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Stor4Build
U.S. DEPARTMENT OF ENERGY

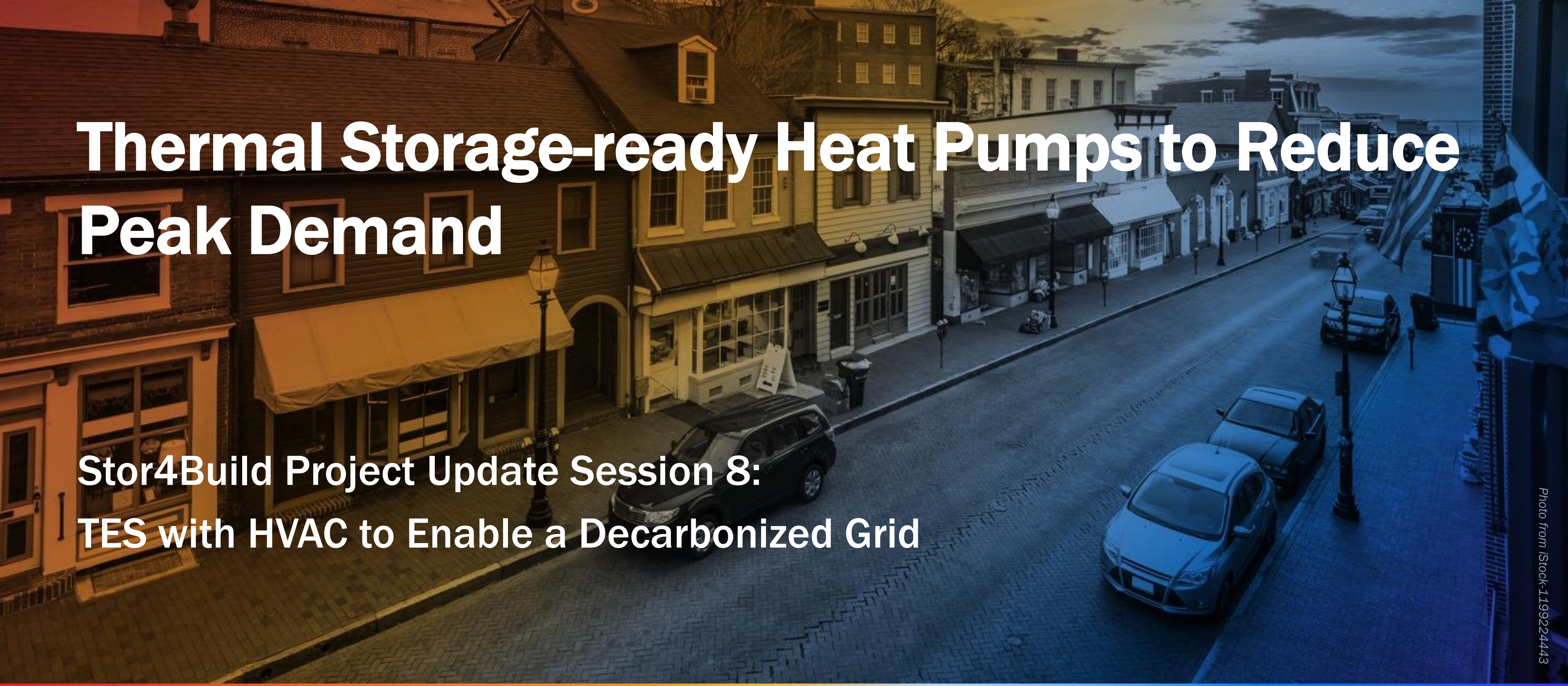
Stor4Build Project Updates

TES with HVAC to enable a decarbonized grid

Chair: Xiaobing Liu, Sr. R&D Staff, ORNL

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

Thermal Storage-ready Heat Pumps to Reduce Peak Demand



Stor4Build Project Update Session 8:

TES with HVAC to Enable a Decarbonized Grid

Kyle Gluesenkamp, Bo Shen, Yiyuan Qiao, Lingshi Wang, Xiaobing Liu, Zhenning Li, Yifeng Hu, William Doktycz
Oak Ridge National Laboratory

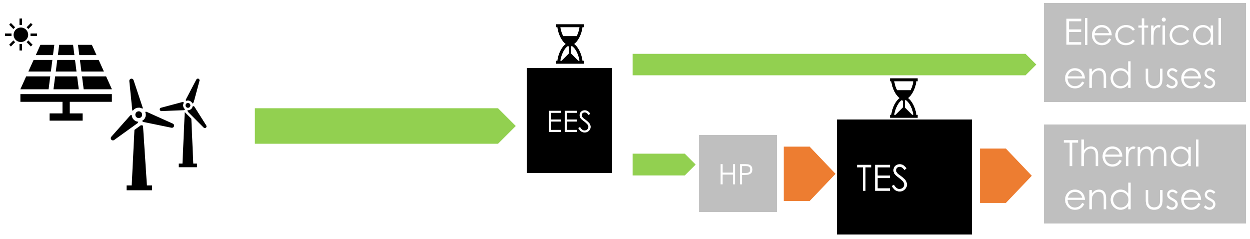
Agenda

- Options for combining TES with HP
- Simulation to show technology potential and guide materials development
- Experimental progress
- Next steps

What about thermal storage?

Scenario using only electrical storage

Scenario using both electrical and thermal storage



National scale of storage

- The US electric grid: about 1 TW electrical power
- Example: store 100% of 1 TW for 24 hours: 24 TWh energy
- This equates to an average of:
  - 88 kWh per residential building and
  - 2.16 MWh per commercial building
  - (assuming each sector has half the nation’s storage).
- At rate of $11.5k installed per 13.5 kWh Li-ion battery, this implies **$20T**:
  - $75,000 per residential building with Li-ion
  - $1,840,000 per commercial building with Li-ion

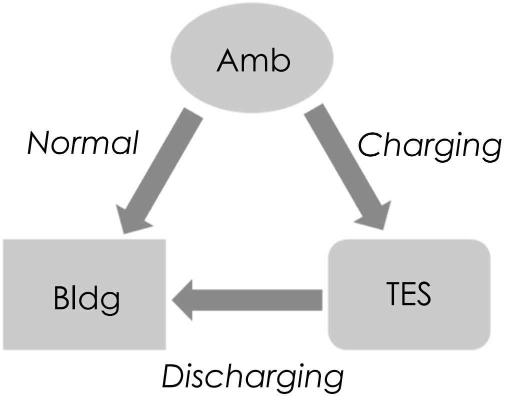
Innovation to lower cost is needed

https://www.marketwatch.com/guides/home-improvement/tesla-powerwall-cost/

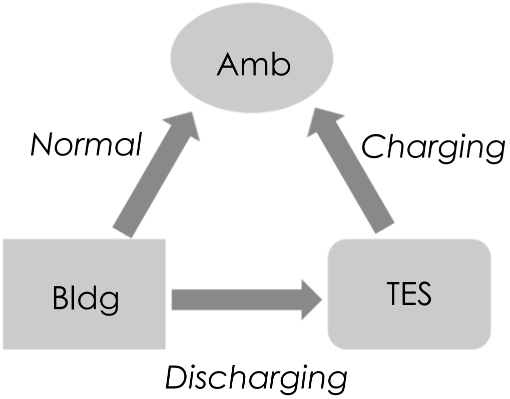
How to implement TES with HPs?

6 fundamental modes of operation

Heating season



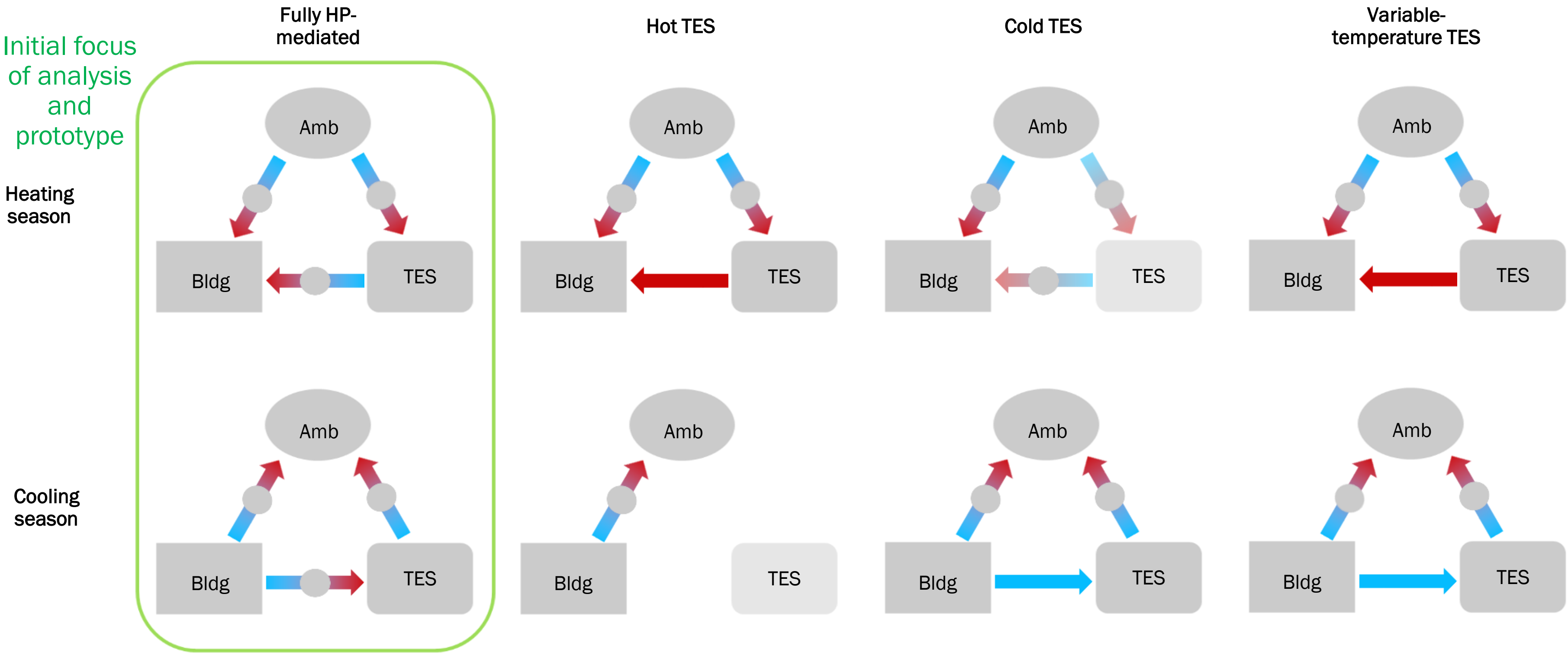
Cooling season



Along a thermal gradient (no heat pump)

Against a thermal gradient (with heat pump)

Thermodynamic options for TES-HP



Useful winter and summer, but least demand reduction potential

Best winter demand reduction, but not useful in summer

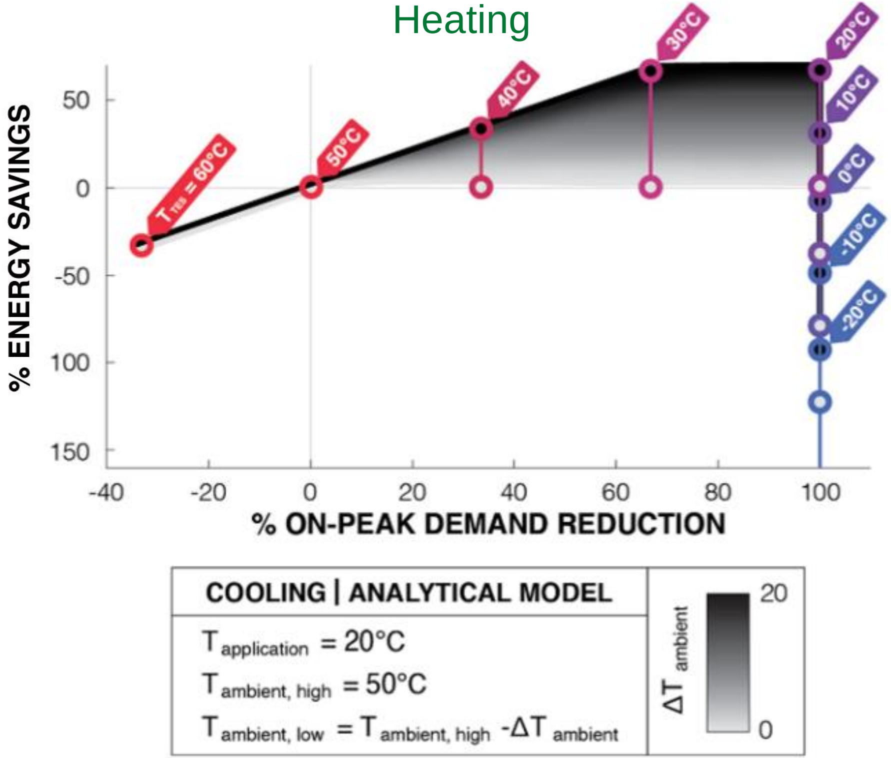
Best summer demand reduction, but less useful in winter

Can be accomplished with sensible storage or two PCMs

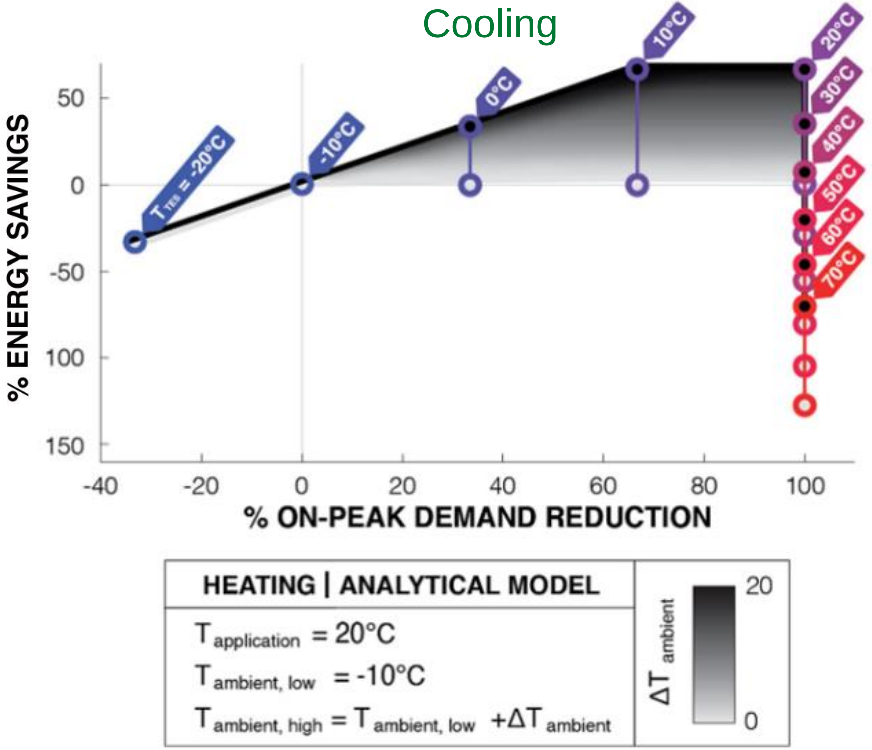
Energy and demand limits for HP-mediated TES-HP

Calculated using ideal Carnot performance

Heating



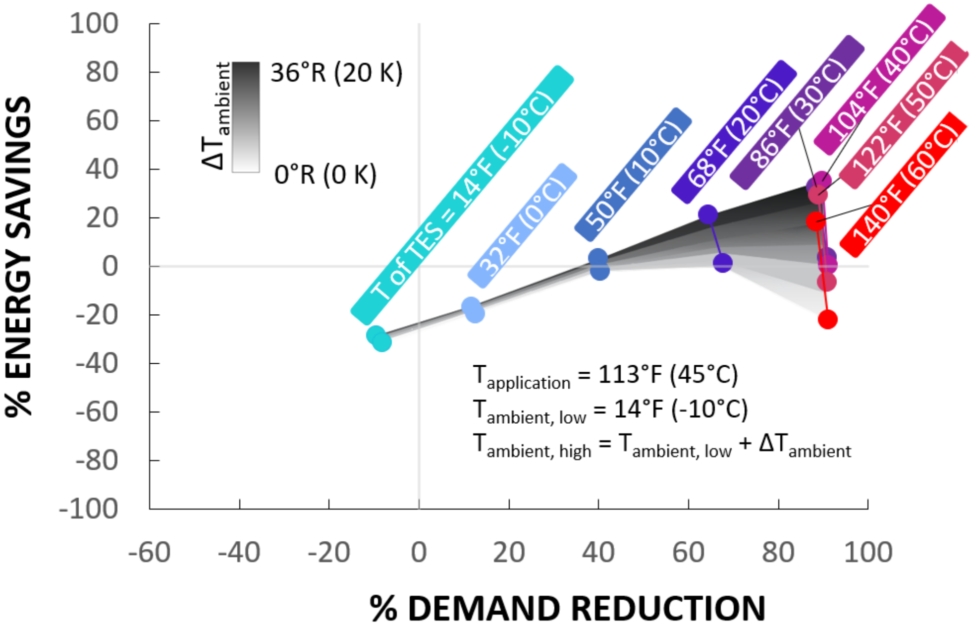
Cooling



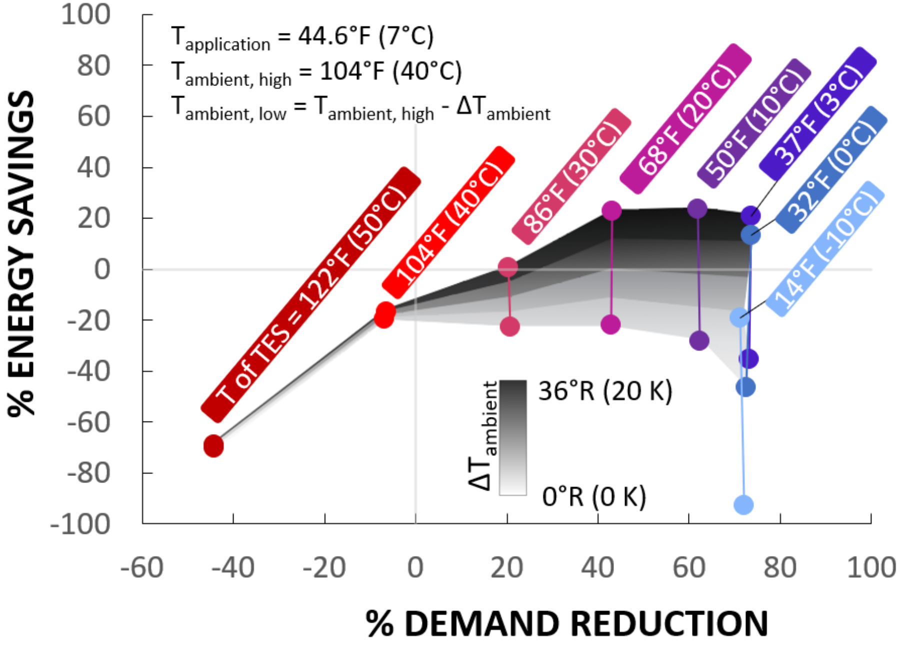
Energy and demand limits for HP-mediated TES-HP

Calculated using realistic model of vapor compression cycle

Heating (14°F day)

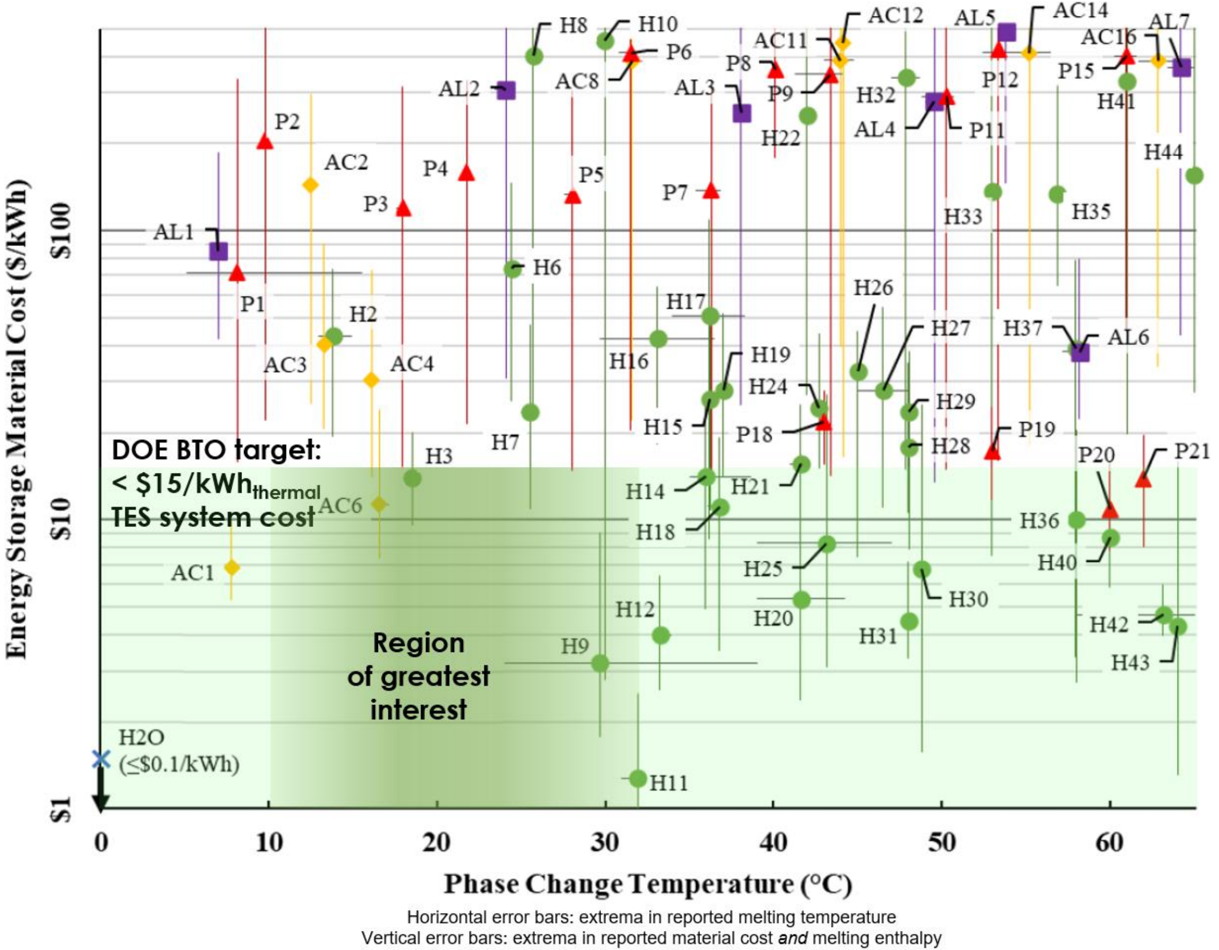


Cooling (104°F day)



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

Informs direction of materials development



Notable Labels:

AC1	Formic Acid
AC6	Acetic Acid
H9	Calcium Chloride Hexahydrate
H11	Sodium Sulfate Decahydrate

Figure adapted from:

1. Manuscript submitted to journal
2. Hirschey, Jason R.; Navin Kumar, Tugba Turnaoglu, Kyle R. Gluesenkamp, Samuel Graham (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.

How can it be built cost-effectively?

- Must accommodate 6 or more modes, instead of 2
- Prefer to use commoditized valves already present in heat pumps
  - 4-way reversing valves
  - EXVs
  - check valves
- Refrigerant charge management during operation can be complex
  - Dead volumes, idle heat exchangers
  - Numerous mode switching scenarios

TES-Ready Heat Pump Prototype Development

A new heat pump (HP) configuration that can **electrify** heating and cooling, provide **demand flexibility**, improve **resilience**, and **improve comfort** during defrost using thermal energy storage (TES)

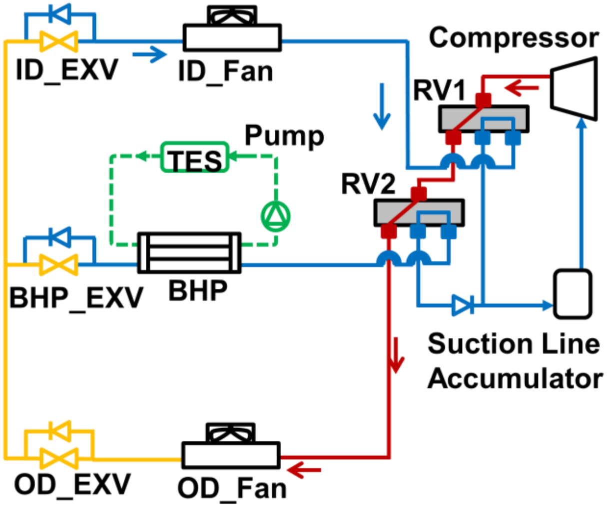


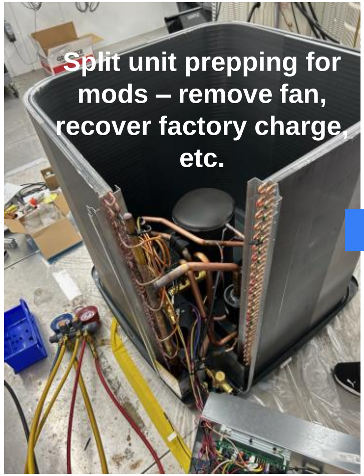
Diagram of patented TES-ready HP system

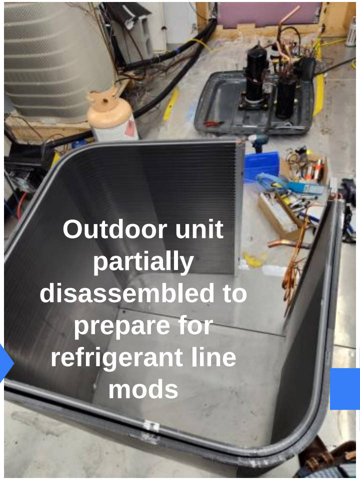
Provisional Application 63/446,366
PCT/US24/16070

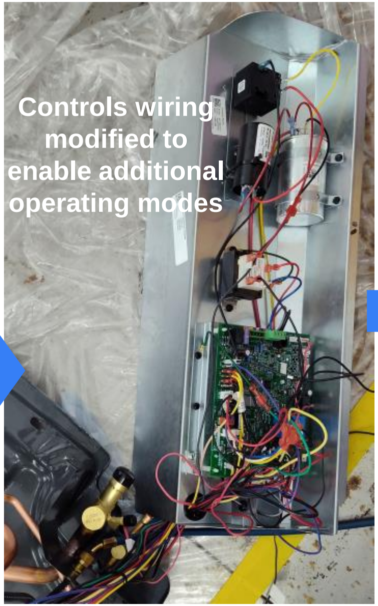
Accesses 6 modes of operation using a single TES material with near-room temperature phase-change temperature

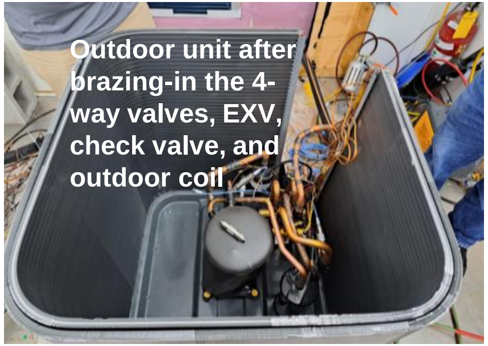
Mode	Heat Source	Heat Sink
Heating	Air	Building
Heating charging	Air	TES
Heating discharging	TES	Building
Cooling	Building	Air
Cooling charging	TES	Air
Cooling discharging	Building	TES

Residential TES-HP prototype at ORNL

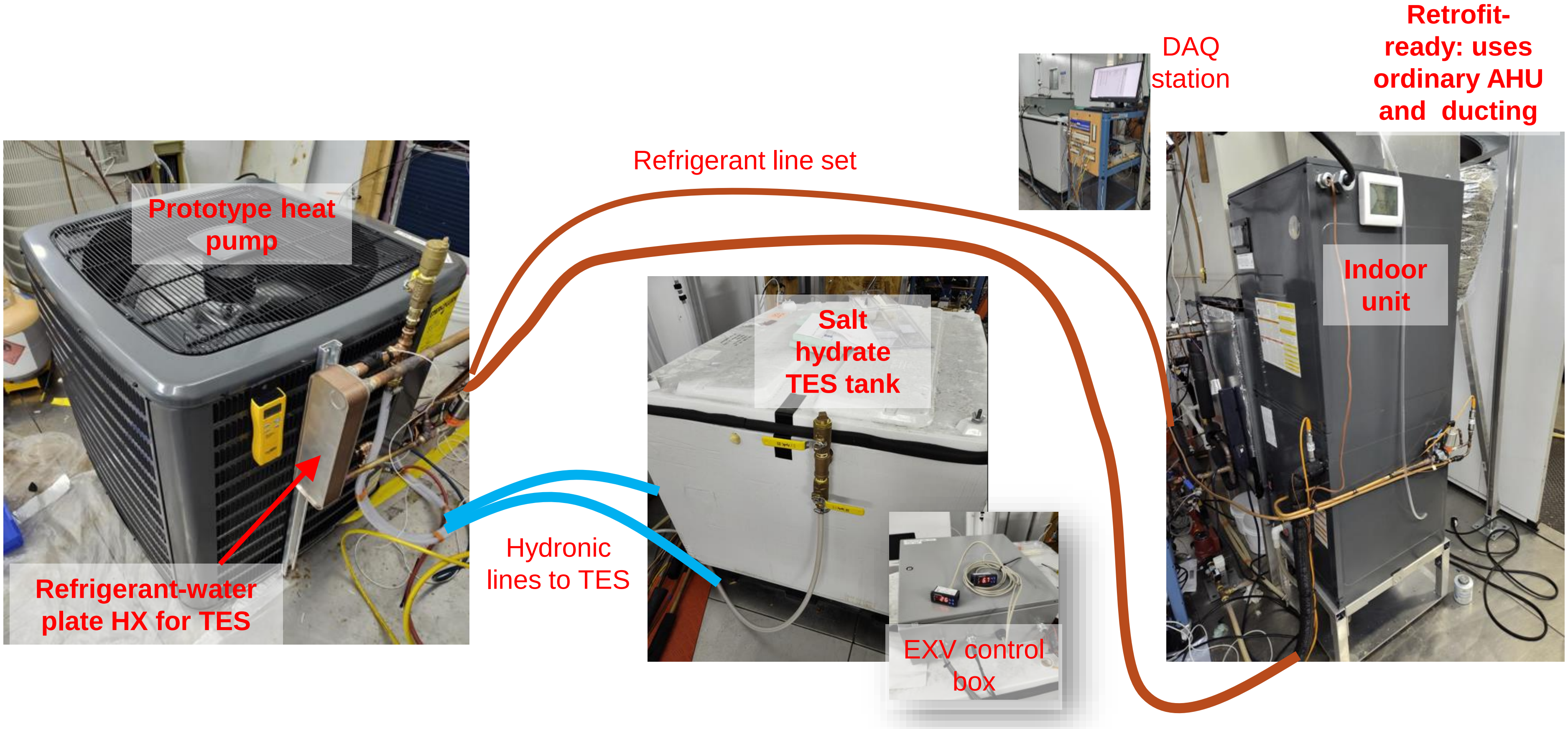








Residential TES-HP prototype at ORNL

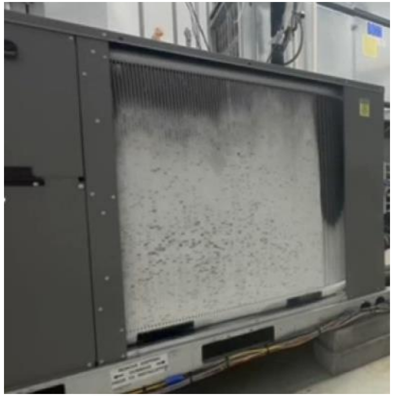


Commercial RTU TES-HP prototype at ORNL

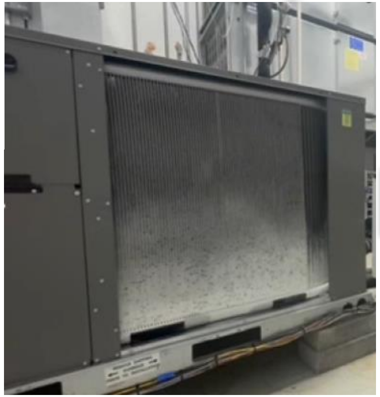
Commercial RTU TES-HP prototype at ORNL

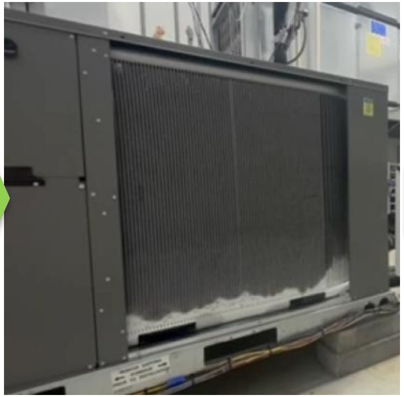
4-ton RTU with heavily frosted outdoor coil in 35°F chamber

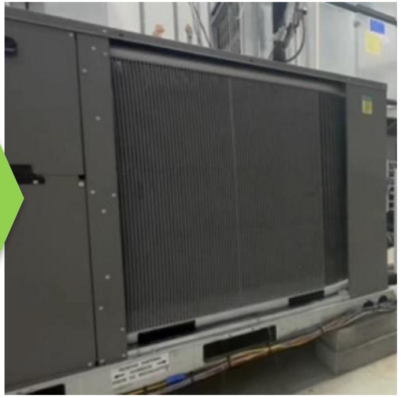
Salt hydrate PCM



Defrost completed in about 3 minutes (compared with typical 10 minutes) while extracting heat from TES instead of building







Conclusions and next steps

- Conclusions
  - Demand reductions of about 85% in heating mode and 75% in cooling mode are possible, even when running compressor during peak time
  - 2-3 hour load shift using a 4x4x3 ft TES tank for a 3-ton split system
  - 3-4 hour load shift using two 4x4x3 ft TES tanks for a 4-ton RTU
  - In addition, more efficient and comfortable defrost was demonstrated
- Next steps
  - Field testing
    - Finalize development of supervisory controls
    - Residential central-ducted split unit: FRP2 and Yarnell research home
    - Commercial RTU: installation in FY25 in Rancho Cucamonga, CA
  - Expand industry partnerships

Acknowledgments

- Department of Energy (Contract DE-AC05-00OR22725)
- Sven Mumme, Payam Delgoshaei, Wyatt Merrill, DOE Building Technologies Office

Thank You

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Additional slides

Heat Pump Integration System Configuration

ORNL Developed an approach with HP integrated with TES that can accommodate a large number of operating modes, with low cost, higher flexibility, and ease of installation

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

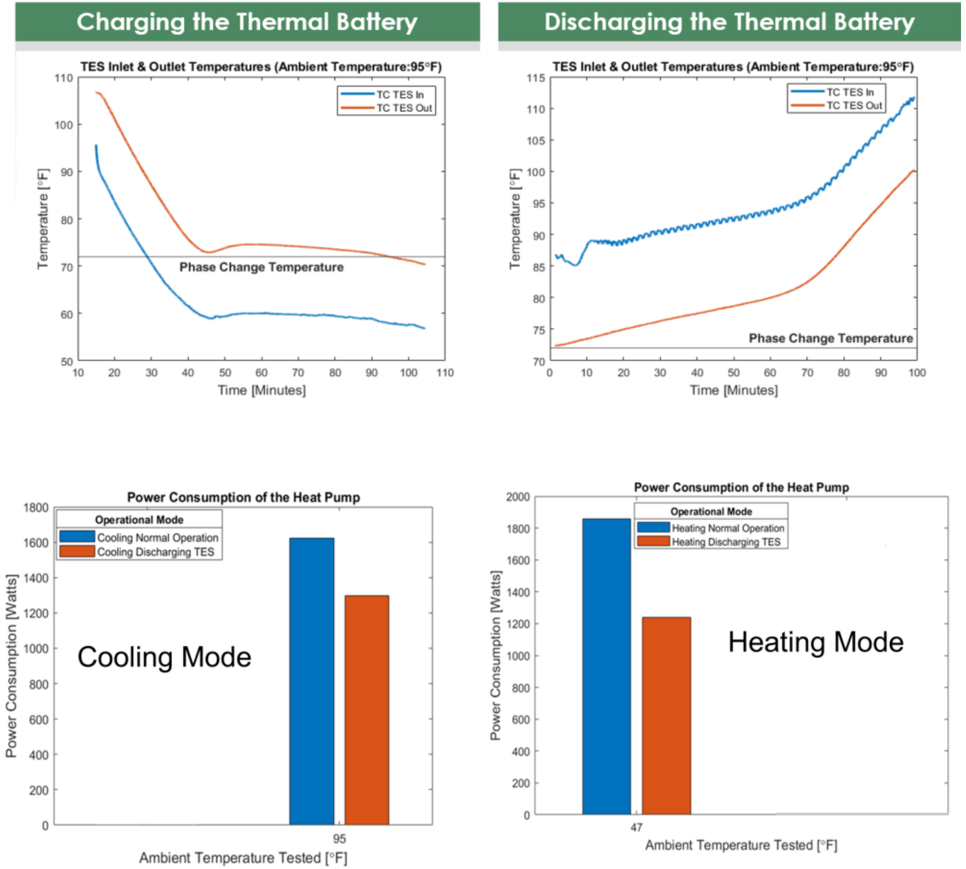
ORNL's innovative approach leverages low-cost commoditized valves

Limited market due to installation challenges

HX: Heat Exchanger, DX: Direct Expansion

Residential TES-HP prototype at ORNL

- All the six operation modes have been tested under several operating conditions
- TES achieved expected charging and discharging performance (for single speed compressor)
- TES-mediated HP reduces electricity consumption for both heating and cooling compared with conventional ASHP at rating conditions

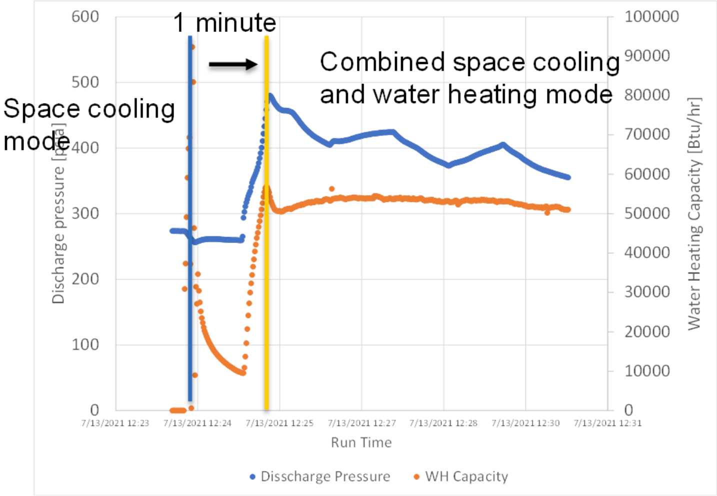


Cold climate integrated HP example (laboratory)

Outdoor unit connected in the laboratory

Indoor air hander, compressor, suction line accumulator, brazed plate heat exchanger, and 50-gallon water tank

Using the refrigerant valve switching, the system was experimentally demonstrated to transition modes and establish new charge distribution within



Mode switch within one minute

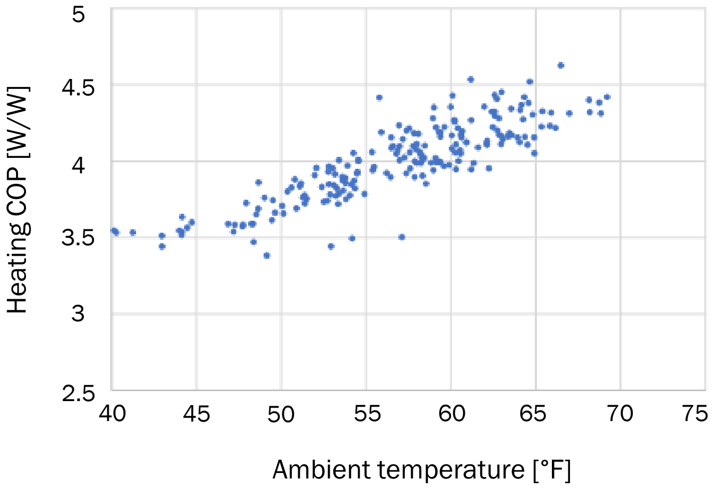
Bo Shen, Jeff Munk, Kyle Gluesenkamp "Cold Climate Integrated Heat Pump", *19th International Refrigeration and Air Conditioning Conference at Purdue*, July 10 - 14, 2022.

Cold climate integrated HP example (field)

Outdoor unit installed in 2023 for field test in Syracuse, NY

Indoor unit and 50-gallon domestic hot water tank installed in the field site

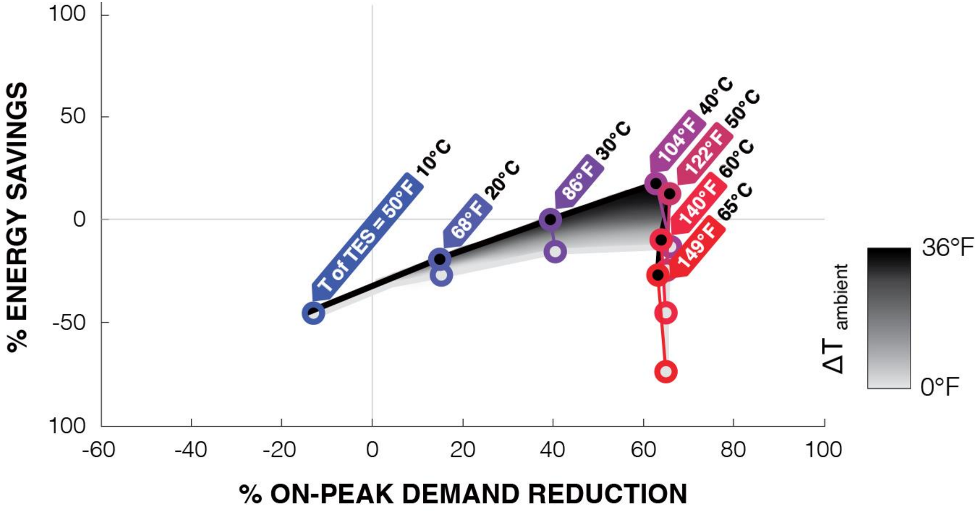
Dedicated water heating COP at the compressor high (3rd) stage in field tests



Energy and demand limits for HP-mediated TES-HP

Calculated using realistic model of vapor compression cycle

Heating (50°F)

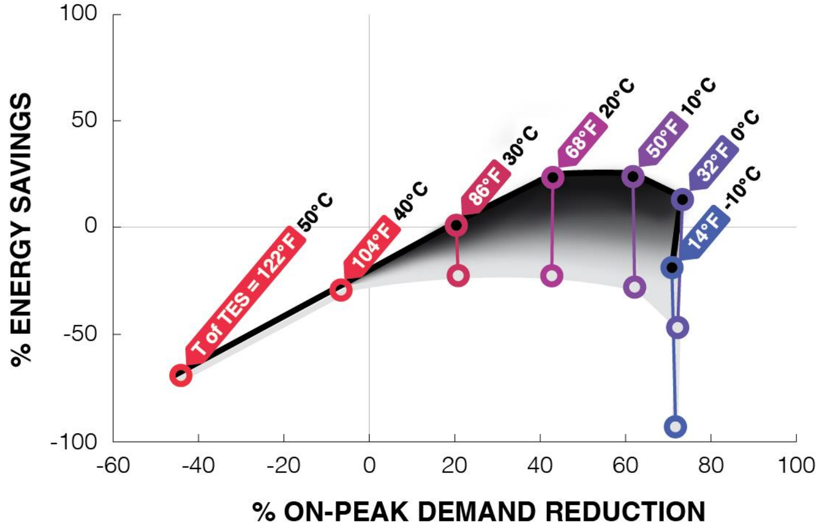


$T_{application}$ = 113°F (45°C)

$T_{ambient,\ low}$ = 50°F (10°C)

$T_{ambient,\ high} = T_{ambient,\ low} + \Delta T_{ambient}$

Cooling (104°F)



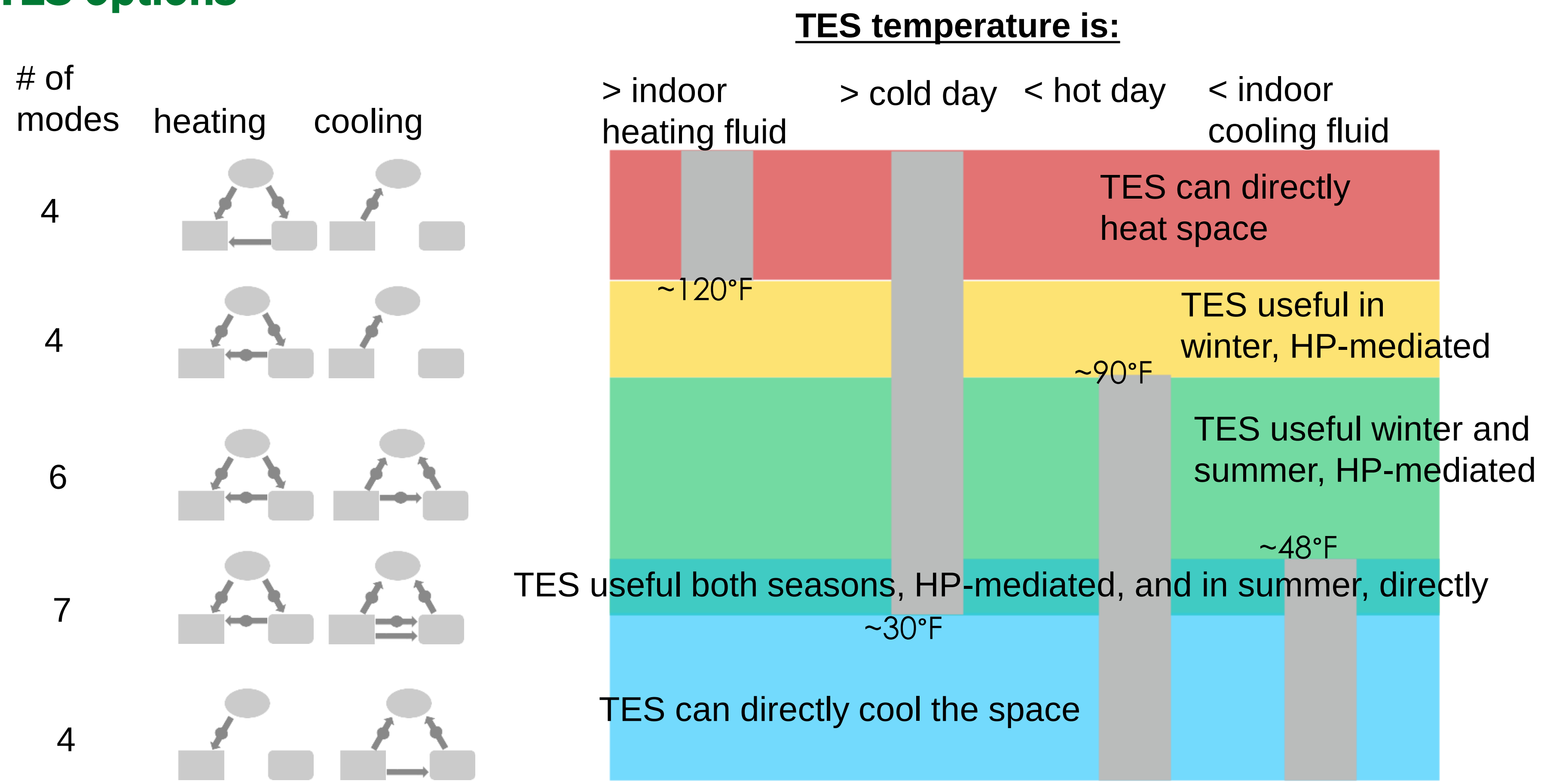
$T_{application}$ = 44.6°F (7°C)

$T_{ambient,\ high}$ = 104°F (40°C)

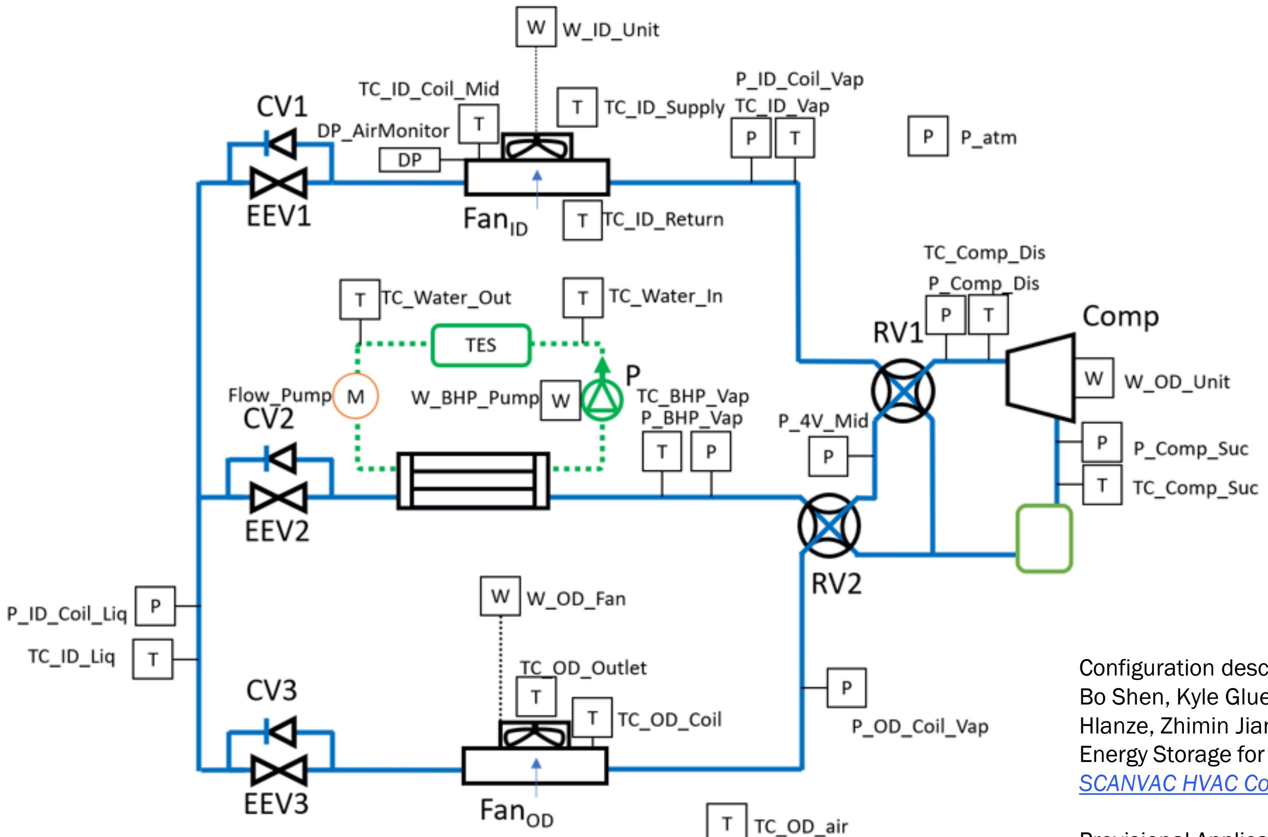
$T_{ambient,\ low} = T_{ambient,\ high} - \Delta T_{ambient}$

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

TES options


TES temperature is:
# of modes
heating
cooling
4
4
6
7
4
> indoor heating fluid
> cold day
< hot day
< indoor cooling fluid
TES can directly heat space
~120°F
TES useful in winter, HP-mediated
~90°F
TES useful winter and summer, HP-mediated
~48°F
TES useful both seasons, HP-mediated, and in summer, directly
~30°F
TES can directly cool the space

ORNL-developed configuration using standard valves



Configuration described further in:
Bo Shen, Kyle Gluesenkamp, Zhenning Li, Jie Cai, Philani Hlanze, Zhimin Jiang "Cold Climate Integrated Heat Pump with Energy Storage for Grid-Responsive Control", *ASHRAE and SCANVAC HVAC Cold Climate Conference 2023*

Provisional Application 63/446,366
PCT/US24/16070

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Price-responsive Control of AWHP + TES Systems to Access Abundant Power

S4B Annual Meeting - Integration Thrust Area

Photo from iStock-1199224443

Presenter: Marco Pritoni (LBNL), George Baker (GW)

Contributors: George Baker, Jessica Millar, Peter Grant, Thomas Defauw

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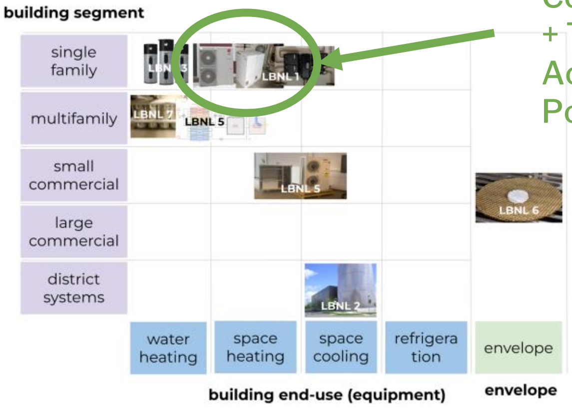
BERKELEY LAB

OAK RIDGE National Laboratory

ACEEE American Council for an Energy-Efficient Economy

NREL Transforming ENERGY

Pacific Northwest NATIONAL LABORATORY



Price-responsive Control of AWHP + TES Systems to Access Abundant Power

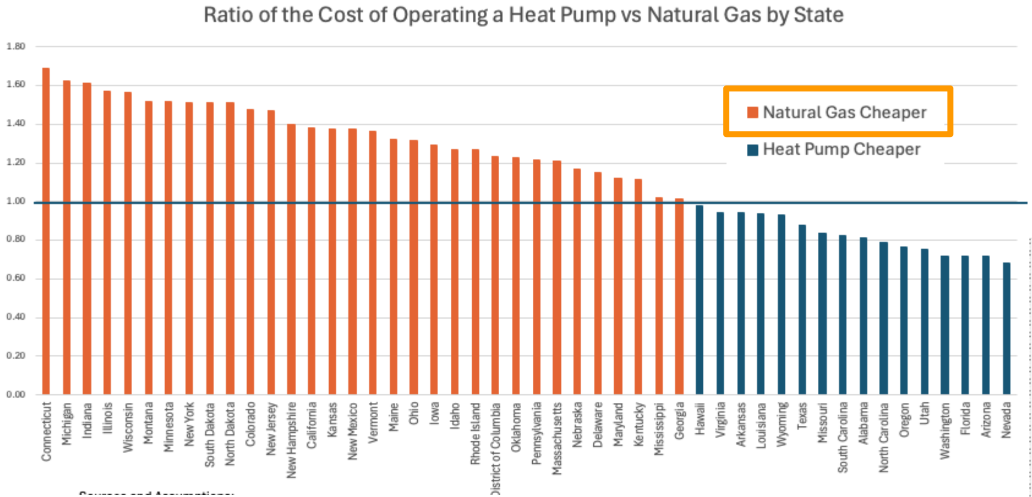
efficiency MAINE

GridWorks Consulting

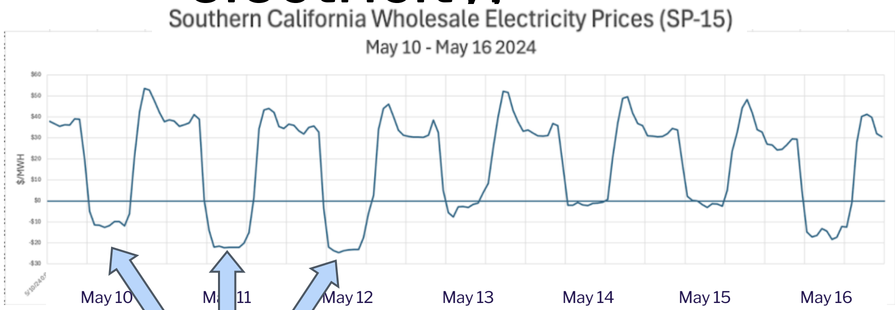
- Show that AWHPs can keep homes in northern Maine warm
- Demonstrate cost savings from thermal storage by accessing cheap renewable generation
- Reduce wind and solar curtailment through Transactive Energy Management

Decarbonizing Space Heating with Heat Pumps may increase Utility Costs

- Heat pumps currently have higher fuel costs than Natural Gas furnaces/boilers on many



- TES can:
  - Allow space heating and cooling to access intermittent cheap electricity,



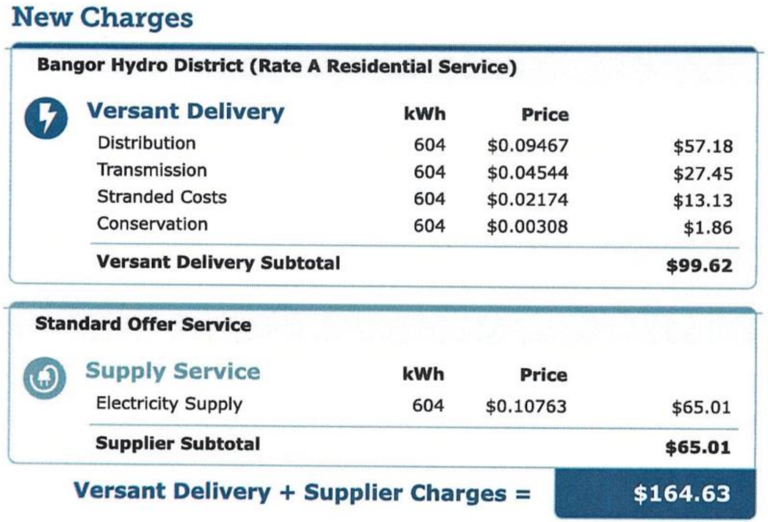
Negative wholesale prices for >8h/day

for Homeowners/Tena

Stor4Build

Market Adoption of TES in Residential Buildings Faces Challenges

- Limited adoption of TES in single family residential buildings
  - Typically **utility tariffs** do not incentivize flexible load
  - Lack of industry accepted **HP+TES designs** and **business models**
  - Lack of **forward-looking controls** for HP+TES systems to use electricity when it is cheap and abundant
    - Need automated system to to charge and discharge the TES based on weather and price forecasts



New Charges

Bangor Hydro District (Rate A Residential Service)

Versant Delivery	kWh	Price	
Distribution	604	$0.09467	$57.18
Transmission	604	$0.04544	$27.45
Stranded Costs	604	$0.02174	$13.13
Conservation	604	$0.00308	$1.86
Versant Delivery Subtotal			$99.62

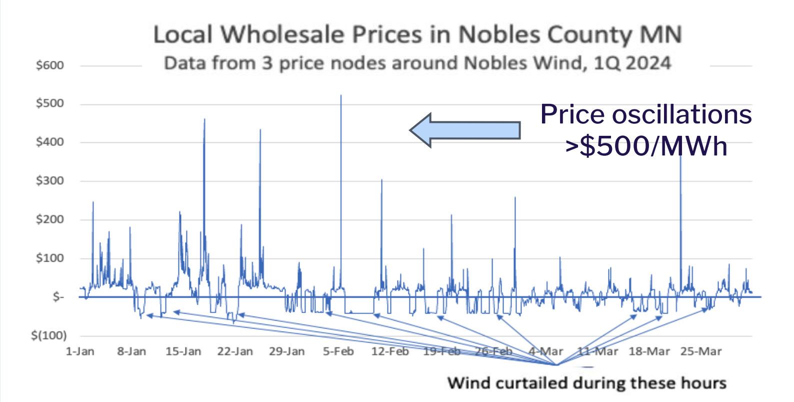
Standard Offer Service

Supply Service	kWh	Price	
Electricity Supply	604	$0.10763	$65.01
Supplier Subtotal			$65.01

Versant Delivery + Supplier Charges = $164.63

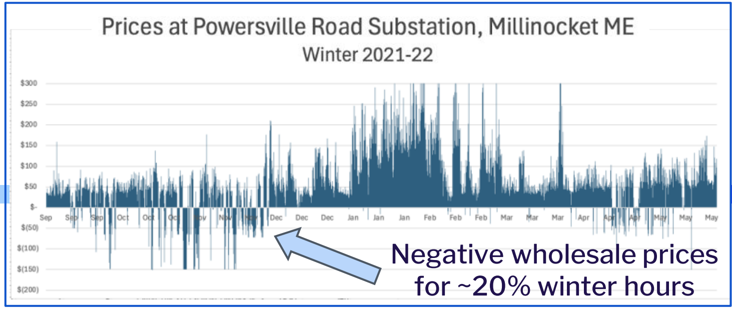
In some grids wholesale and grid-edge (node) prices are very dynamic

- Upper Midwest
  - Wholesale prices around wind farms go negative as much as 38% of the hours in the winter months
- Millinocket, Maine
  - Wholesale prices are negative ~20% of winter hours
  - Residents pay $4 per gallon for fuel oil
  - Local utility has an aggressive Time-of-Use distribution tariff
- This is likely to happen in many other places as we electrify heating and transportation



Prices were negative at these price nodes in 1Q 2024 in 38% of the hours

- Grid-edge needs:
  - Electrified heat should be flexible to reduce the need for distribution upgrades and reduce renewable curtailments



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Thermal Storage for Improving the Heat Pump Defrost Process

Jason Woods, Thomas Freeman, Ravi Kishore, Ransisi Huang, Zechao Lu
National Renewable Energy Laboratory

Stor4Build Annual Meeting
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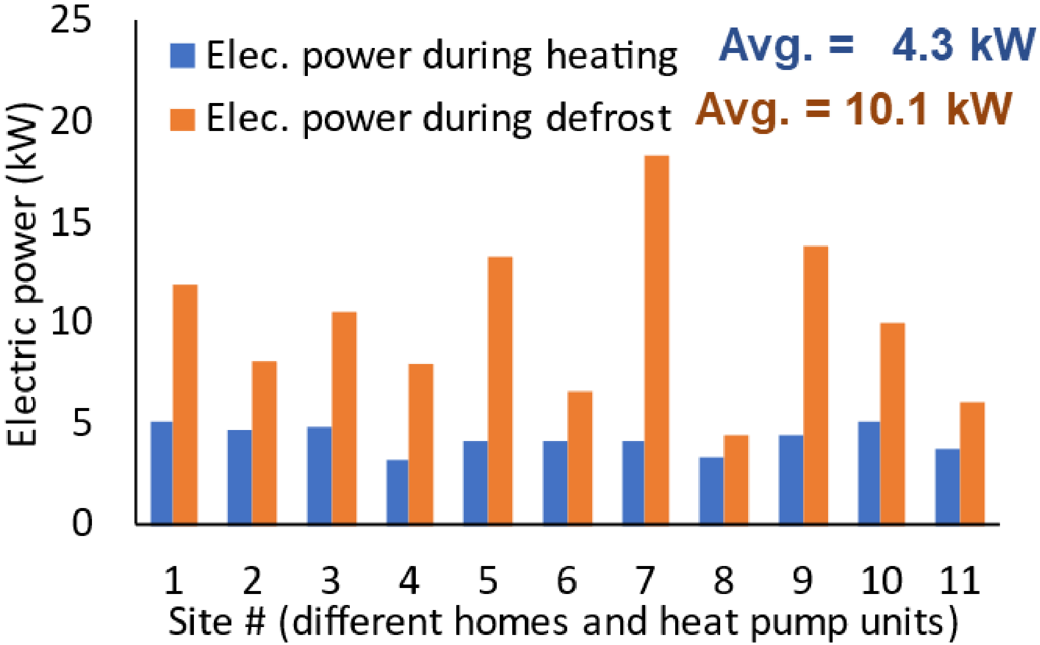
What is defrosting?

- Frost forms on the outdoor coil during heat pump operation.

- Defrosting is the process that removes this frost, typically by reversing the refrigerant cycle (running the heat pump as an air conditioner)

Why do we care about defrost?

- Defrost interrupts the heating process
- Defrost increases electricity use and peak electric power

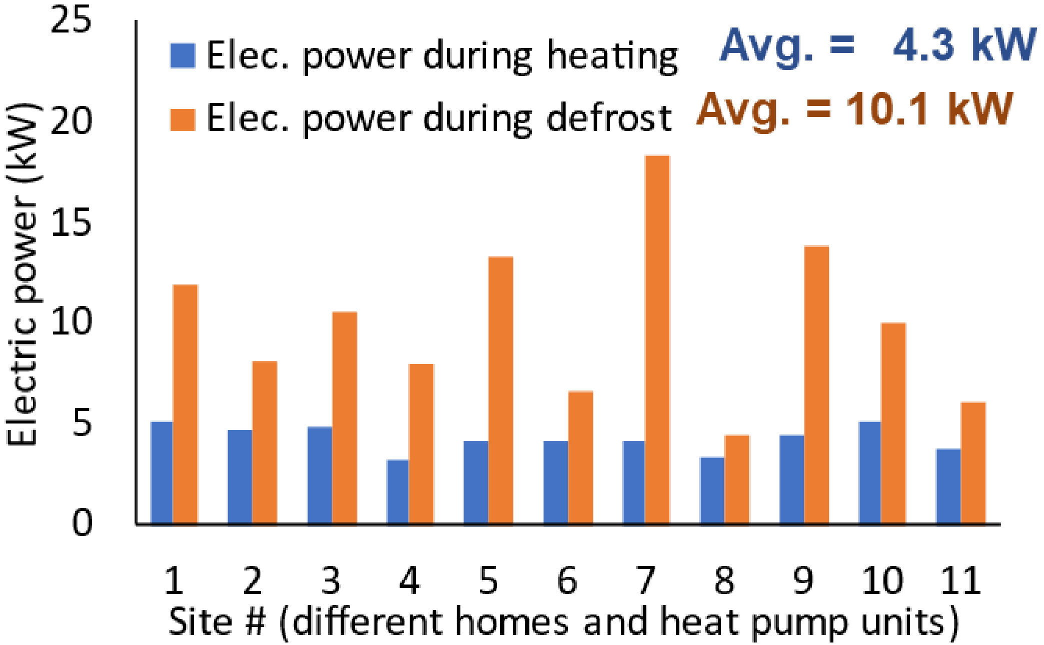


Field data shows peak power from defrost is ~2.5x higher than typical electric power during heating operation. Field data from Winkler and Ramaraj, 2023.

Winkler, Jon and Sugi Ramaraj. 2023. Field Validation of Air-Source Heat Pumps for Cold Climates. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5500-84745. https://www.nrel.gov/docs/fy23osti/84745.pdf

Outline

- Review frost/defrost process
- How can we use TES to mitigate the defrost penalty?
- Modeling
    - Frost/defrost
    - TES
    - Heat pump with TES
- Experimental plan



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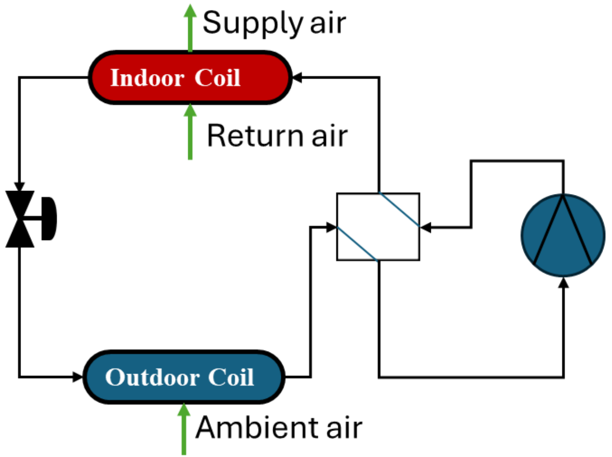
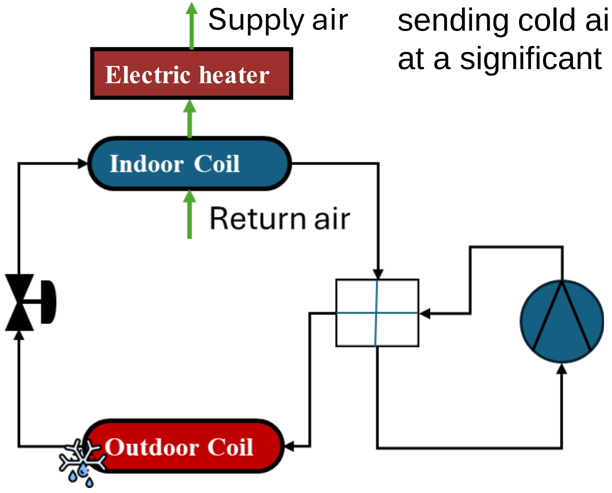
Frost/defrost process



Heat pump operation

Frost forms on outdoor coil if:

- $T_{evap} < 0$ °C, and
- $T_{dp} > T_{evap}$



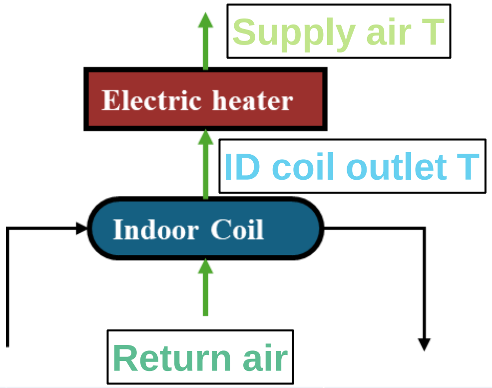
Electric heater added to prevent sending cold air to the building, but at a significant peak-power penalty.

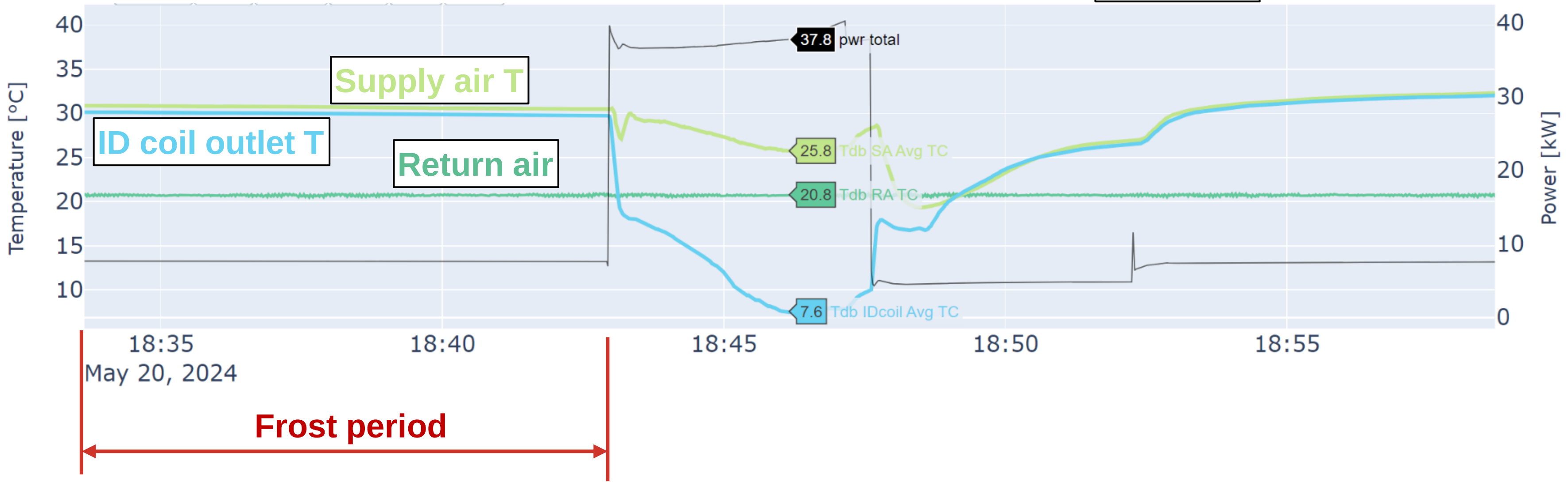
Defrost operation

System pulls heat from indoors to melt the frost on the outdoor coil

Frost/defrost process

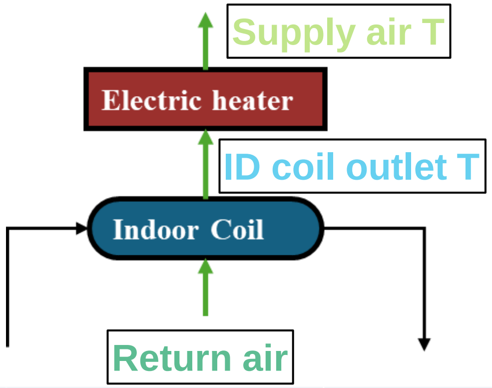
Lab data from 7.5-ton HP rooftop unit

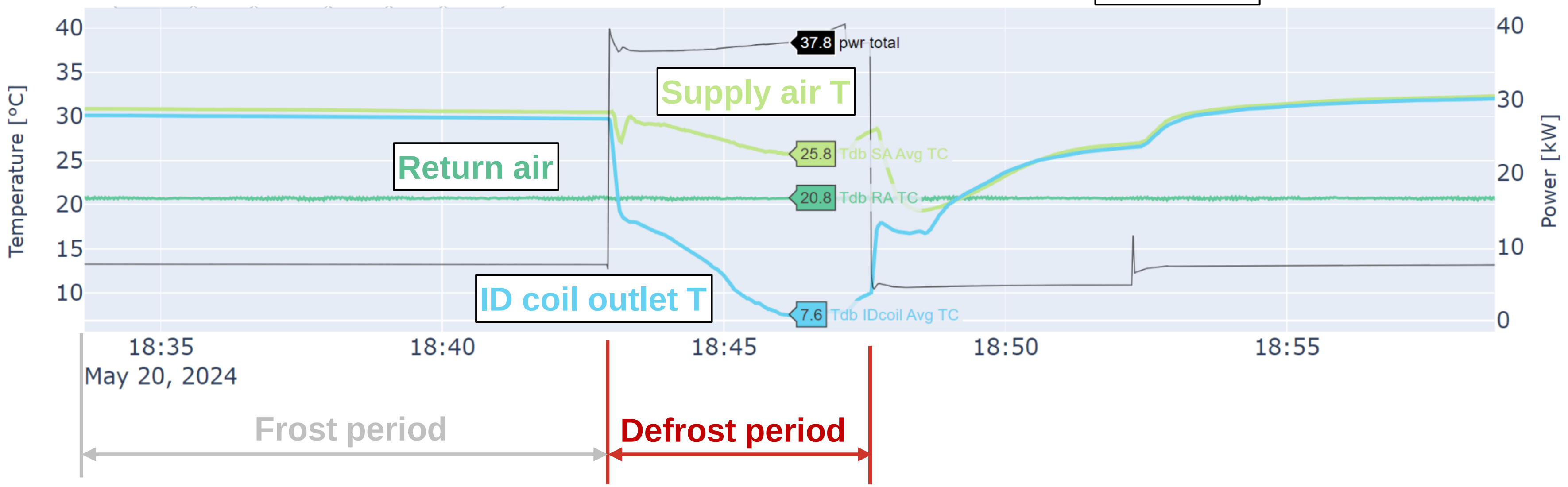




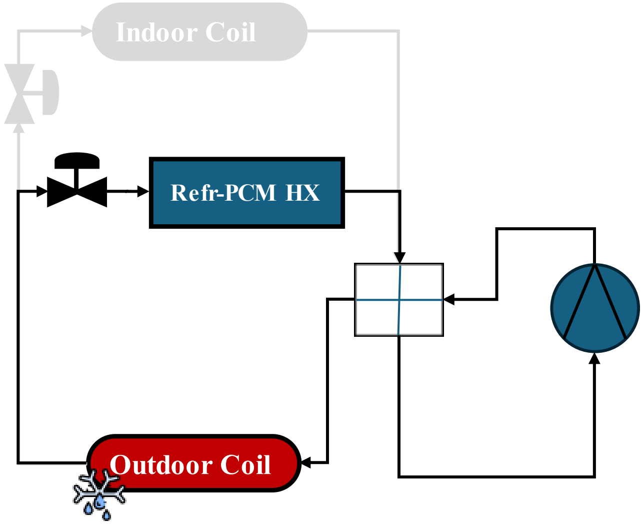
Frost/defrost process

Lab data from 7.5-ton HP rooftop unit

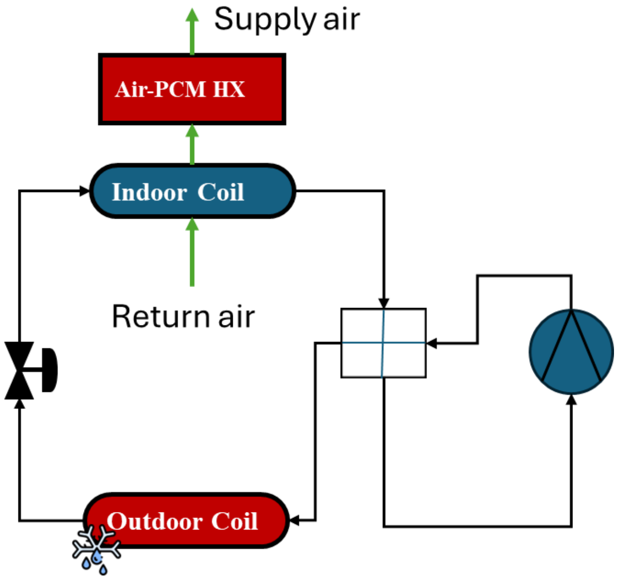




How can we use TES to mitigate the defrost penalty?



Option #1



Option #2

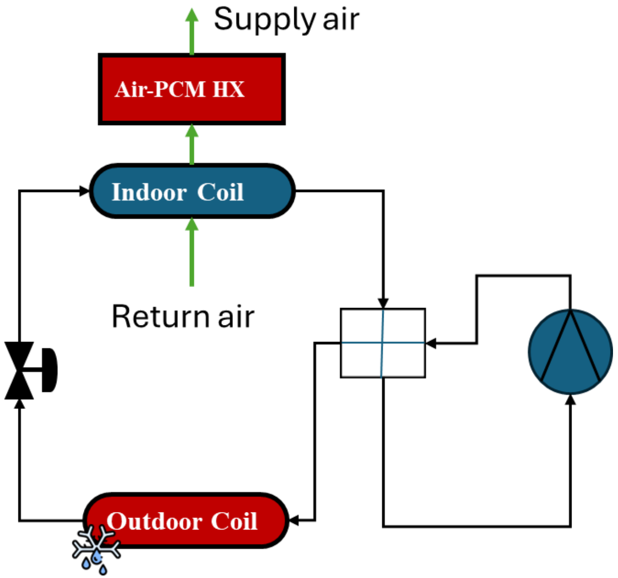
How can we use TES to mitigate the defrost penalty?

Pros:

- Applicable to different HVAC designs
- Retrofittable
- Could fit in roof curb or indoors near ceiling
- Low-cost

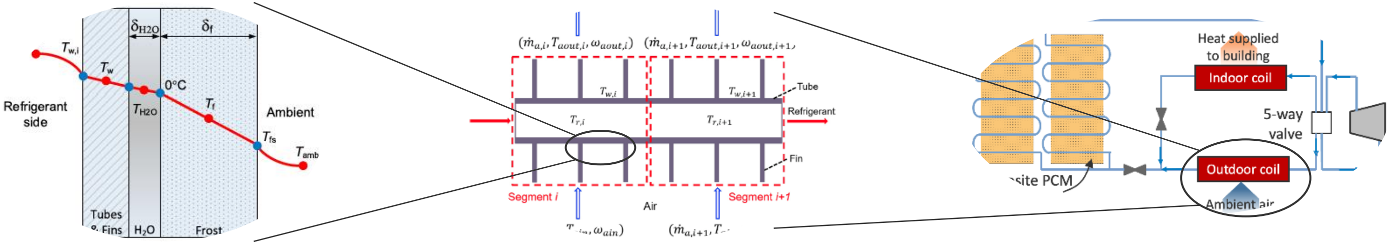
Cons:

- Added airside pressure drop
- Air is a poor heat transfer fluid



Modeling: frost and defrost process

Frost/defrost model → HX model → Heat pump model

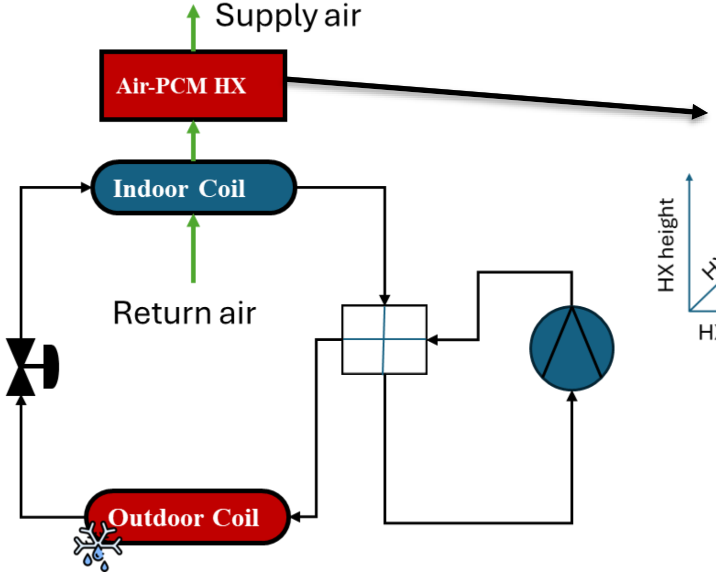


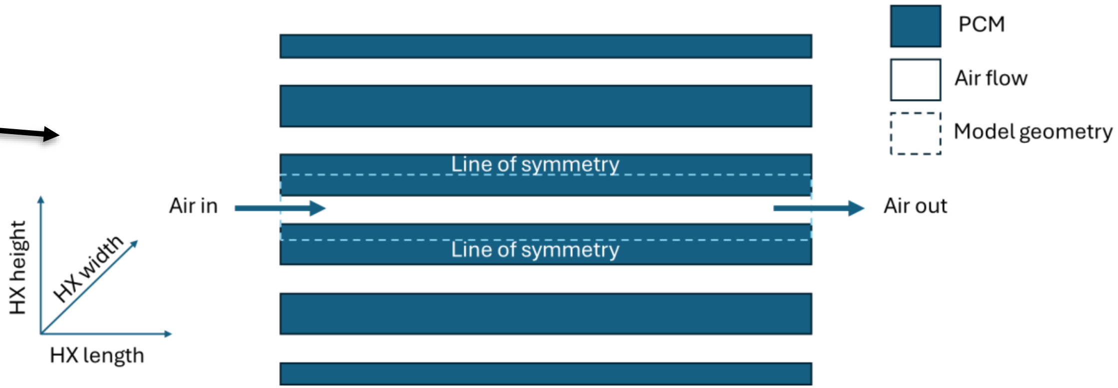
Frosting on a surface
Defrosting of a frost layer

Frosting of a heat exchanger
Defrosting a heat exchanger

Frosting during heat pump operation
Heat pump defrosting operation

Modeling: Thermal energy storage

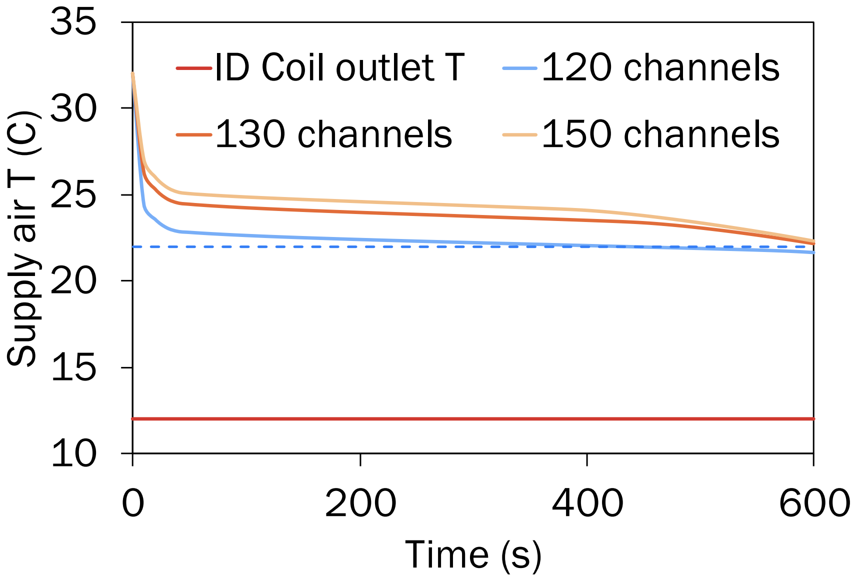




Selected PCM:

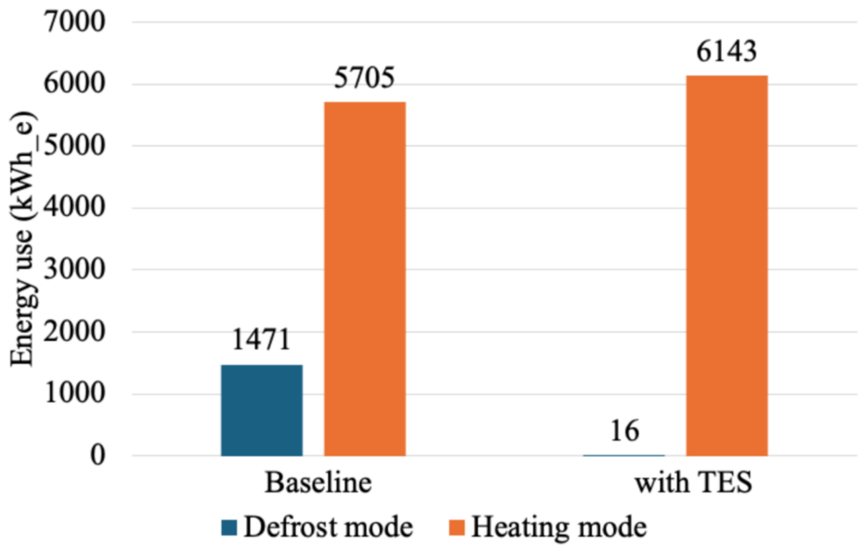
- 27 °C transition temperature
- 206 J/g
- 0.2 W/m-K
- 800 kg/m^3

Modeling: Thermal energy storage design

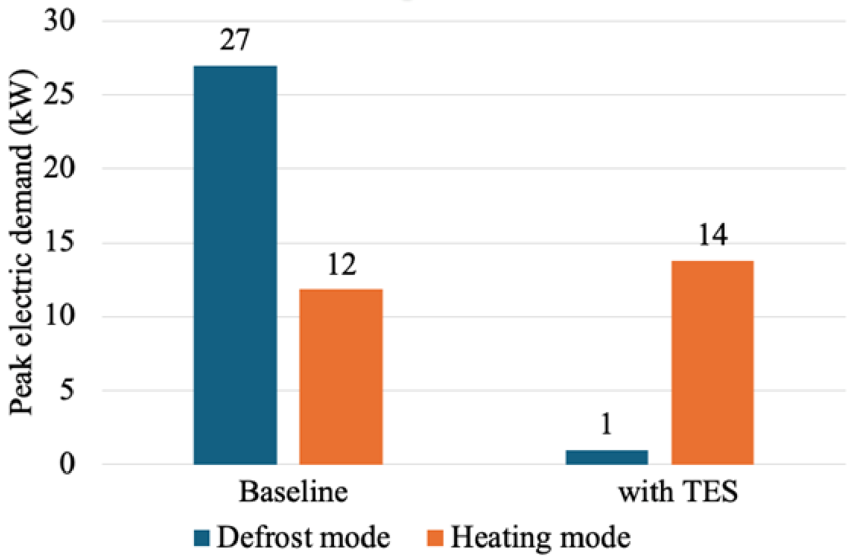


Heat Exchanger (HX) design for 10-ton RTU		
Number of channels	130	-
Air channel thickness	3.0	mm
PCM thickness	2.3	mm
HX width	1.0	m
HX length	0.4	m
HX height	1.0	m
Airside pressure drop	70	Pa

Modeling: Heat pump system



TES reduces total electricity use by 14% compared to baseline with electric resistance heater



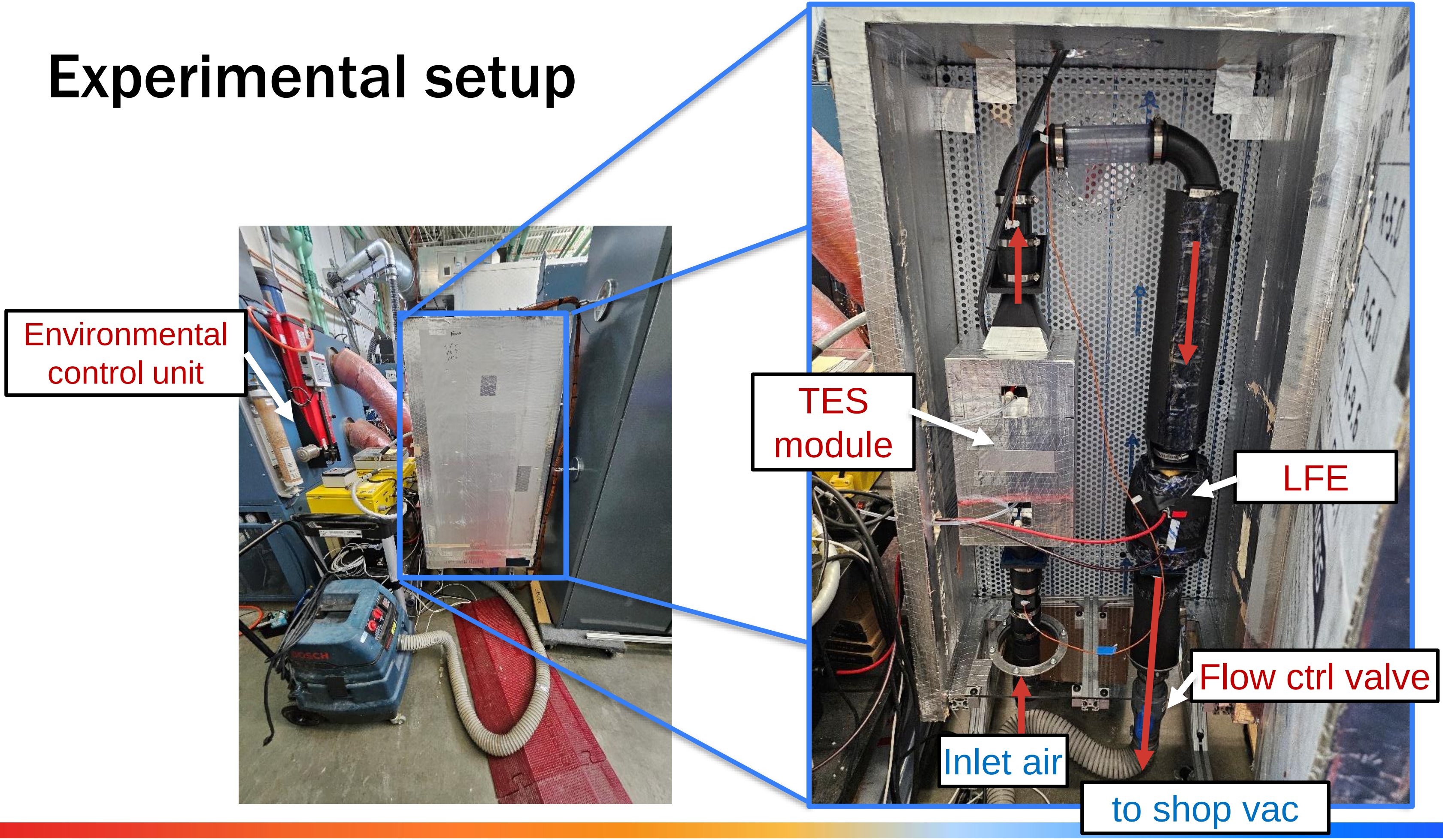
TES cuts peak electric power by half compared to baseline with electric resistance heater

Initial cost analysis indicates payback of less than 4 years

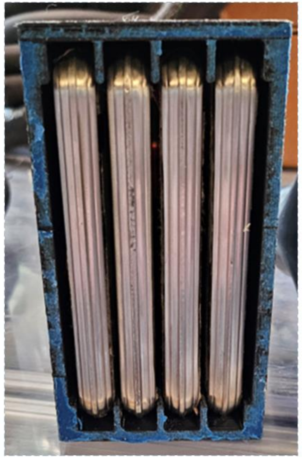
Simple payback for defrost application vs. traditional load shifting. Assumed $0.12/kWh avoided utility costs

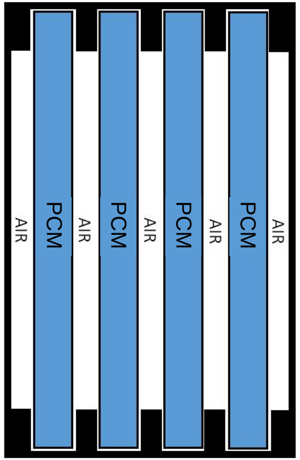
	Defrost	Load shifting
Required TES size	5 kWh_{th}	100 kWh_{th}
TES cost per kWh_{th}	$100/$kWh_{th}$	$100/$kWh_{th}$
TES cost	$500	$10,000
Cycles / year	400	150
kWh_e shaved / cycle	2.7	36
kWh_e shaved / yr	1080	5400
$ saved / yr	$130/yr	$650/yr
Simple payback	3.8	15.4

Experimental setup



TES prototype





Previous bench-scale prototype

Scaled-up prototype will use commercially available PCM panels from Rubitherm[1]

Minimum PCM thickness = 5 mm

[1] https://www.rubitherm.eu/en/productcategory/makroverkaspelung-csmRubitherm

Summary and next steps

- We typically think of TES as a load-shifting technology. But there are other potential value propositions.
- One promising application is using TES to eliminate electric resistance heat during defrost.
- In 2025, we will build a ¼-scale prototype (~1.5 kWh) and measure its performance in the lab.
- We hope to demonstrate this use case in the field in 2026.

Acknowledgements

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Thank You

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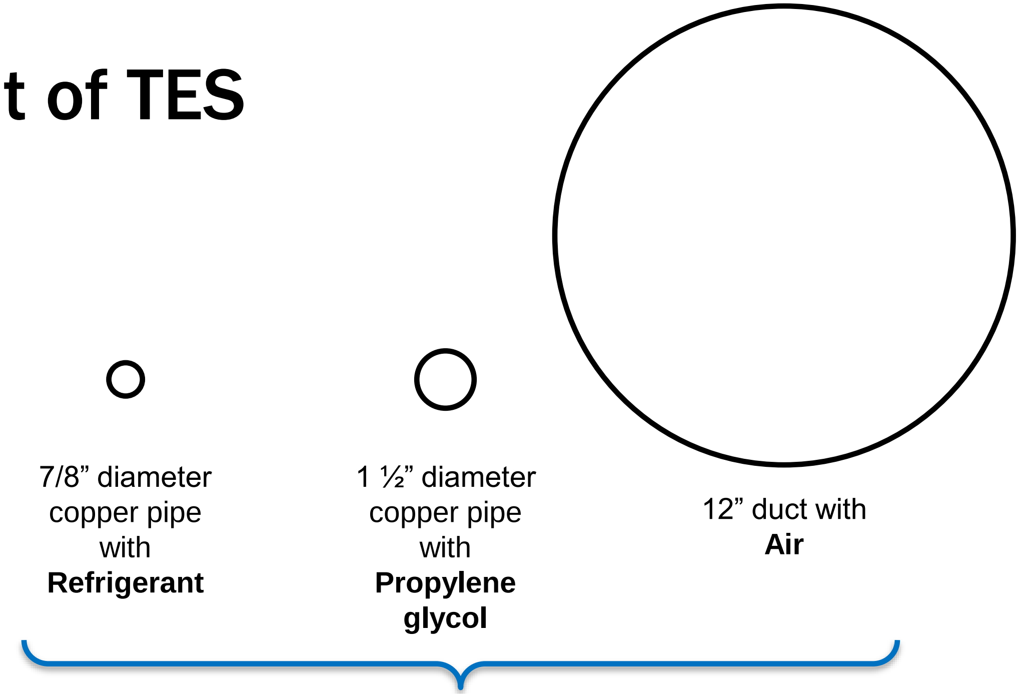
National Renewable Energy Laboratory

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

Moving heat into / out of TES

<u>How well do fluids carry heat?</u>

- Great: Refrigerants
- Good: Water/glycol solutions
  - But they require a secondary loop between refrigerant and air
- Poor: Air
  - But air is the fluid that is used by the application

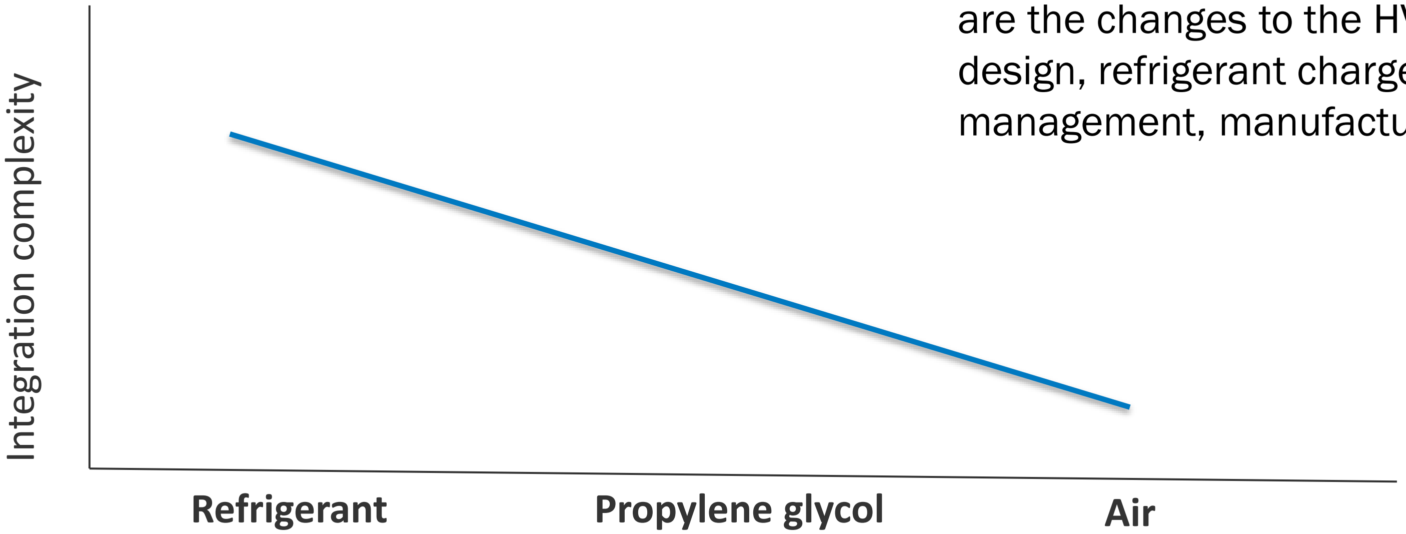


20 kW_{th}

Thermal transport with different heat transfer fluids

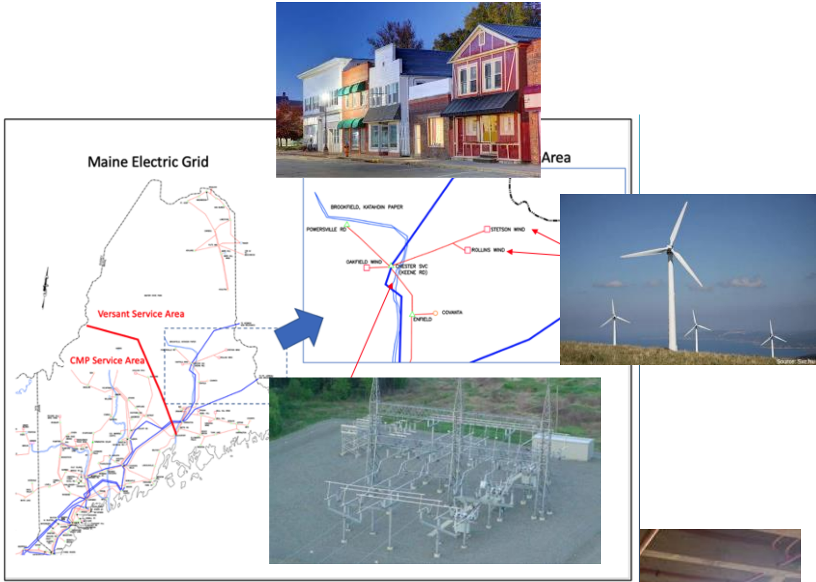
Minimizing integration costs

Integration complexity: How significant are the changes to the HVAC system design, refrigerant charge management, manufacturing, controls?



We are conducting a project in one of those grids in Millinocket, Maine

- Partnering with **Efficiency Maine Trust** to build out an aggregation of **6 homes** located at the most **constrained** location on the **ISO-New England** electric grid
- Millinocket, Maine:
    - Former paper mill town, **low income**, **no natural gas infrastructure** and **high heating costs**
    - Heating degree days: 8782
    - 99% heating temp: -5 °F
    - Two of the largest wind farms in New England plus hydro from the now-closed paper mills drive **local overgeneration**
- 2 homes operated in 2023-24, 4 more being retrofitted this summer
    - Close collaboration with local HVAC contractor, Moscone Heating

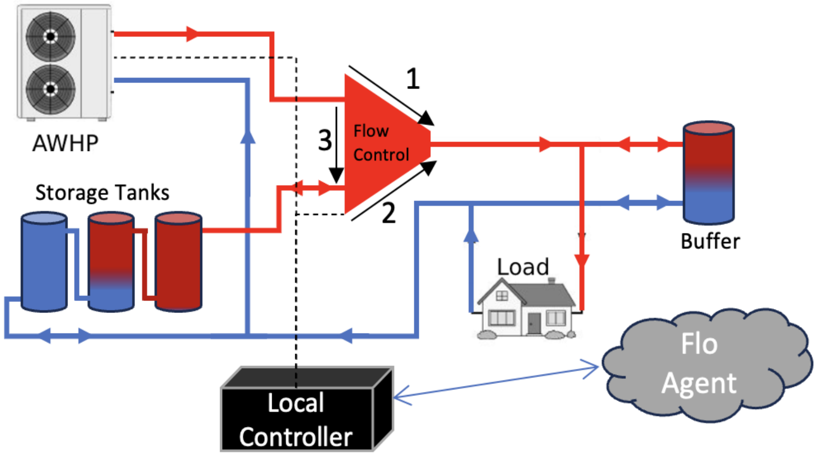


The project explores design and control of HP + TES for grid-edge benefits

- How do we **design** a **cost-effective** HVAC system that uses currently **available technologies** to shift the load to low price intervals in a cold climate home ?
- How do we develop a **control system** that operates the HVAC to take advantage of **dynamic prices**?
- What can we learn from a field deployment of such a system?

System Design: Air-to-Water HP + Water Tank TES

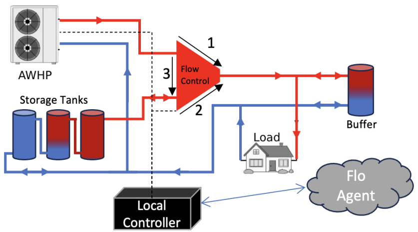
- Design specifications
    - Use existing hydronic heat distribution system (baseboard or radiator)
    - Nominal "Required Source Water Temperature" of 180° F
    - No hard constraints on weight/size (basement)
    - Use off the shelf components
    - Modes of operation shall:
        - Heat the house from the heat pump
        - Heat the house from the TES
        - Heat the TES from the heat pump
    - Control system need to:
        - Monitor temp, flow rates, and electrical kW
        - Control the HP and the hydronic distribution
        - Optimize for prices

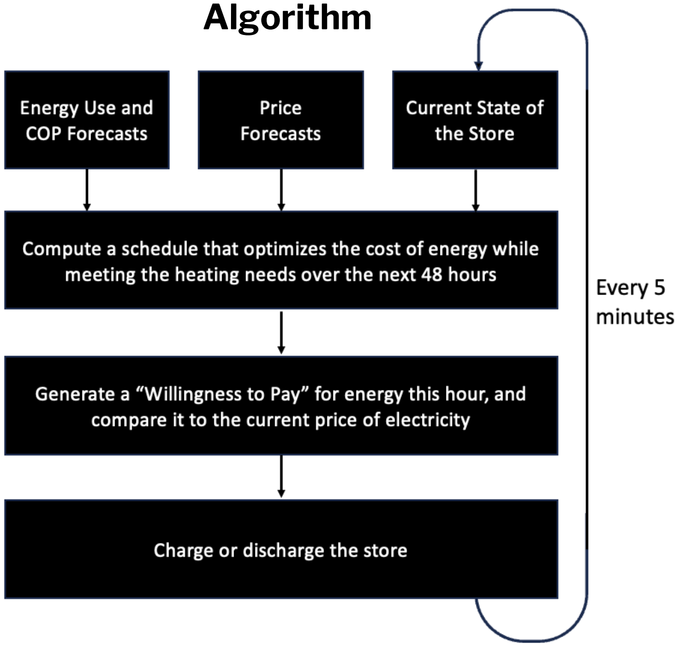


- Final Design
    - 10 kW LG Hydro-kit 2-stage heat pump
    - 3 water tanks, and buffer tank (each one Vaughn 120 gallons)
    - Flow control manifold (Belimo controllable valves, Caleffi zone controller)
    - Components are all off-the-shelf

Controls Design: Forward-looking optimizer

- Final Design: Two-level control system
  - **Local controller** monitors system and control HP and distribution manifold
  - **FLO** Optimizer runs in the cloud and sends schedules to the local controller

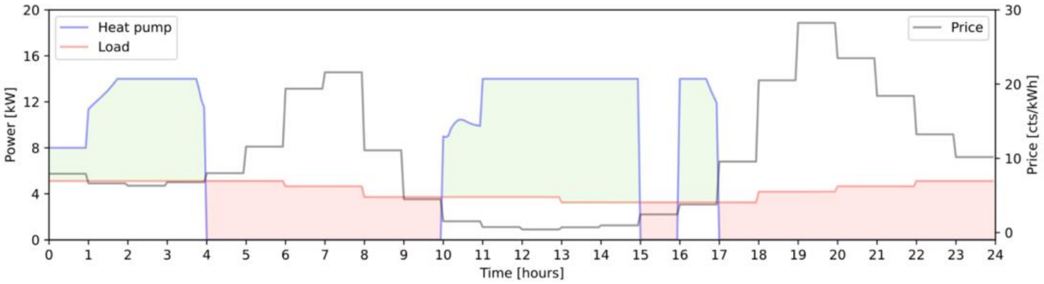




Status:

- Prototype software developed
- Tested on a model of the system

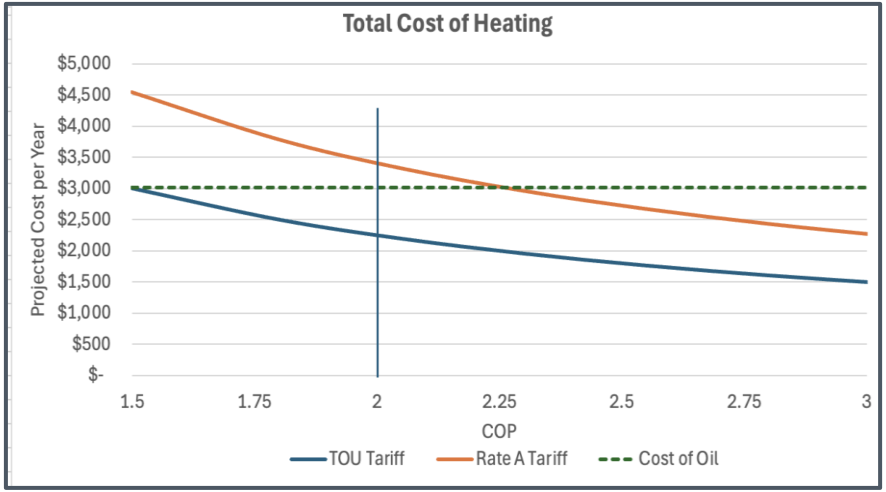
Charging / **discharging** storage during off- / on-peak hours



Simulation Results:

- **67% energy cost savings** compared to no load shifting in some scenarios

Field Deployment: Projected Economic Benefits



Estimated customer cost savings with COP = 2

- vs fuel oil: **$3,000/y**
- vs AWHP on std tariff : **$3,400/y**
- vs AWHP + TES on TOU tariff: **$2,250/y**

Benefit for the grid:

- reduced load during peak demand on the distribution grid

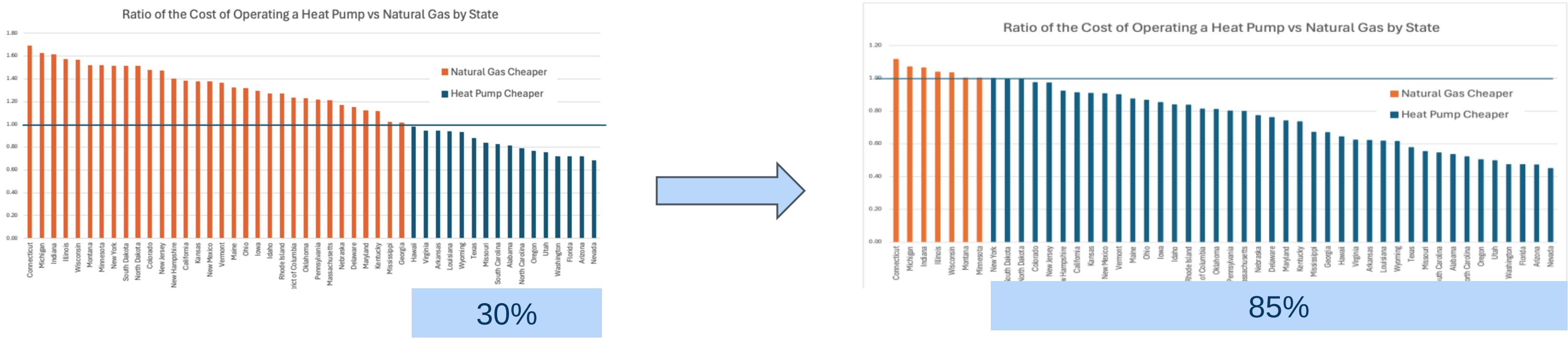
- With FLO algorithms, these systems can respond to grid conditions in real time, and provide lucrative balancing services and support grid-edge
  - Estimated additional +$1,000/year if access to hourly wholesale prices
- This is critical to addressing the affordability of HP/TES systems

Lessons Learned

- Water Stratification
  - Good stratification is very important to the efficient performance of a air-to-water heat pump
    - Heat pumps work better with lower return water temps and long cycle times
  - Many (direct) storage tanks do not achieve good stratification, especially when in charging mode
- Water Temperatures
  - In first two homes system kept homes warm at all times with 120° F supply water (vs 180° design)
- COP
  - COP was not as high as we would like (~1.8-2.2)
    - but should improve with deployment of FLO
  - COP was measurably higher with cooler supply water temperatures and warmer OAT
    - If we can reduce max supply water temperatures this can improve COP and economics

Conclusion and impact

- AWHPs+ TES can keep homes warm, even in cold climates
- With the right tariff structure, and dynamic prices, AWHPs will be significantly cheaper to run than fossil-fuel heating



- Residential AWHPs can be cost-effective and scalable, but
  - need right tariffs and price access
  - need TES packaged with HP as industrial products
  - need forward-looking controls
- Results will inform how to mitigate key barriers to transforming the grid edge and accelerating onsite emission reductions (DOE Decarbonization blueprint).

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Thank You

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