuration
  3. Smart and adaptive HP-TES controls
  4. Market mechanisms to capture the value

The overarching project goal is to address these barriers

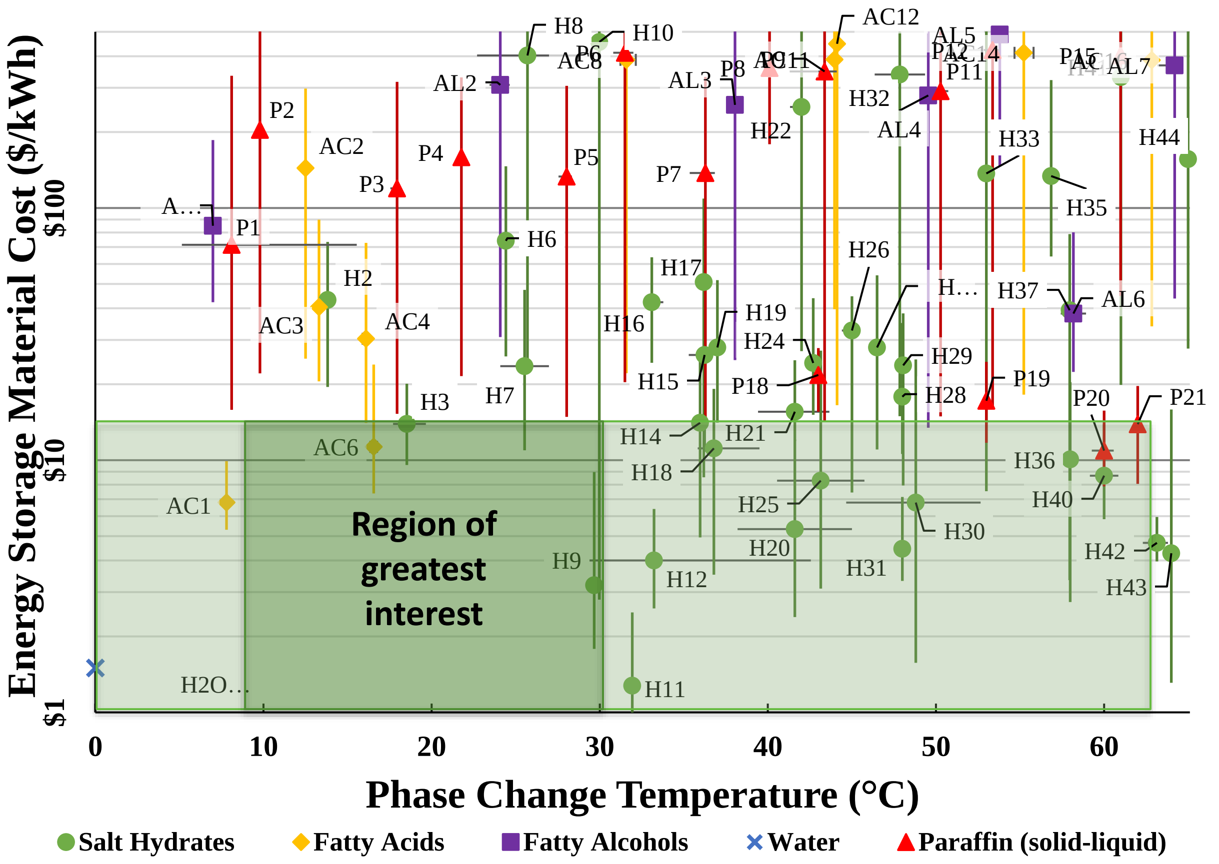
BTO's goal is to enable shifting 50% of thermal loads over 4 hours with the system target:

- <$15/kWh thermal
- >80 kWh/m^3 energy density
- >10,000 cycles
- >200% charge/discharge rate over SOA

https://www.energy.gov/eere/buildings/thermal-energy-storage

Approach – Low Cost PCM Development

- **Key Barrier 1:** Lack of a commercially available PCM within BTO targets
- DOE's cost target eliminates paraffins, waxes, fatty alcohols.
- Salt hydrates meet DOE's cost, energy density, and phase change temperature target, but have stability issues



Hirschey, Jason R et al (2021). "Review of Low-Cost Organic and Inorganic Phase Change Materials with Phase Change Temperature between 0°C and 65°C," 6th *International High-Performance Buildings Conference*, virtual online, May 24-28, 2021

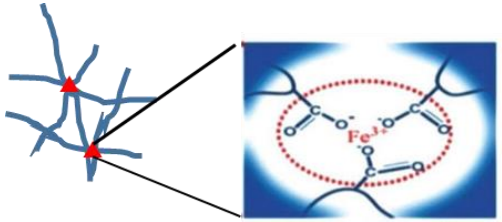
Metric Description	BTO Target	Project Target
Phase Change Temperature	<30°C	18-28°C
Energy Density	>100 kWh/m³	>120 kWh/m³
Thermal Conductivity	>1.0 W/m.K	
Thermal Stability	>90 % after 7500 cycles	~100 cycles
Supercooling	<2°C	<2°C

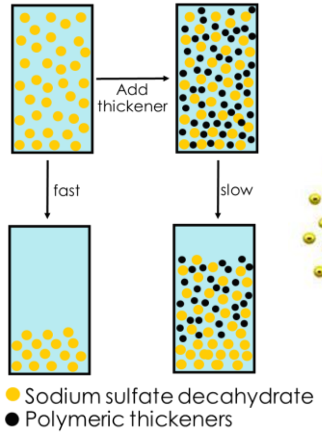
- Technical Challenges with salt hydrates:
  - Reaching desired phase change temperature
  - Phase separation and incongruent melting
  - Supercooling

(1) Energy storage loss over melting-freezing cycles
(2) Reduces the full utilization of the storage capacity

Approach – Low Cost PCM Development

1. Physical and chemical stabilization
   - Physical (Graphite) and Chemical (Dextran salt)
   - Combination of physical-chemical gave the best results
   - **Pro: Improved both thermal conductivity and stability with same mechanism**
2. Eutectics
   - Tunability of phase change temperature
   - **Pro: Requires no expensive chemical stabilizers – reduce overall cost**
3. Hydrogel
   - Alginate “encapsulation”
   - Crosslinking to stabilization
   - **Pro: High Stability, low cost**





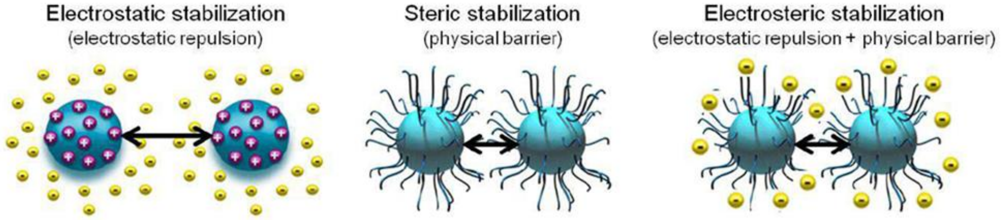


Image Source: https://wiki.anton-paar.com/en/zeta-potential/

Properties	**Physical & Chemical SSD/DSS/GF/Borax**	**Eutectic SSD/SPDD/Borax**	**Hydrogel SSD/ Alginate**
Cycle	150	150	50
Gravimetric Capacity [J/g]	170	167	154
Volumetric Capacity [J/cc]	221	197	-
Thermal Conductivity [W/m-K]	>4	>4	-
Supercooling [°C]	<3	<2.5	<6
Cost [$/kWh]	8	<6.5	-

Progress – Low Cost PCM Heat Pump Integration

Key Barrier 2(a): Low-cost HP-TES system Integration

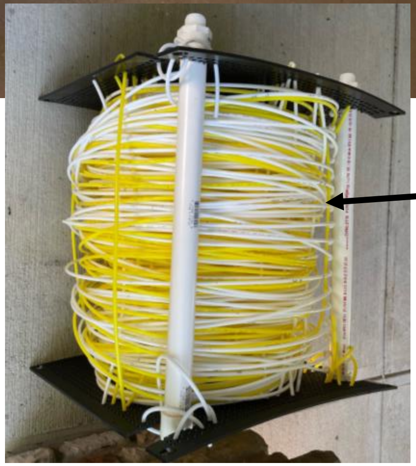
- A PCM Heat Exchanger (HX) was integrated with the existing hydronic lines of a heat pump

Outdoor Unit

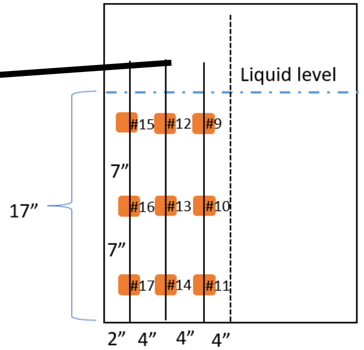
Heat Pump (Indoor Unit)

TES tank containing PCM Integrated Heat Exchanger

(Tank H=35 ¼"
and D=29 ¼")



Tubing network

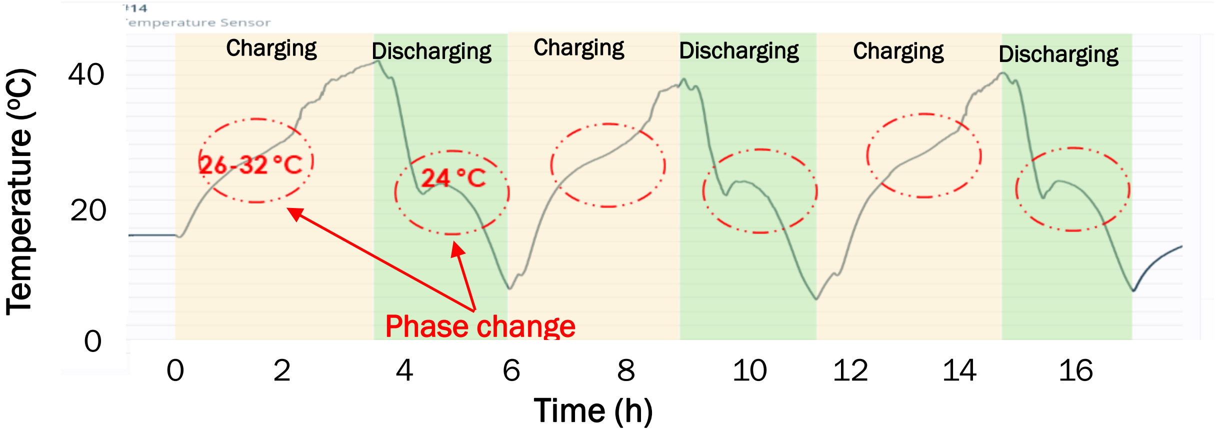


Nine wireless temperature sensors

Design capacity of PCM HX and HP	Value
Discharge Power of PCM HX	1.5 ton (5.3 kW)
Total PCM Volume	48 gal
Thermal Storage Capacity of PCM HX	2.6 ton-hr (9 kWh)
Cooling capacity of HP	2 ton (7 kW)

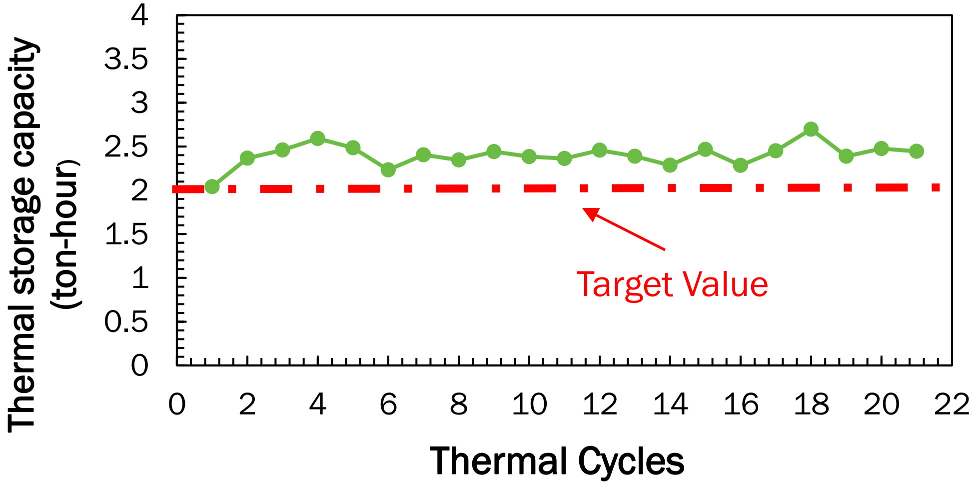
Progress – Completed Experiment on Charging and Discharging

Temperature Profile



- Phase change took place during both charging and discharging
- Identical melting-freezing cycles indicates stable PCM

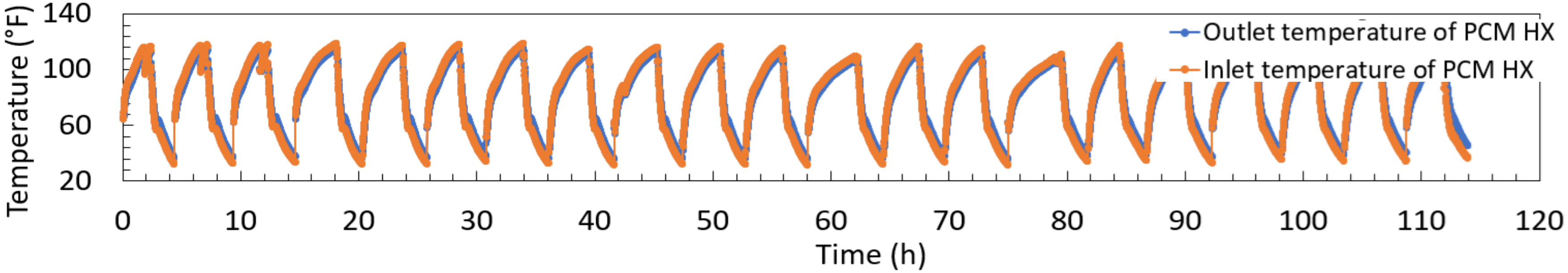
Thermal Storage Capacity



- Thermal storage capacity of each cycle is higher than 2 ton-hr., **met the milestone target**

Inlet and outlet temperature of PCM HX

- The large temperature range indicates that the heat transfer performance of the PCM HX needs to be further improved



PCM-HX Challenges

- Compatibility of PCM
- Required large heat transfer surface area to compensate for low k
- Compactness to fit into residential buildings

Progress – Heat Pump Integration System Configuration

- Key Barrier 2(b): HP integrated with TES must accommodate a large number of operating modes, with low cost, low complexity, and ease of retrofit

Approach	Type of Heat Exchange with PCM	Mechanism of Switching Operating Modes	Challenges	Strengths
Fully refrigerant-based	DX refrigerant-based	Refrigerant valves	Large refrigerant charge	The best charge and discharge rates
Fully hydronic	Hydronic-coupled	Hydronic	Charge migration issues for parallel HXs	Uses commercially available components
Air distribution, hydronic TES coupling	Hydronic-coupled	Refrigerant valves	Many valves required on refrigerant-side	Solves the charge migration issues – extra charge stored in SL accumulation, and EXV balances charge in multiple modes
TES in supply air duct	Air-side coupled		Difficult installation Low flexibility Sensitive to PCM temperature	Conventional HP can be used.

Not feasible with A2L or A3 refrigerants

Limited US market due to lack of hydronic products in the US

ORNL’s innovative approach leverages low-cost commoditized valves

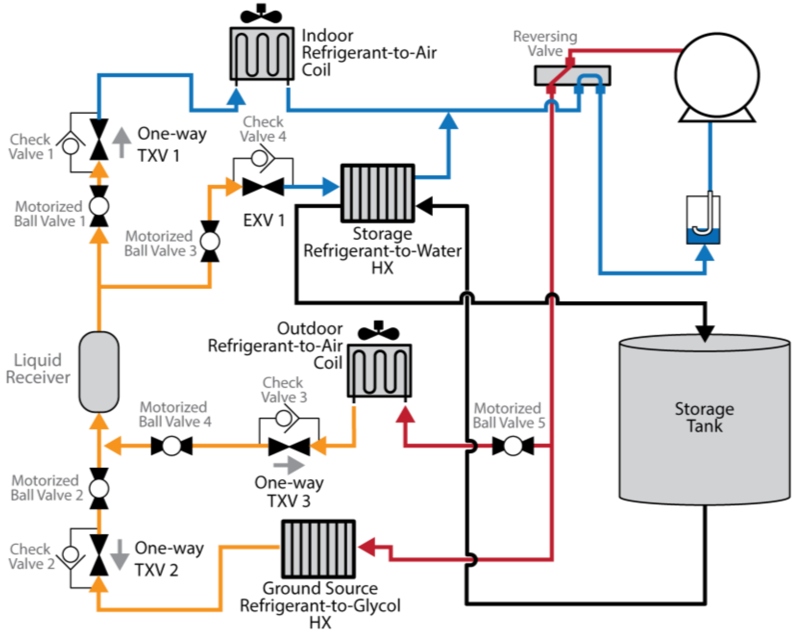
Limited market due to installation challenges

HX: Heat Exchanger, DX: Direct Expansion

Progress – Evaluated Three Configurations of HP-TES System

ORNL has developed a portfolio of IP around integration options for integrating TES with HPs

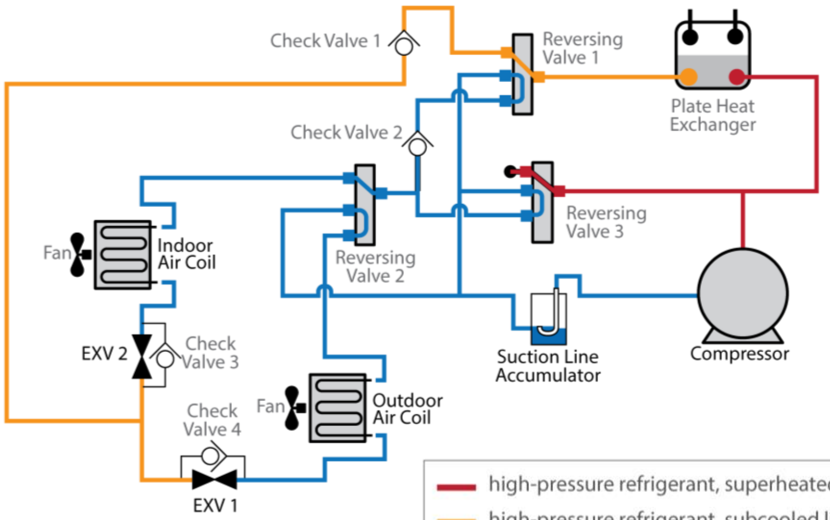
Dual Source HP



Provisional Application
63/428,364

Dissemination: Lingshi Wang, Xiaobing Liu, Bo Shen, Xiaoli Liu, Anthony Gehl, Liang Shi, and Ming Qu. “Experimental Performance Analysis of a Dual-Source Heat Pump Integrated with Thermal Energy Storage.” *IGSHPA Research Track*, Las Vegas NV, Dec 6-8, 2022.

Packaged HP

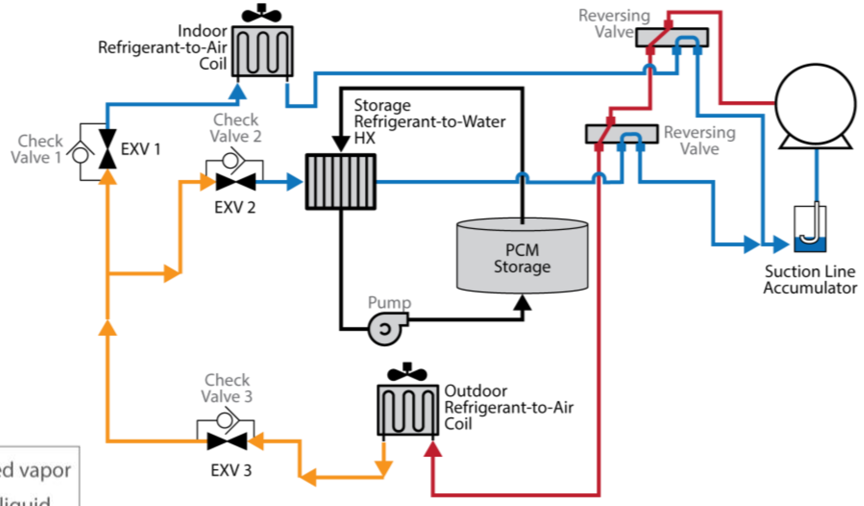


- 🟥 high-pressure refrigerant, superheated vapor
- 🟧 high-pressure refrigerant, subcooled liquid
- 🟦 low-pressure refrigerant
- ⬛ hydronic lines

Provisional application
63/358,298

Dissemination: Bo Shen, Jeff Munk, Kyle Gluesenkamp “Cold Climate Integrated Heat Pump”, *19th International Refrigeration and Air Conditioning Conference at Purdue*, July 10 - 14, 2022.

Cold Climate Integrated HP

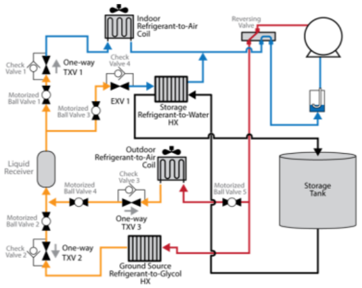


Provisional Application
63/446,366

Dissemination: Bo Shen, Kyle Gluesenkamp, Zhenning Li “Cold Climate Integrated Heat Pump with Energy Storage for Grid-Responsive Control”, ASHRAE and SCANVAC HVAC Cold Climate Conference 2023

Progress – Heat Pump Integration System Configuration

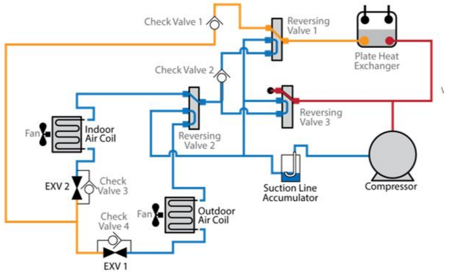
Dual Source HP



- Dual source – air and ground, direct heating and cooling of space with TES
- Maximum load shifting
- Limitation is PCM temp must be low, then sensible is used for heating

Key components:
(5) motorized ball valves
(1) reversing valve (commoditized)
(4) TXVs
(4) passive check valves

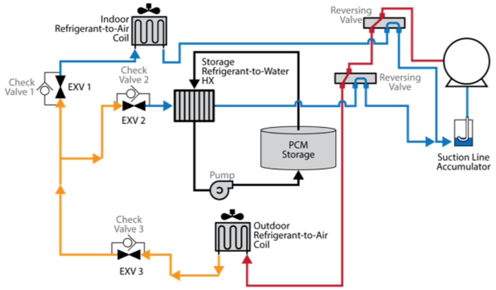
Packaged HP



- Compact packaged system
- Indirect conditioning of space
- Versatile
- Less load shifting, but more flexibility
- High PCM utilization, uses the same PCM for heating and cooling

Key components:
(2) reversing valves (commoditized)
(2) passive check valves
(3) TXV or EXVs

Cold Climate Integrated HP



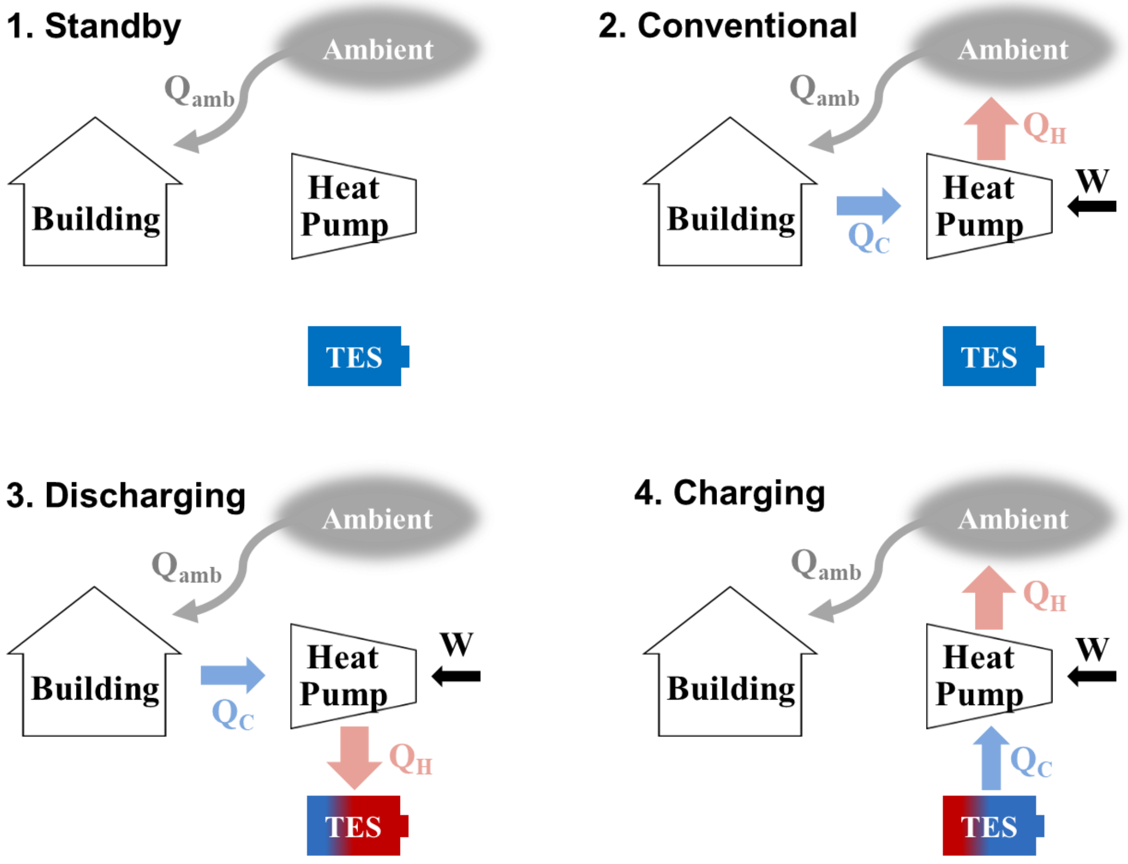
- Ideal for cold climates
- Less versatile: heating only
- Higher energy efficiency in cold climates

Key components:
(3) reversing valves (commoditized)
(2) passive check valves
(2) EXVs

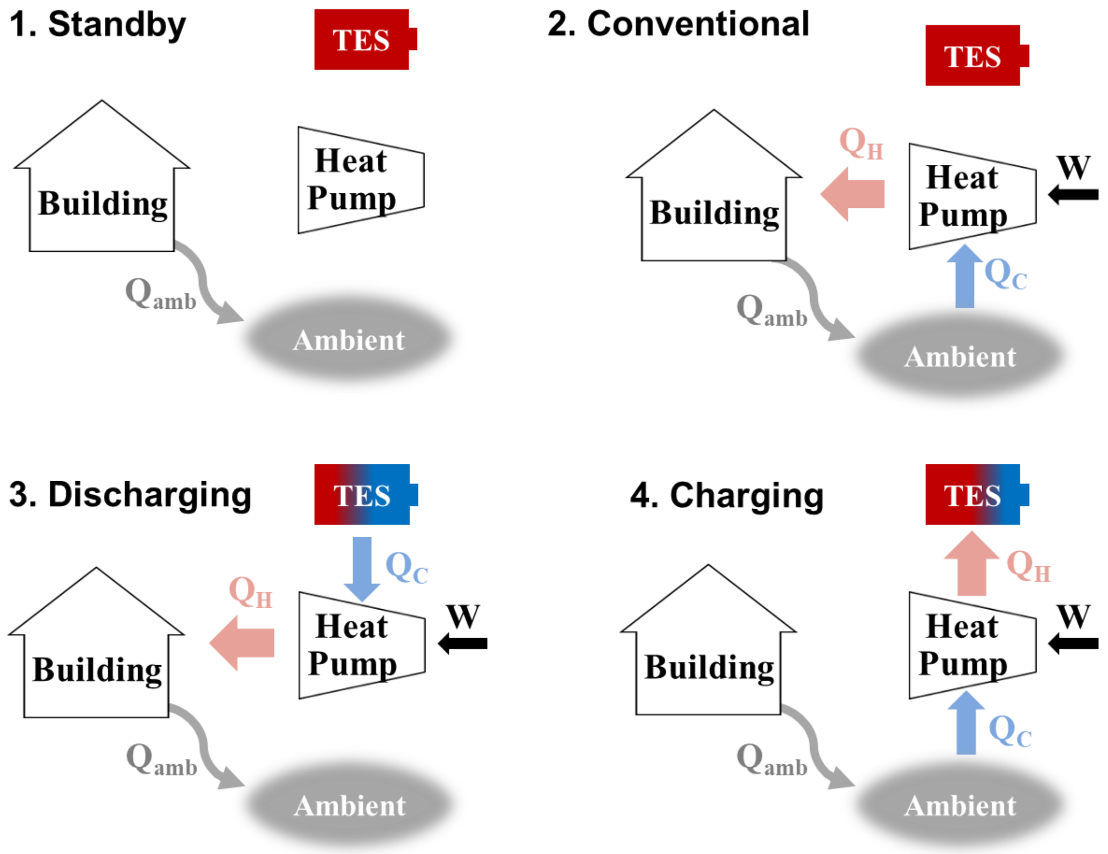
Progress – Heat Pump Integration System Configuration

TES integrated-HP requires many operation modes and it is challenging to do it cost-effectively

Cooling Modes



Heating Modes



Dissemination (page 1 of 2)

FY23 Patents

1. US Patent 11,560,503, 2023. “Stable salt hydrate-based thermal energy storage materials.” Yuzhan Li, Kyle R Gluesenkamp, Monojoy Goswami, Navin Kumar, Timothy J LaClair, Orlando Rios. Granted January 24, 2023.

FY23 Journal Publications:

Published

1. Jason Hirschey, Zhenning Li, Kyle R. Gluesenkamp, Tim J. LaClair, Samuel Graham, Demand Reduction and Energy Saving Potential of Thermal Energy Storage Integrated Heat Pumps, **International Journal of Refrigeration**, (2023), DOI:10.1016/j.ijrefrig.2023.01.026
2. Damilola O. Akamo, Ahmed Olanrewaju Ijaola, Toyosi T. George, Katharine Page, David J. Keffer, Yuzhan Li, Monojoy Goswami, Tim J. LaClair, Kyle Gluesenkamp & Orlando Rios (2022) Bibliometric review and recent advances in total scattering pair distribution function analysis: 21 years in retrospect, **European Journal of Materials**, DOI: 10.1080/26889277.2022.2150897
3. Jason Hirschey, Monojoy Goswami, Damilola O. Akamo, Navin Kumar, Yuzhan Li, Tim J. LaClair, Kyle R. Gluesenkamp, Samuel Graham (2022). “Effect of Expanded Graphite on the Thermal Conductivity of Sodium Sulfate Decahydrate ($Na_2SO_4 \cdot 10H_2O$) Phase Change Composites,” ***Journal of Energy Storage*** v 52 (104949). https://doi.org/10.1016/j.est.2022.104949 (IF=6.6)

Manuscripts in Preparation/in Review

1. Damilola O. Akamo; Navin Kumar; Yuzhan Li; Collin Pekol; Kai Li; Jason Hirschey; Tim J. LaClair; Monojoy Goswami; David J. Keffer; Kyle R. Gluesenkamp; Orlando Rios. Stabilization mechanisms that enable the adoption of low-cost phase change materials. (in journal review)
2. Sara Sultan, Jason Hirschey, Navin Kumar, Borui Cui, Xiaobing Liu, Tim LaClair, Kyle R. Gluesenkamp. Techno-Economic Assessment of Residential Heat Pump Integrated with Thermal Energy Storage. (submitted to journal)
3. Damilola O. Akamo, Kai Li, Tugba Turnaoglu, Navin Kumar, Yuzhan Li, Collin Pekol, Nitish Bibhanshu, Monojoy Goswami, Jason Hirschey, Tim J. Laclair, David J. Keffer, Orlando Rio, Kyle R. Gluesenkamp. Enhanced Thermal Reliability and Performance of Calcium Chloride Hexahydrate Using Cellulose Nanofibril And Graphene Nanoplatelet, (2023).

Dissemination (page 2 of 2)

FY23 Conference Publications:

1. Dami Akamo, Navin Kumar, Yuzhan Li, Collin Pekol, Kai Li, Monojoy Goswami, Jason Hirschey, Tim J. LaClair, David J. Keffer, Orlando Rios, Kyle R. Gluesenkamp. “Thermal and Rheological Properties of Sodium Sulfate Decahydrate Phase Change Materials with various Thickening and Stabilization Mechanisms” **The Minerals, Metals & Materials Society 2023 Annual Meeting and Exhibition**, San Diego, CA, March 19-23, 2023.

FY23 Conference Publications (Accepted, not yet published):

1. Jason Hirschey, Kyle R. Gluesenkamp, Bo Shen, Zhenning Li, Samuel Graham. "A proposed methodology to reduce heat pump size with integrated thermal energy storage," **14th IEA Heat Pump Conference**, May 15-18, 2023, Chicago, IL.
2. Sara Sultan, Jason Hirschey, Zhenning Li, Bo Shen, Samuel Graham, Kyle R. Gluesenkamp. "Carbon Mitigation Potential of Heat Pump Integrated with Thermal Storage for Grid-Interactive Residential Buildings," **14th IEA Heat Pump Conference**, May 15-18, 2023, Chicago, IL.
3. Tugba Turnaoglu, Navin Kumar, Jason Hirschey, Yuzhan Li, Damilola O Akamo, Tim J. LaClair, Orlando Rios, Kyle R. Gluesenkamp, Samuel Graham, Phase Change Material For Thermal Energy Storage In Buildings Based On Sodium Sulfate Decahydrate And Disodium Hydrogen Phosphate Dodecahydrate, (2023). Proceedings of the ASME 2023,17th **International Conference on Energy Sustainability**,July 10-11, 2023, Washington, DC, USA.

Future Work

(1) Optimize Material for Deployment

- Material performance is crucial in the HX and heat pump integration. Compatibility is also a big challenge in the deployment. The next step is to address the compatibility issues that are critical for the deployment

(2) Optimize HP-TES system configuration and controls to reduce cost and improve performance

- Experiment on TES-HP integration showed promising results. The next step is to further investigate the various system configurations to simplify the integration and to investigate the control strategies

(3) Field test will be conducted to demonstrate real world performance of TES integrated heat pump system

- The field test will be conducted at a research house in Knoxville, TN. It is a 2-story single-family house with a 3-ton air-source heat pump.
- The new HP-TES system is designed to shift 50% electric demand for HVAC duration each day.

ORNL Research House in Knoxville, TN

Thank you

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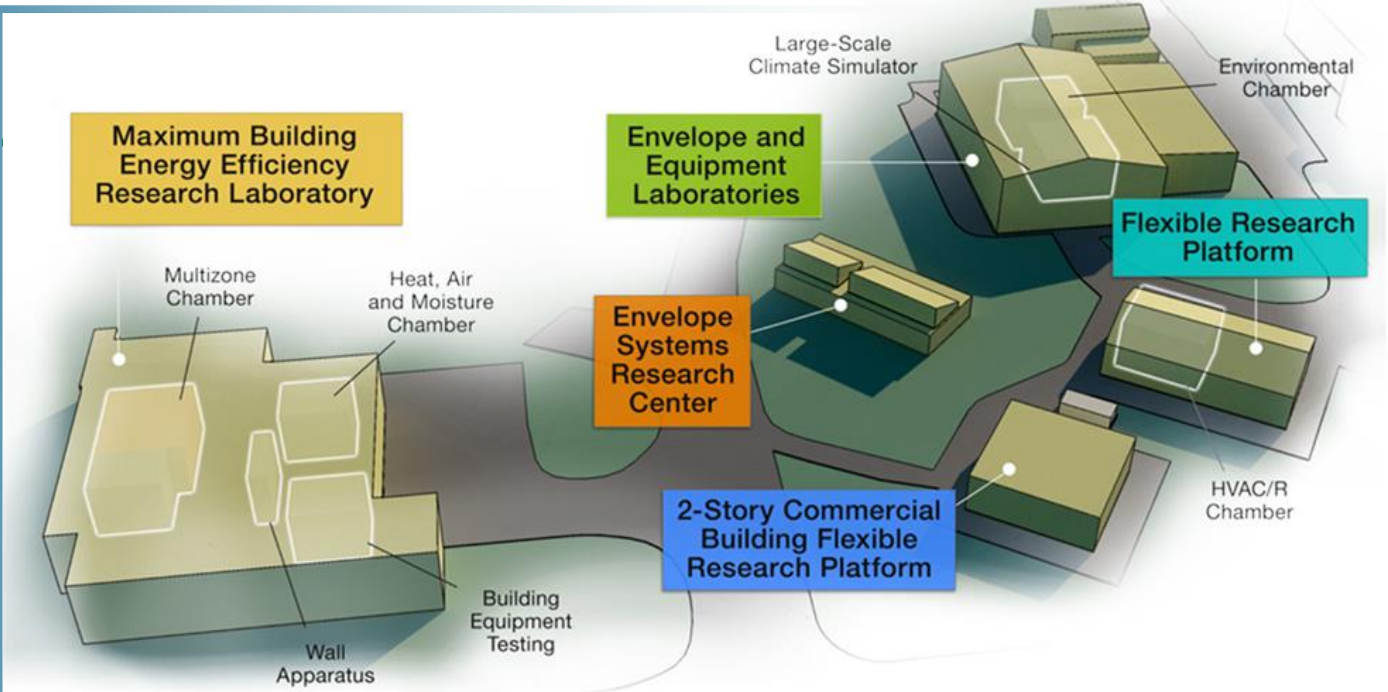

ORNL's Building Technologies Research and Integration Center (BTRIC) has supported DOE BTO since 1993. BTRIC is comprised of 60,000+ ft^2 of lab facilities conducting RD&D to support the DOE mission to equitably transition America to a carbon pollution-free electricity sector by 2035 and carbon free economy by 2050.

Scientific and Economic Results

236 publications in FY22
125 industry partners
54 university partners
13 R&D 100 awards
52 active CRADAs

BTRIC is a DOE-Designated National User Facility

REFERENCE SLIDES

Project Execution

	FY2023			
	Q1	Q2	Q3	Q4
Past Work				
Q1 Milestone: Field demonstration planning and partnering	🟦 ◆			
Q2 Milestone: Low-cost reduced melting point PCM		🟦 ◆		
Q2 Milestone: Initial selection and design of the integrated HP-TES system.		🟦 ◆		
Current/Future Work				
Q3 Milestone: Low-cost functional polymer additives for stabilization of PCM		🟦	🟦 ◇	
Q4 Milestone: Shakedown testing of prototype HP-TES system			🟦	🟦 ◇

FY24 Milestones are being determined through Stor4Build Consortium

Team

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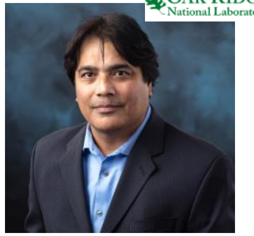
Monojoy Goswami
R&D Staff


Shean Huff
R&D Staff


Zhenning Li
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Industry Partner


Micah Zender
New Product Development

Previous Project Team Members


Navin Kumar


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