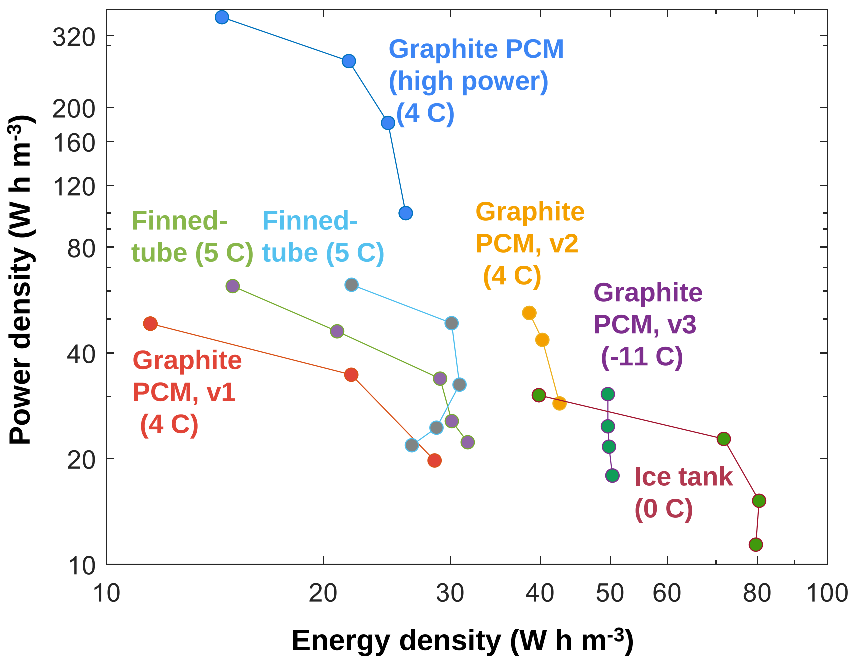
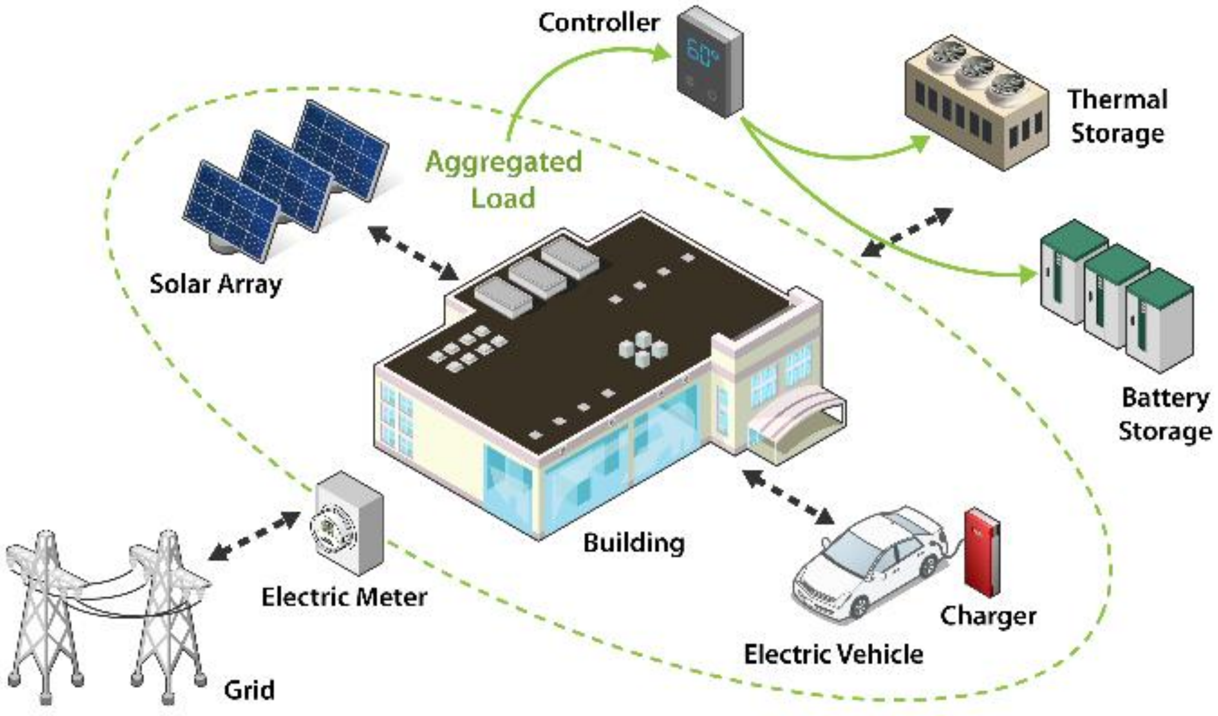
Behind-the-meter thermal energy storage





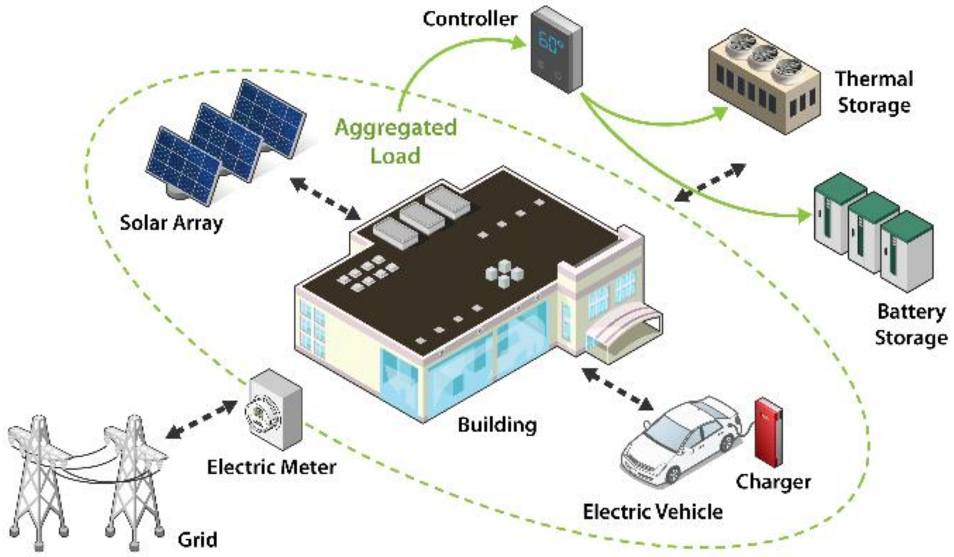
National Renewable Energy Laboratory
Dr. Jason Woods, Senior Research Engineer
720.441.9727; jason.woods@nrel.gov

WBS # 3.4.6.63

Project Summary

Objective and outcome

This project focuses on reducing the cost of thermal-storage heat exchangers, their integration into HVAC systems, and their interaction with other building distributed energy resources.



Team and Partners

Emerson

NETenergy LLC

Colorado School of Mines

Trane Technologies

Stats

Performance Period: 10/2019 – 03/2023

DOE budget: $3,250k, Cost Share: $200k

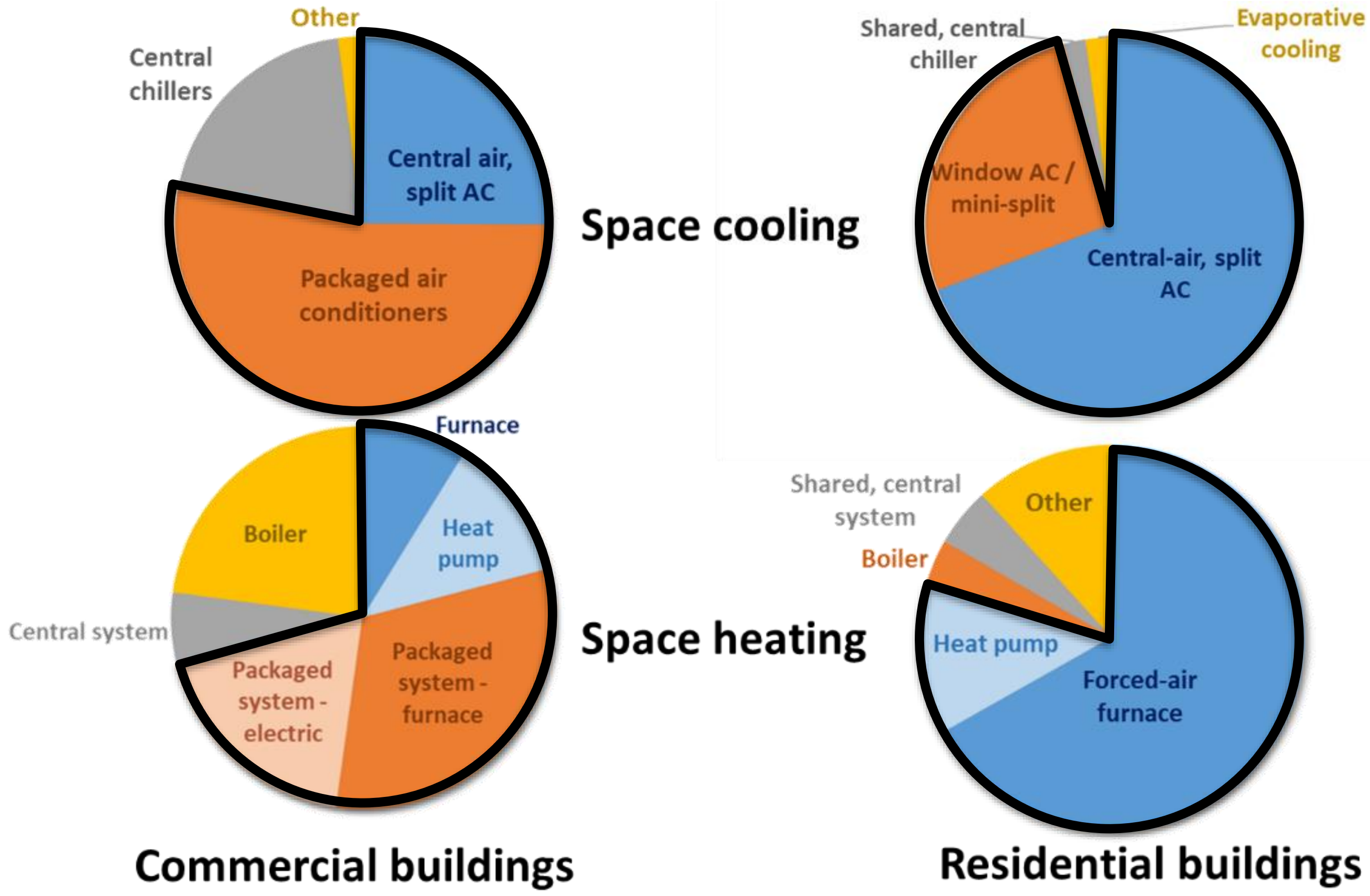
Milestone 1: *Publication:* Modeling and experimental results on PCM HX showing power-energy tradeoff

Milestone 2: *Publication:* Design rules and C-rate requirements for TES using Ragone framework

Milestone 3: HVAC-TES system design complete, supported by modeling results

Problem

Existing thermal energy storage (TES) is used in central chiller plants, but…



Only 20% of US floor area has a central plant

…while **80% of US floor area has a packaged or split HVAC system**

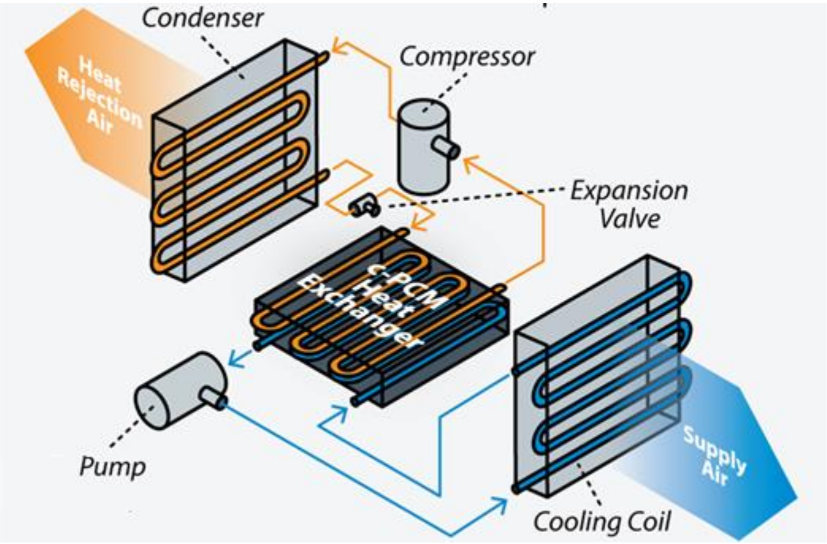
Source: EIA 2018 Commercial Buildings Energy Consumption Survey; EIA 2020 Residential Energy Consumption Survey.

Problem

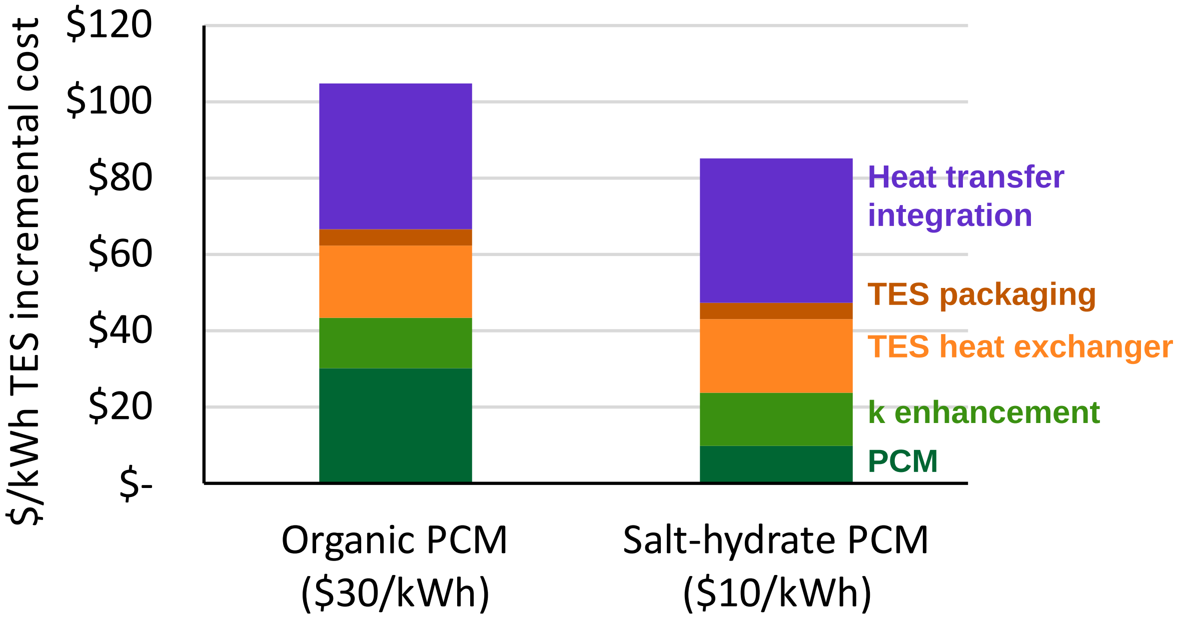
80% of US floor area has a packaged or split HVAC system, but…

…adding TES into these smaller, distributed HVAC systems is difficult and is dominated by **heat exchanger and integration costs**

Example integration of PCM into 5-ton air conditioner



Incremental per kWh costs for a 10-tonh glycol-coupled TES in a 5-ton air conditioner



Alignment and Impact

Connecting to priorities towards EERE/BTO 2050 vision

Accelerate building electrification

Designs for integrating TES into cold-climate heat pumps that can improve efficiency and reduce demand by 50%

Transform the grid edge at buildings

Increase power capability / flexibility of TES, amplifying building load flexibility, and reduce costs for PCM-integrated HXs below $40/kWh$_{th}$

Prioritize equity, affordability, and resilience

Develop techniques to lower HVAC-integration costs for TES by minimizing additional components and simplifying installation

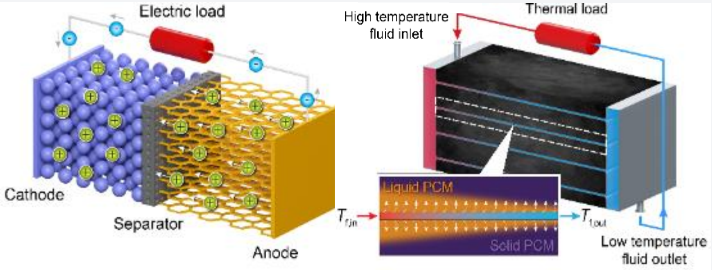
Long-term project impact: Reduce US carbon emissions by expanding the benefits of TES to commonly-used distributed HVAC systems, for both heating and cooling.

Approach

Outcome 1: Low-cost, high-performing TES heat exchangers for distributed HVAC systems

Create framework for PCM HX design and characterization

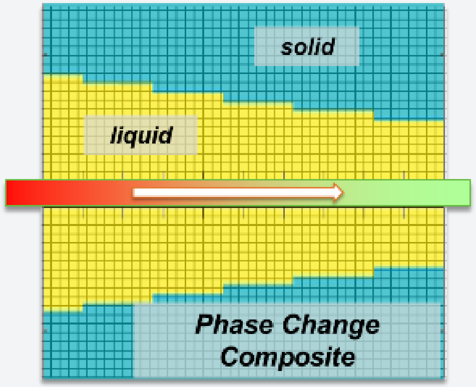
No prior framework
Standard heat exchanger methods not applicable



Collaboration with battery researchers at NREL, ANL, SNL, and INL

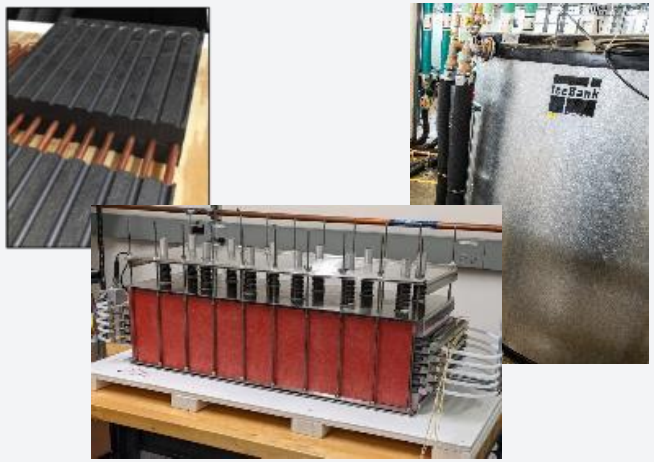
Create 2d transient models for designing PCM HXs

Design PCM HXs using new framework and detailed, validated models



Design, build, and characterize PCM HXs

Build a range of PCM HX prototypes and evaluate them under the new framework

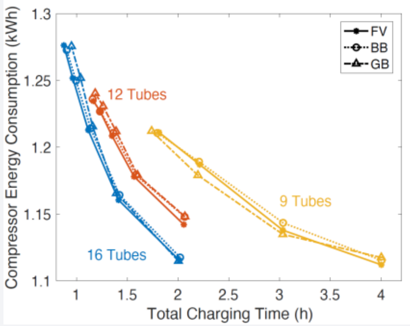


Approach

Outcome 2: Designs for TES-HVAC systems for grid-interactive and cost-effective heating and cooling

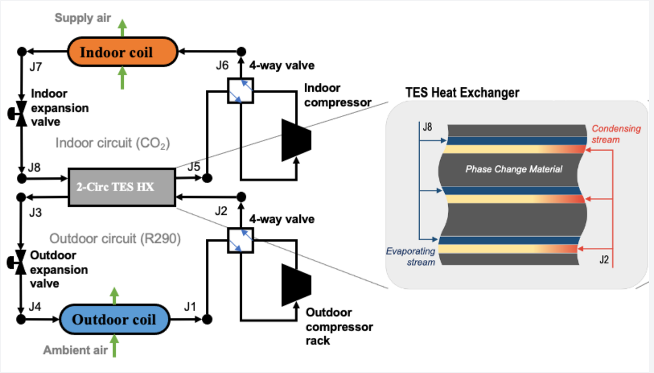
Develop heat pump + TES models

Complex models not suitable for annual simulations
Integrate reduced-order TES models with heat pump models, and use binned approach to minimize computation time



Explore heat pump + TES configurations

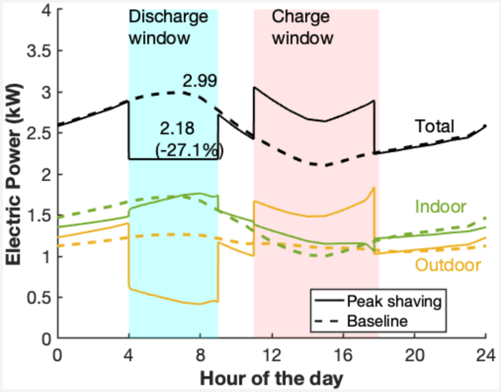
- Cascade heat pump with PCM HX
- Split system with PCM HX on secondary loop
- CO_2 heat pump with sensible storage tank



Detailed design and evaluation

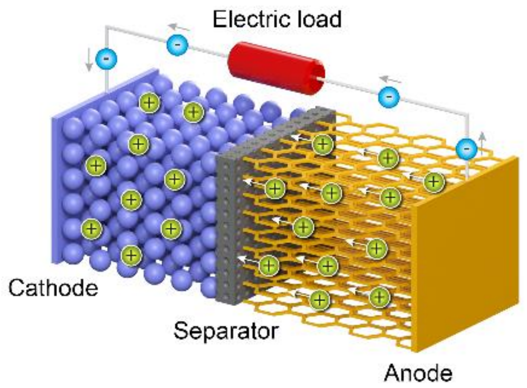
Model-based design determines:

- TES size
- Controls
- Compressor selection
- PCM transition temperature

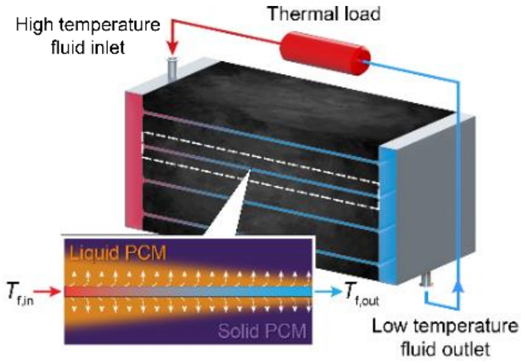


Designing phase-change TES is surprisingly similar to designing batteries

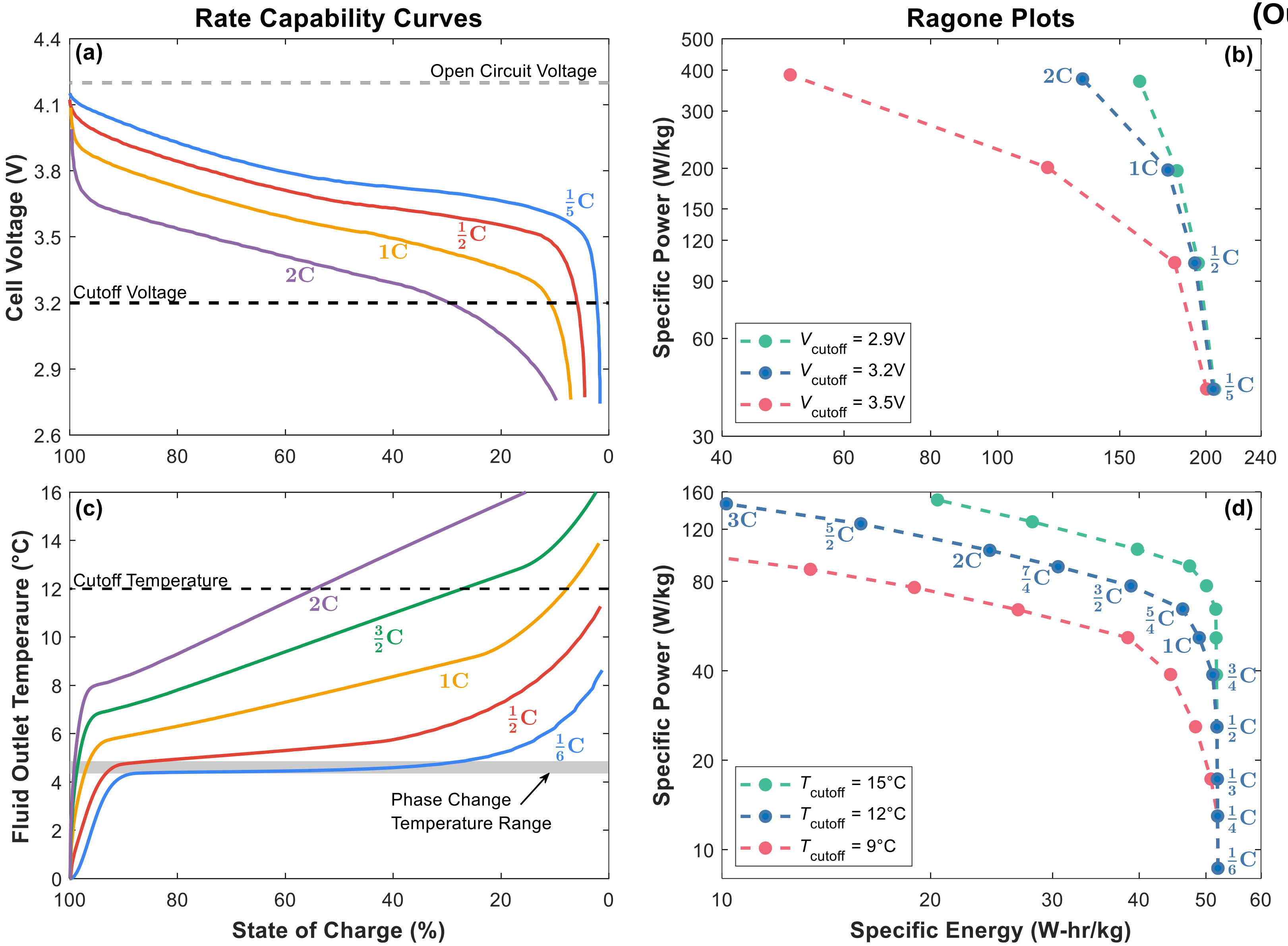
(Outcome 1)



Electrochemical battery



Phase change thermal battery

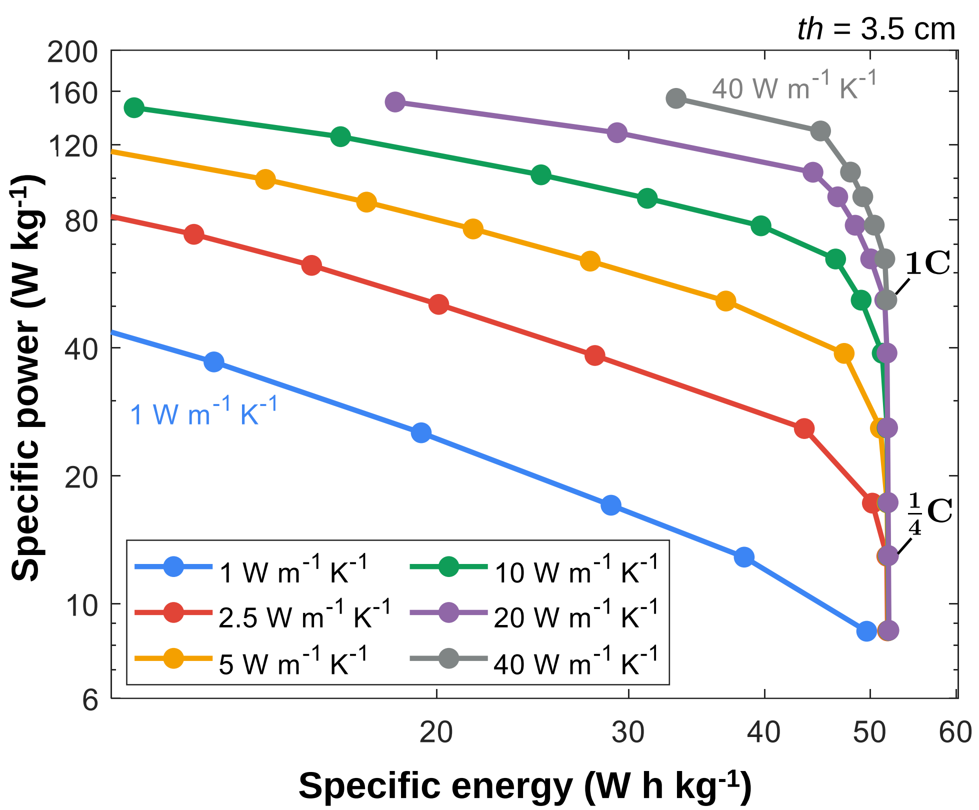


Woods et al. Rate capability and Ragone plots for phase change thermal energy storage. *Nature Energy* 6, 295–302 (2021).

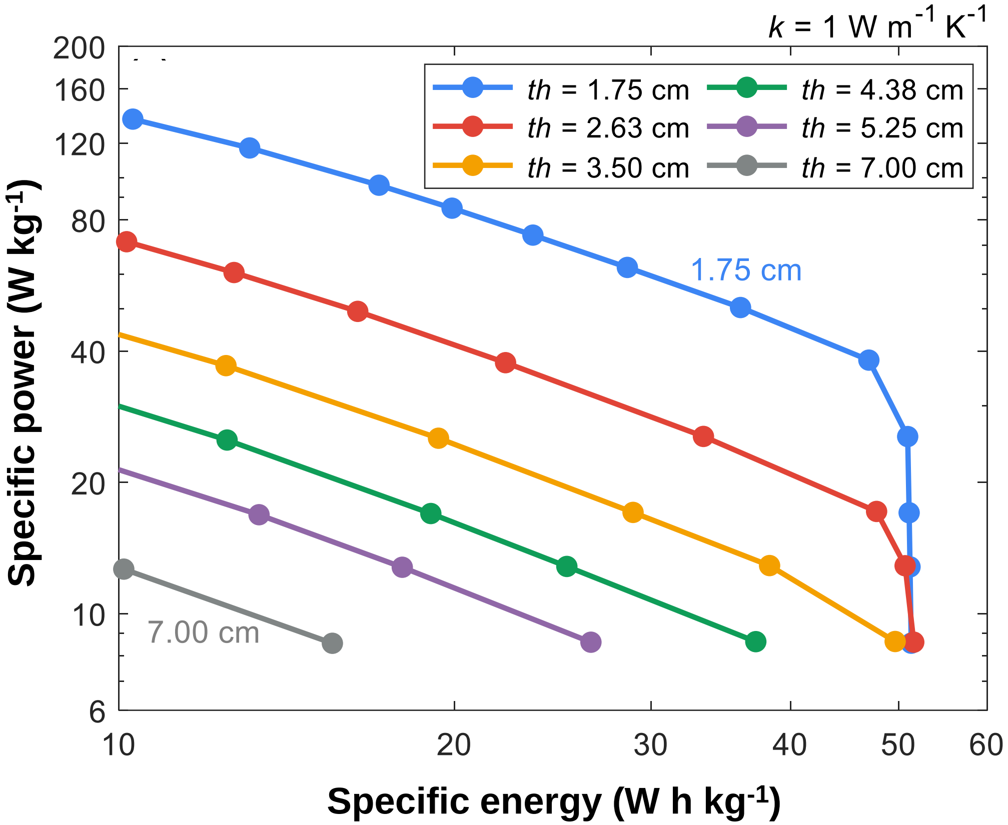
Ragone plots clearly compare performance over a range of materials and heat exchanger designs

(Outcome 1)

Effect of thermal conductivity (*k*)



Effect of PCM thickness (*th*)



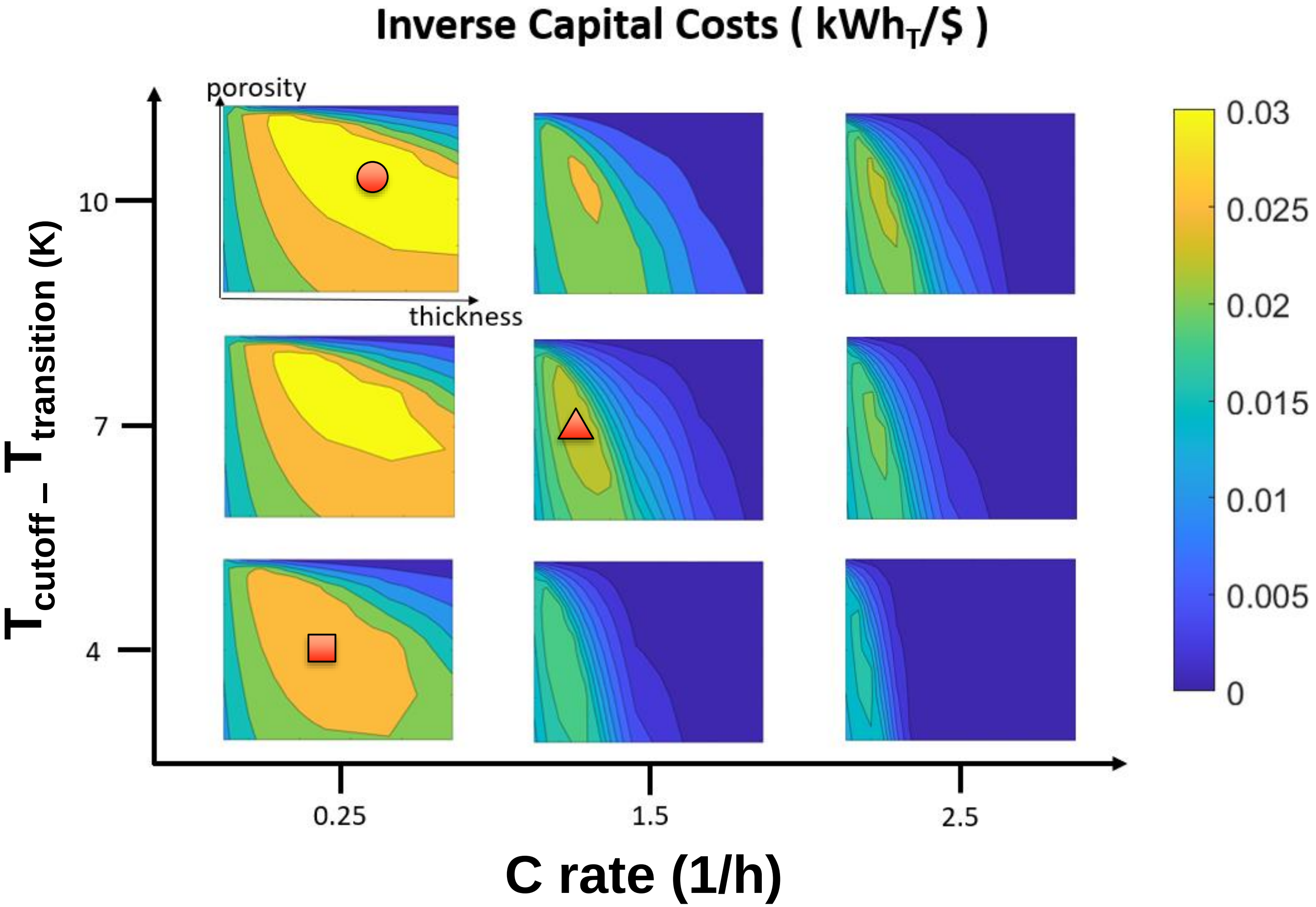
The Ragone framework enables us to compare TES materials or devices, whether as an experimental characterization technique or to develop potential improvements through modeling and design

Woods et al. Rate capability and Ragone plots for phase change thermal energy storage. *Nature Energy* 6, 295–302 (2021).

The Ragone framework enables methods for optimizing design

(Outcome 1)

Designing TES heat exchangers is not the same as typical heat exchangers. The Ragone framework developed here provides a clear pathway to achieving energy density, power density, and cost targets.



- 4-hour discharge, $|T_{PCM} - T_{cutoff}| = 10$ K
  - 10% graphite loading
  - 8 cm tube spacing (PCM thickness)
  - $30/kWh$_{th}$
- 4-hour discharge, $|T_{PCM} - T_{cutoff}| = 4$ K
  - 15% graphite loading
  - 5 cm tube spacing (PCM thickness)
  - $40/kWh$_{th}$
- 40-minute discharge, $|T_{PCM} - T_{cutoff}| = 7$ K
  - 15% graphite loading
  - 2 cm tube spacing (PCM thickness)
  - $50/kWh$_{th}$

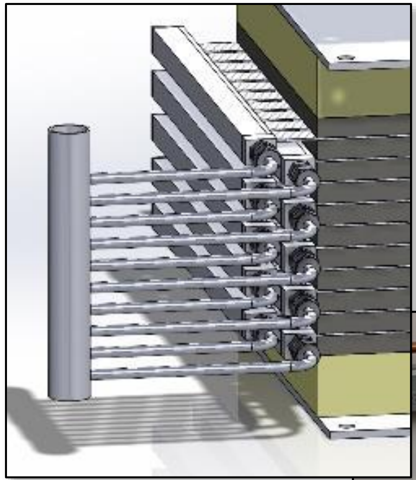
James, N., A. Mahvi, J. Woods. Optimizing phase change composite thermal energy storage using the thermal Ragone framework. J Energy Storage. 56 (2022) 105875.

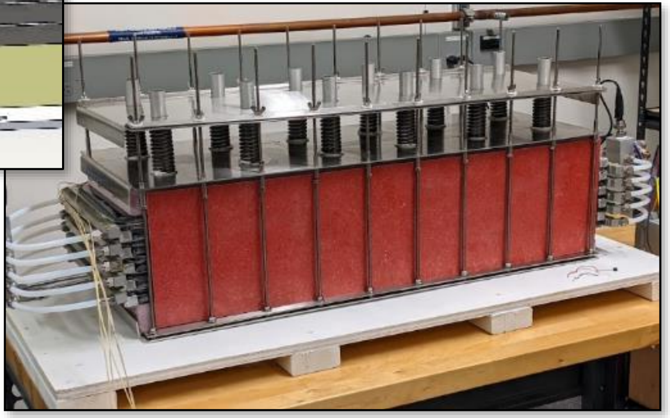
Leveraging this model, we build and characterized different PCM HXs for integration with HVAC systems

(Outcome 1)

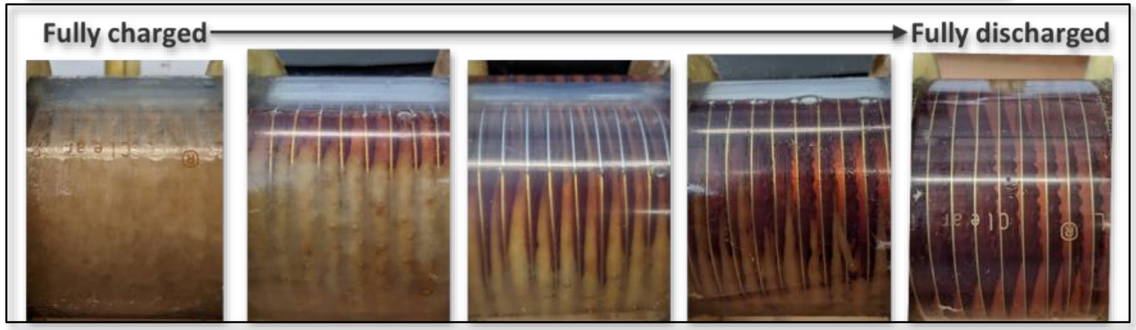
Ice-on-coil storage tank
570 kWh
T_t = 0 ºC

High-power graphite + PCM – Al microchannels
1 kWh
T_t = 4 ºC





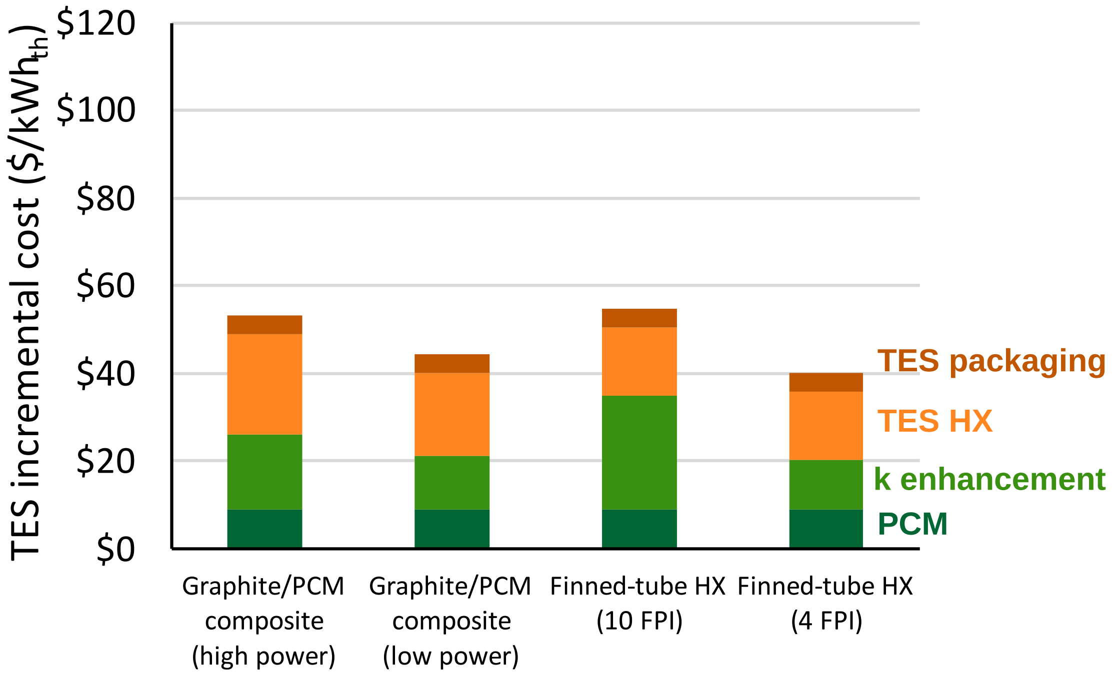
Finned-tube HX
300 Wh
T_t = 5 ºC

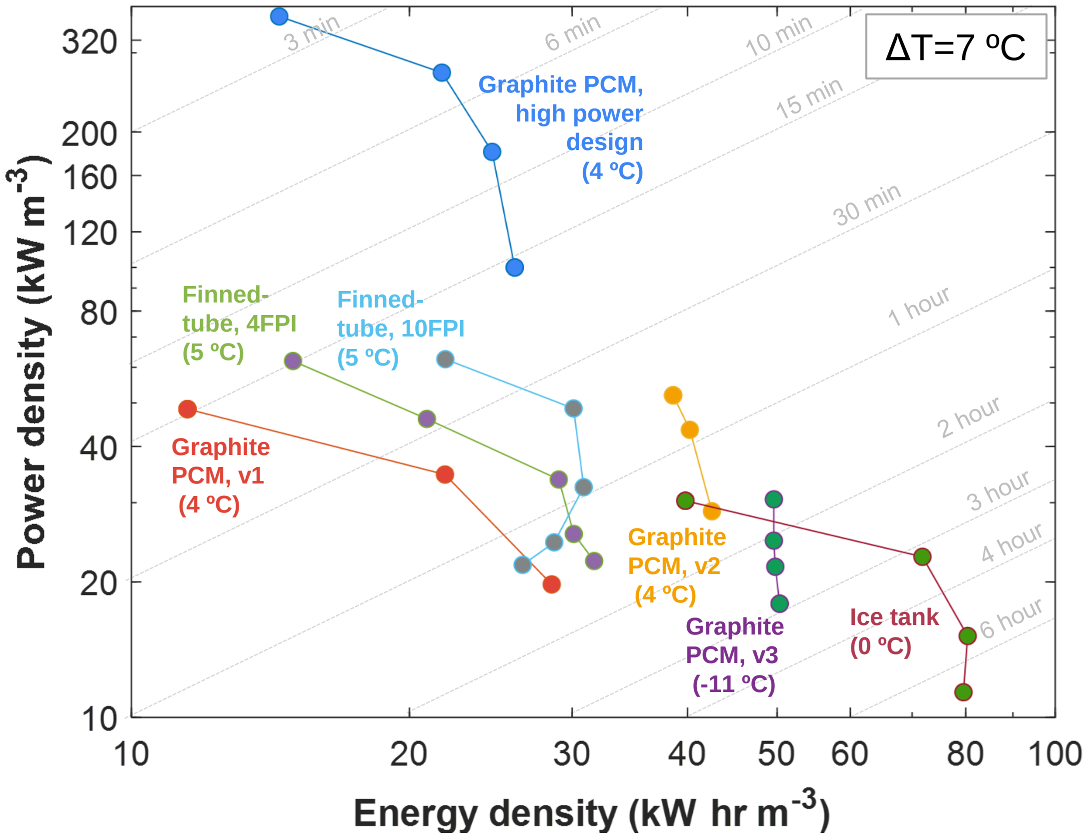


Ragone framework allows easy comparison of power and energy capabilities between different designs.

(Outcome 1)

Cost estimates for PCM HXs using low-cost salt hydrate PCM



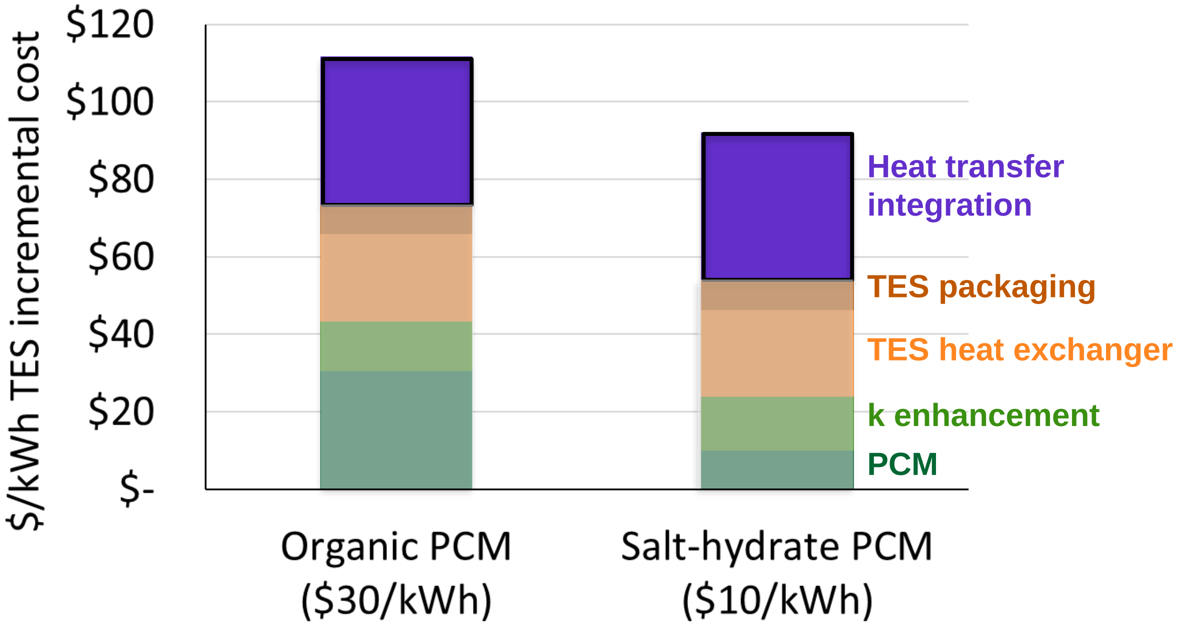


Ragone plot for comparing performance of various PCM HX designs

Objective 2: Develop HVAC systems that use TES for both heating and cooling

(Outcome 2)

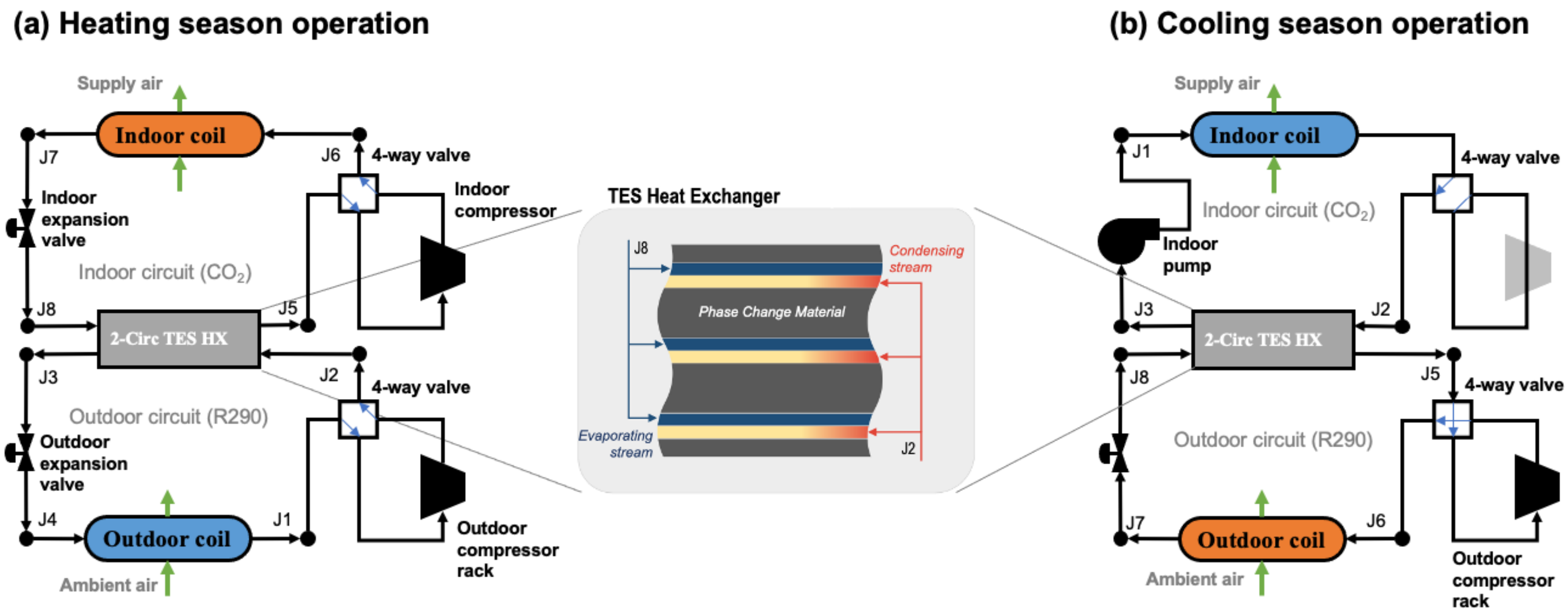
- Integrating the TES into the HVAC system remains one of the dominant costs
- In this project, we have explored several options for integrating TES:
  - Single-circuit PCM HX (glycol or refrigerant coupled)
  - **Dual-circuit PCM HX (refrigerant coupled)**
  - High-dT sensible storage



Cascade heat pump with PCM TES enables combined heating and cooling

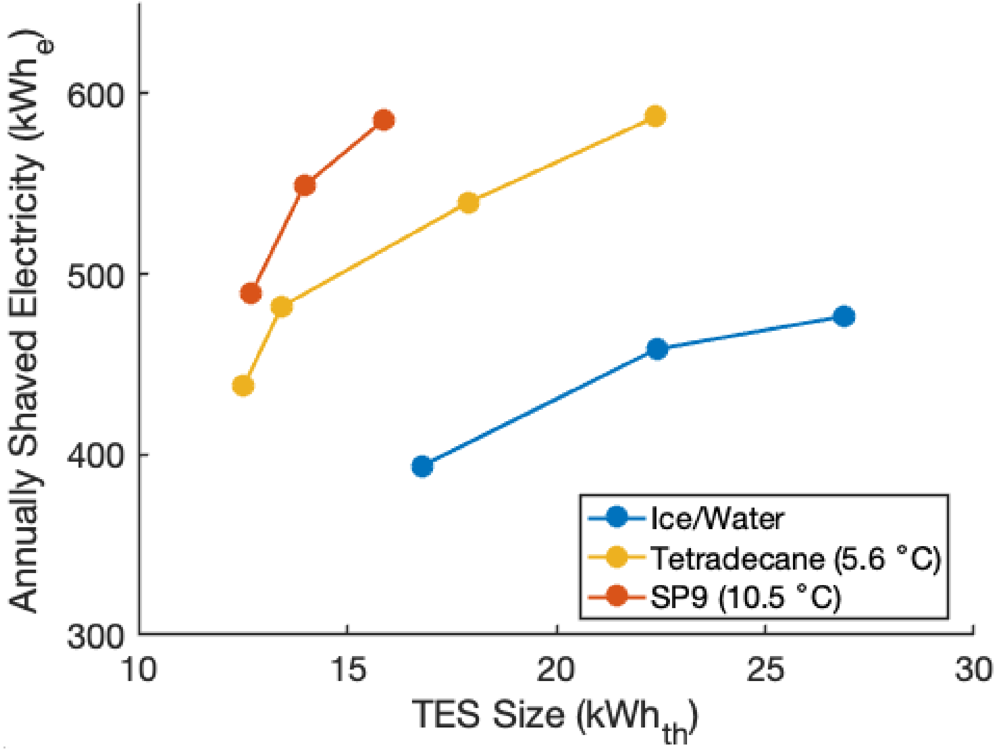
(Outcome 2)

- Integrating TES in this cascade system minimizes added costs (no glycol loop, indoor and outdoor coils unchanged)
- Cascade design also enables low-GWP refrigerants (R290 outdoors only) and cold climate operation



TES performance in cascade heat pump

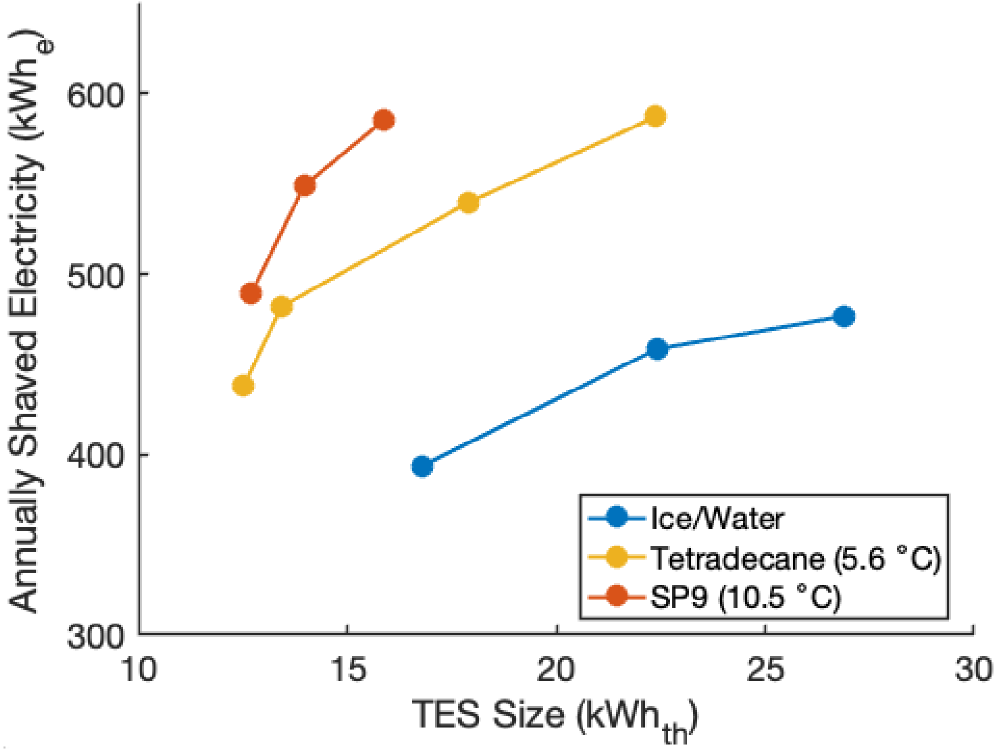
(Outcome 2)

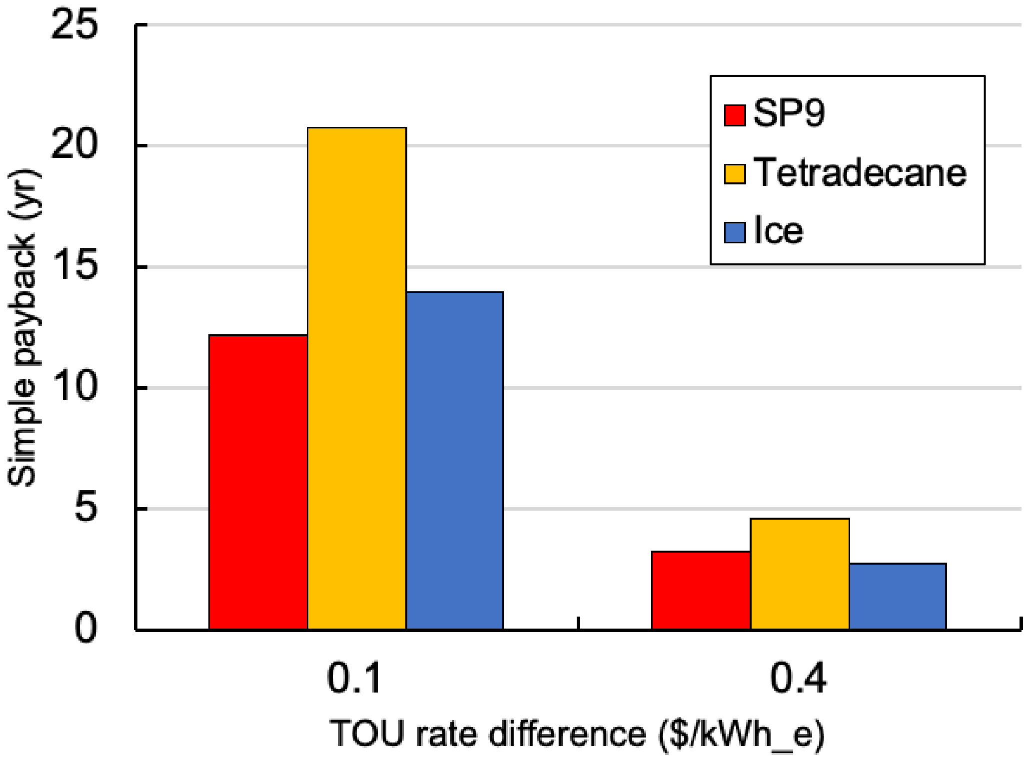


- TES in a 3-ton cascade system shaves 400 – 600 kWh$_e$ annually (Minneapolis)
- PCM of 10.5 C T_t (SP9) shaves the most electricity

TES performance in cascade heat pump

(Outcome 2)





- TES in a 3-ton cascade system shaves 400 – 600 kWh_e annually (Minneapolis)
- PCM of 10.5 C T_t (SP9) shaves the most electricity
- At time-of-use (TOU) rate difference of $0.1/ kWh_e, SP9 presents the shortest payback period

Future Work

Project outcomes

- Foundational research on power/energy tradeoff through Ragone plots for designing PCM heat exchangers
  - High visibility in Nature Energy; 60 citations since 2021
- Developed and characterized low-cost, high-performing PCM heat exchangers
- Designed novel HVAC+TES systems
- Demonstrated synergies between TES and battery storage (not presented)
- Provisional patent application on HVAC+TES system design

Future work

- Multiple researchers leveraging Ragone framework for additional insight into TES design and performance
- Leveraging TES and HVAC+TES models for multiple DOE-funded projects, including integrating TES with a rooftop unit air conditioner, refrigerated case, and split-system heat pump
- Working with two industry partners on HVAC+TES system concepts developed under this project

Publications supported by this project

Peer reviewed articles:

1. Woods, J., A. Mahvi, A. Goyal, E. Kozubal, A. Odukomaiya, and R. Jackson. Rate capability and Ragone plots for phase change thermal energy storage. ***Nature Energy*** 6, 295–302 (2021).
2. James, N., A. Mahvi, J. Woods. Optimizing phase change composite thermal energy storage using the thermal Ragone framework. ***J Energy Storage***. 56 (2022) 105875.
3. Mahvi, A., K.P. Shete, A. Odukomaiya, J. Woods. Measuring the maximum capacity and thermal resistances in phase-change thermal storage devices. ***J Energy Storage***. 55 (2022) 105514.
4. Bulk, A., A. Odukomaiya, E. Simmons, J. Woods. Processing compressed expanded natural graphite for phase change material composites. ***J Thermal Science***. (2022).
5. Huang, R., A. Mahvi, E. Kozubal, J. Woods (2022) Design of phase-change thermal storage device in a heat pump for building electric peak load shaving. *International Refrigeration and Air Conditioning Conference*. West Lafayette, IN. Paper 2146.
6. Brandt, M., J. Woods, P.C. Tabares-Velasco. An analytical method for identifying synergies between behind-the-meter battery and thermal energy storage. ***J Energy Storage***. 50 (2022) 104216.
7. Huang, R., A. Mahvi, W. Odukomaiya, A. Goyal, J. Woods. Reduced-order modeling method for phase-change thermal energy storage heat exchangers. ***Energy Convers. Management***. 263 (2022) 115692.
8. Odukomaiya, A., J. Woods, N. James, S. Kaur, K.R. Gluesenkamp, N. Kumar, S. Mumme, R. Jackson, R. Prasher. Addressing energy storage needs at lower cost via on-site thermal energy storage in buildings. ***Energy & Environmental Science***. 14(10) (2021) 5315-29.
9. Kommandur, S., A. Mahvi, A. Bulk, A. Odukomaiya, A. Aday, and J. Woods. The impact of non-ideal phase change properties on phase change thermal energy storage device performance. ***J Energy Storage (under review).***
10. Huang, R., A. Mahvi, N. James, E. Kozubal, and J. Woods. Evaluation of phase-change thermal storage in a cascaded heat pump. ***(in preparation)***.
11. Kishore, R., A. Mahvi, A. Singh, and J. Woods. Finned-tube-integrated thermally enhanced modular thermal storage system for HVAC load modulation. ***(in preparation)***.

Thank You

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WBS # 3.4.6.63

REFERENCE SLIDES

Project Execution

Milestone	Milestone description	FY19				FY20				FY21				FY22				FY23	
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
Past work																			
FY19Q1	Status update: progress on developing metrics, analysis methods, experiment plan.																		
FY19Q2	Define initial use cases for behind-the-meter PV solar + vehicle charging + thermal storage systems																		
FY19Q3	Select use case(s) and define metrics.																		
FY19Q4	Experimental characterization results on select candidates for emerging thermal storage material systems.																		
FY20Q1	Analysis of results and implications for performance targets, initial impact analysis, and R&D directions.																		
FY20Q1	Document initial list of key parameters for PCM characterization techniques																		
FY20Q2	Report on experimental results and analysis.																		
FY20Q2	Commissioning and initial experimental results on thermal storage and battery integration (status update report)																		
FY20Q2	Review of existing PCM characterization techniques and battery techniques with PCM analogues - Document initial list of techniques to explore further																		
FY20Q3	Draft journal article: Modeling and experimental results for PCM HX for different C-rates. Quantify power and energy density on a Ragone plot.																		
FY20Q4	Draft journal article: Synergistic control of thermal and electrochemical energy storage																		

Project Execution

		FY19				FY20				FY21				FY22				FY23	
Milestone	**Milestone description**	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
Past work																			
FY21Q1	Building-scale modeling results on C-rate requirements for thermal storage																		
FY21Q2	Experimental results on combined thermal and battery energy storage, with the battery emulated and controlled through an inverter.																		
FY21Q2	Identify PCM targets (T_t, power, duration) for different end uses: Cooling, heating, water heating, refr., appliances. Select end use for further analysis.																		
FY21Q3	Draft journal article: Standard characterization techniques for thermal energy storage																		
FY21Q3	Proposal for implementing tunable PCM and thermal switches in E+ using Python EMS																		
FY21Q3	Draft journal article on levelized cost of storage for TES, for submission to Energy and Environmental Science																		
FY21Q4	Draft journal article: C-rate requirements and design rules for PCM thermal storage																		
FY21Q4	Example of optimized material and component using the thermal Ragone-plot framework.																		
FY21Q4	Draft report on a computationally-efficient PCM model																		

Project Execution

		FY19				FY20				FY21				FY22				FY23	
Milestone	**Milestone description**	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
Past work																			
FY22Q1	At least two PCMs identified and characterized for each transition temperature (~10 C and ~50 C)																		
FY22Q2	Modeling methods developed for each PCM non-ideality (sub-cooling, hysteresis, temperature glide)																		
FY22Q3	Selected PCM and TES type / heat exchanger design for further analysis																		
FY22Q4	Draft journal article: Impact of non-idealities on TES heat exchanger performance																		
FY22Q4	Experimental data on selected bench-scale (~1 kWh) TES prototype																		
FY23Q1	Perform updated, higher-resolution LCOS calculation for at least one use case																		
FY23Q2	Draft journal article on cascade heat pump modeling																		
FY23Q2	Draft journal article on finned-tube PCM HX experiments																		
FY23Q2	Modeling results of modular heat pump with glycol-coupled PCM heat exchanger																		

Team

NETenergy: Provided graphite/PCM composite materials

Emerson: Provided compressor performance curves and consulting on vapor-compression system design with thermal energy storage

Colorado School of Mines: Student led modeling of combined batteries and thermal storage, with Professor Paulo Tabares

Trane Technologies: Supported implementation of chiller + ice storage tank in NREL's laboratory, which was used to characterize the power/energy performance of the ice tank and demonstrate control for combined battery + thermal energy storage system

NREL Team


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Allison Mahvi, PhD
Post-doctoral researcher


Ransisi Huang, PhD
Post-doctoral researcher


Ravi Kishore, PhD
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Ana Aday, PhD
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Eric Kozubal
Sr. Researcher


Wale Odukomaiya, PhD
Researcher


Mathilde Wirtz, PhD
Post-doctoral researcher

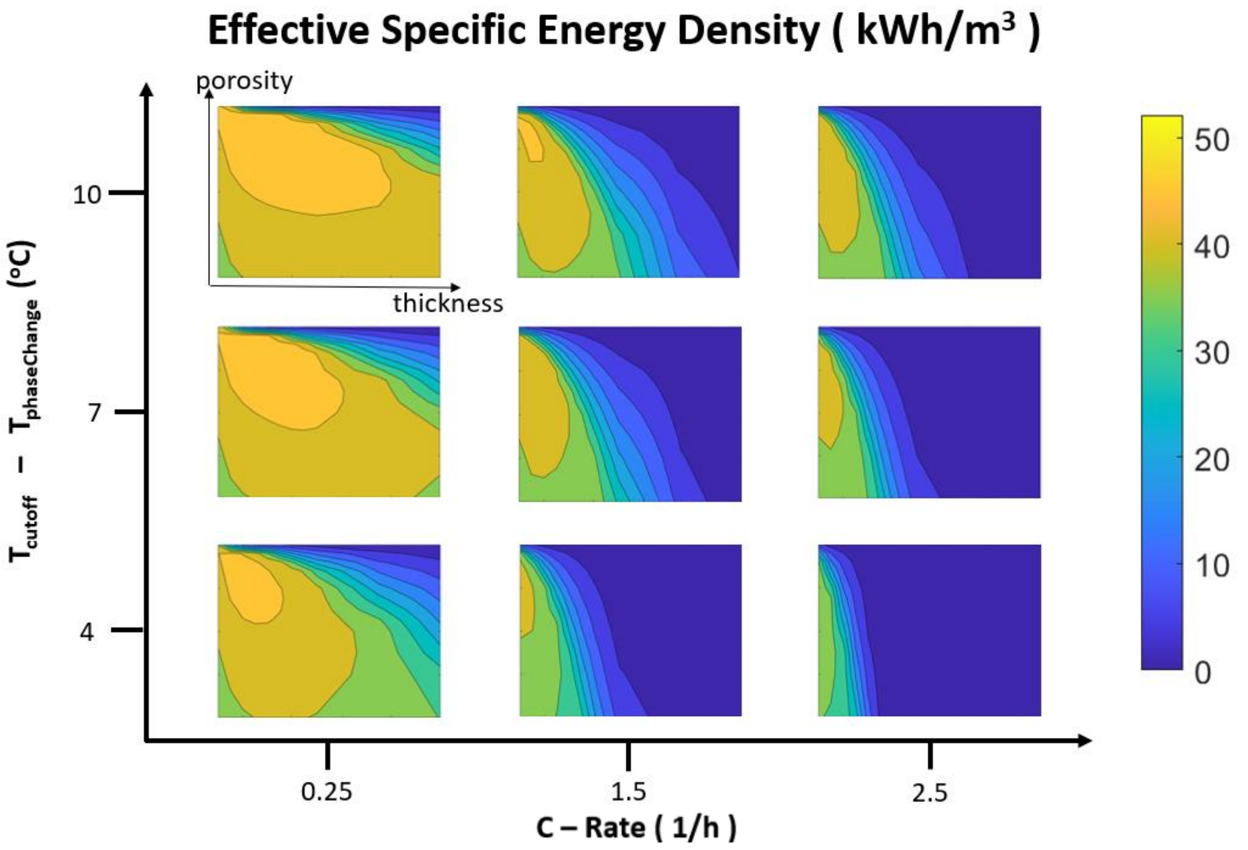

Nelson James, PhD
Researcher


Alex Bulk
Researcher

The Ragone framework enables methods for optimizing design

(Objective 1)

Designing TES heat exchangers is not the same as typical heat exchangers. The Ragone framework developed here provides a clear pathway to achieving energy density, power density, and cost targets.



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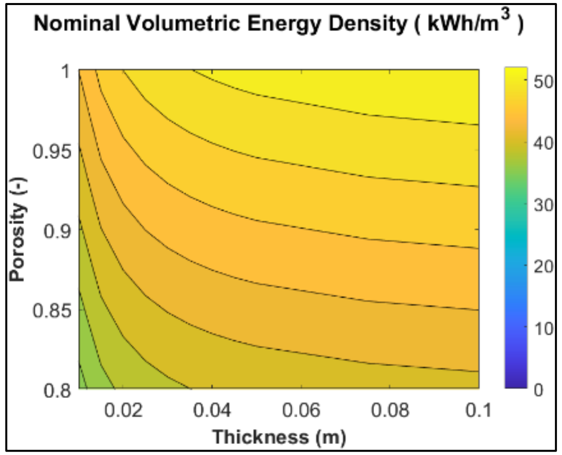
Example: PCM HX with flat aluminum tubes and graphite PCM composite



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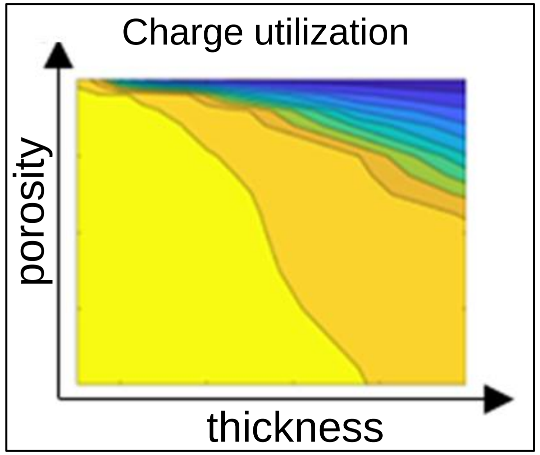
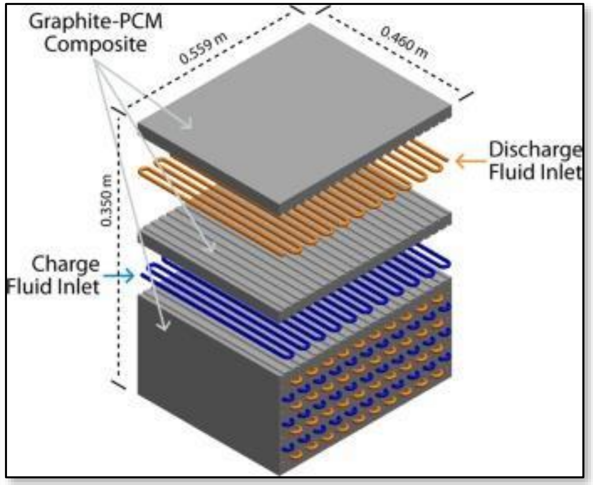


$$\frac{\mathbf{kWh}}{\mathbf{m^3}}_{\mathbf{effective}} = \frac{\mathbf{kWh}}{\mathbf{m^3}}_{\mathbf{nominal}} \times \mathbf{Charge\ Utilization}$$

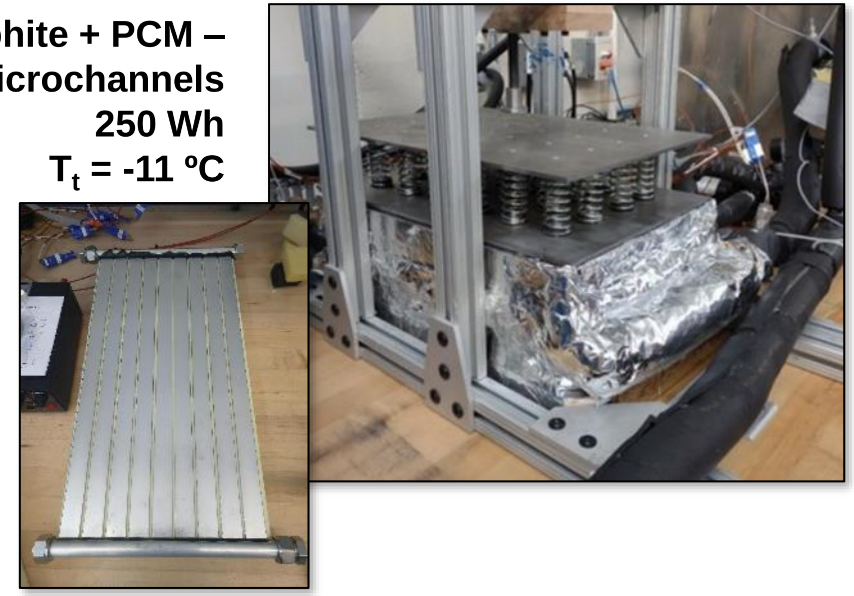
Leveraging this model, we build and characterized different PCM HXs for integration with HVAC systems

(Objective 1)

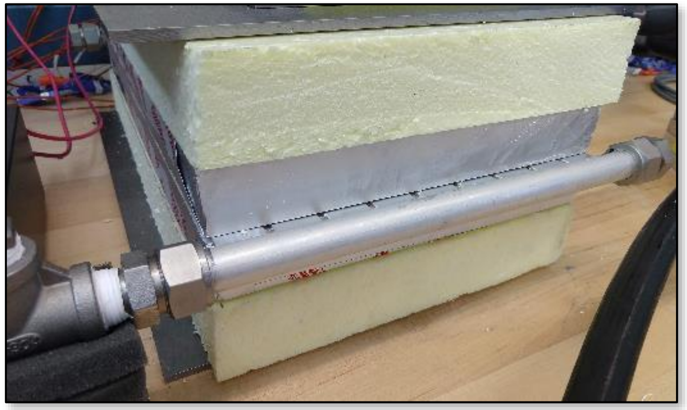
Graphite + PCM – Cu tube
3 kWh
T_t = 4 ºC

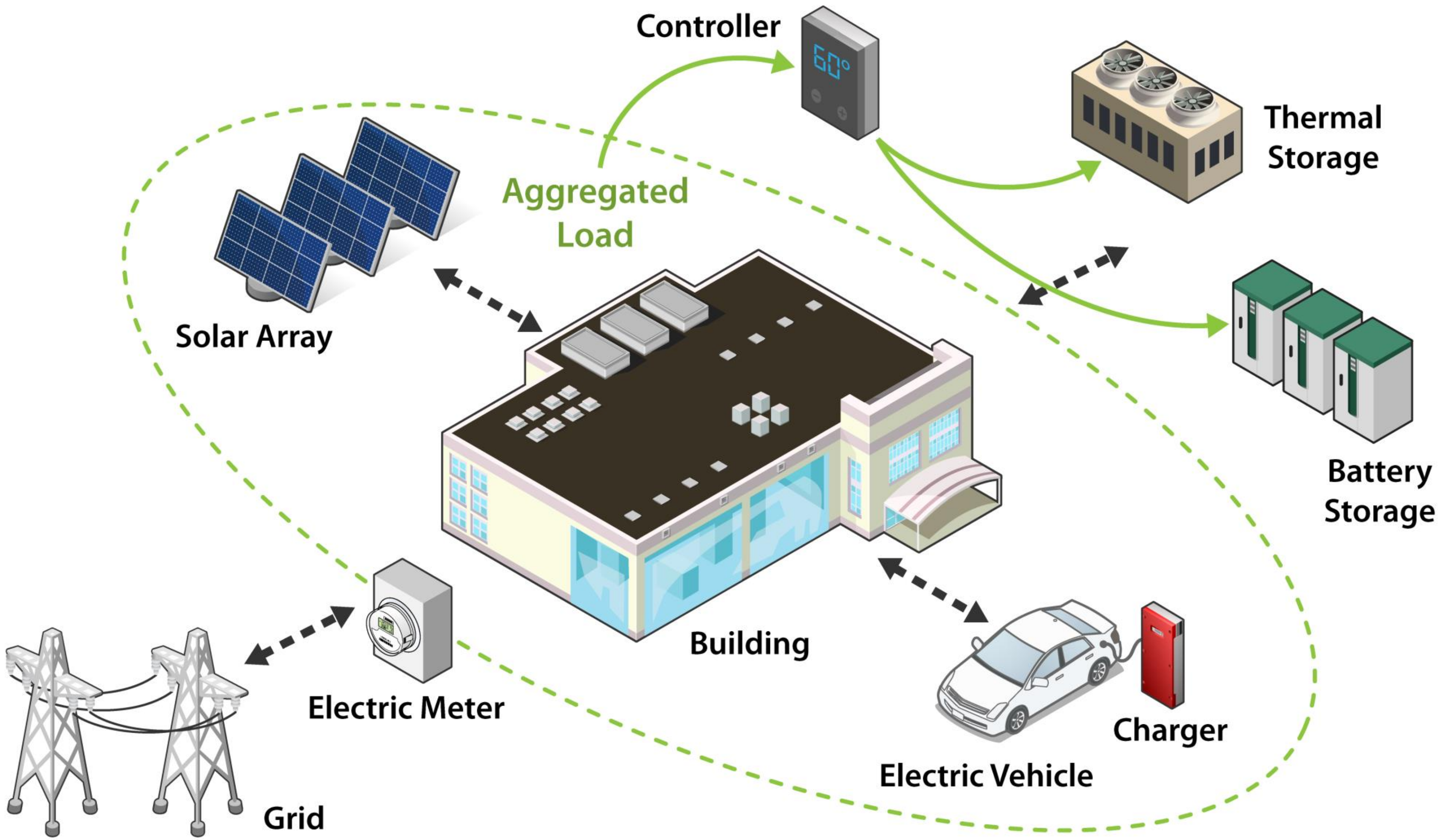
Graphite + PCM – Aluminum microchannels
250 Wh
T_t = -11 ºC



Graphite + PCM – Aluminum microchannels
300 Wh
T_t = 4 ºC

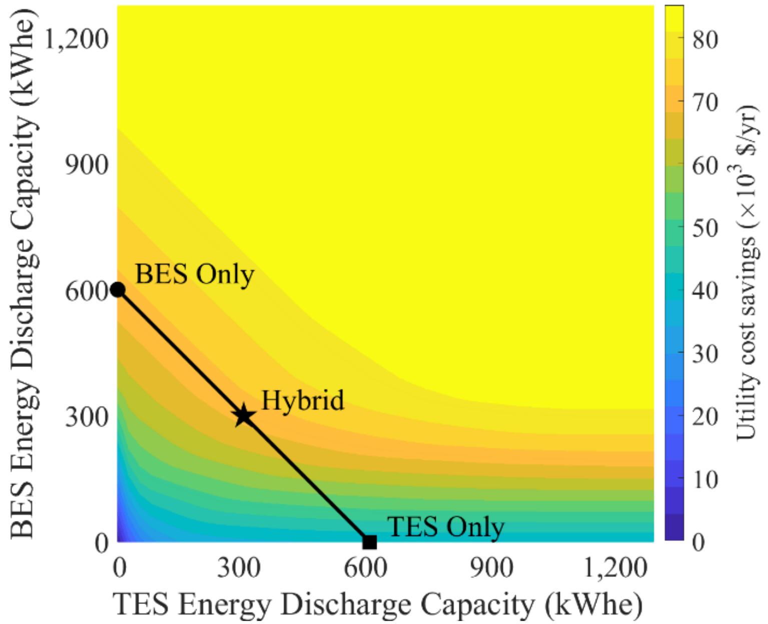


TES needs to fit into the broader building of the future

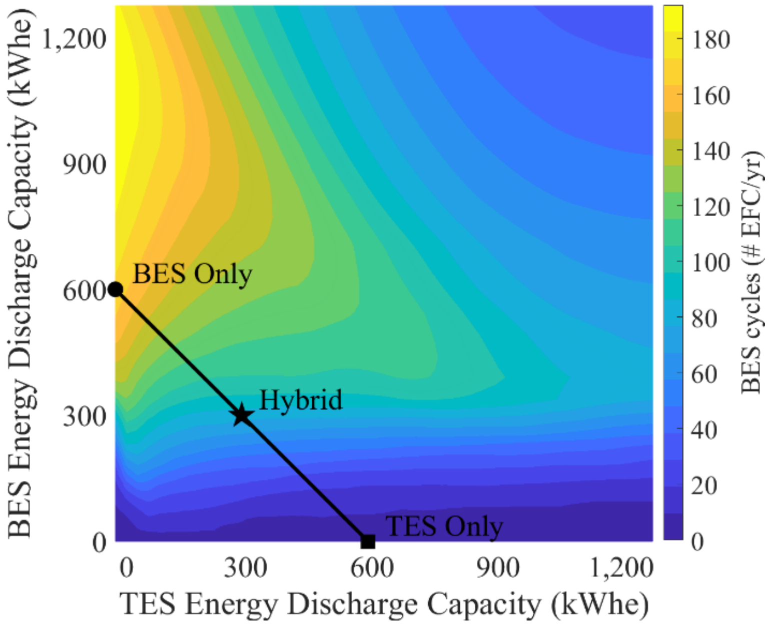


Hybrid battery + TES systems offer cost optimal solutions

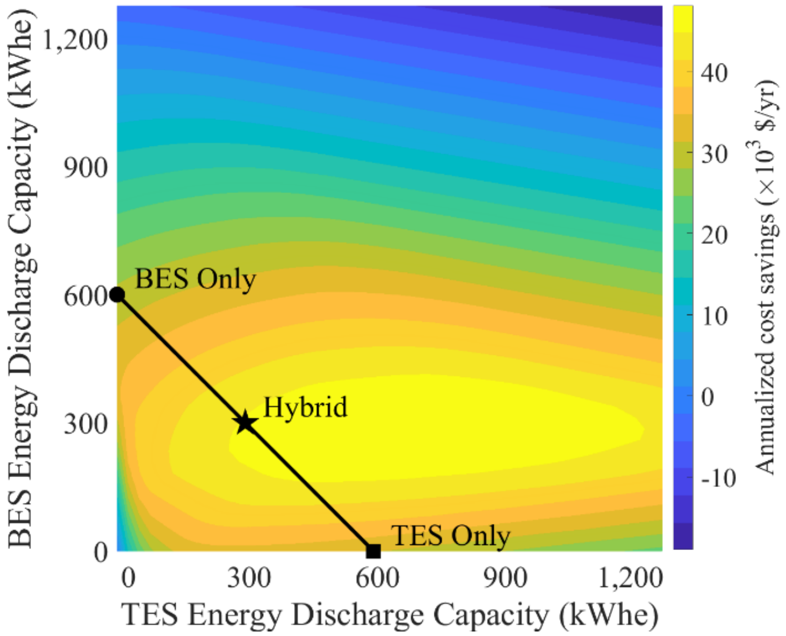
Utility cost savings ($k/yr)



Battery cycles (Eq full cycles / yr)



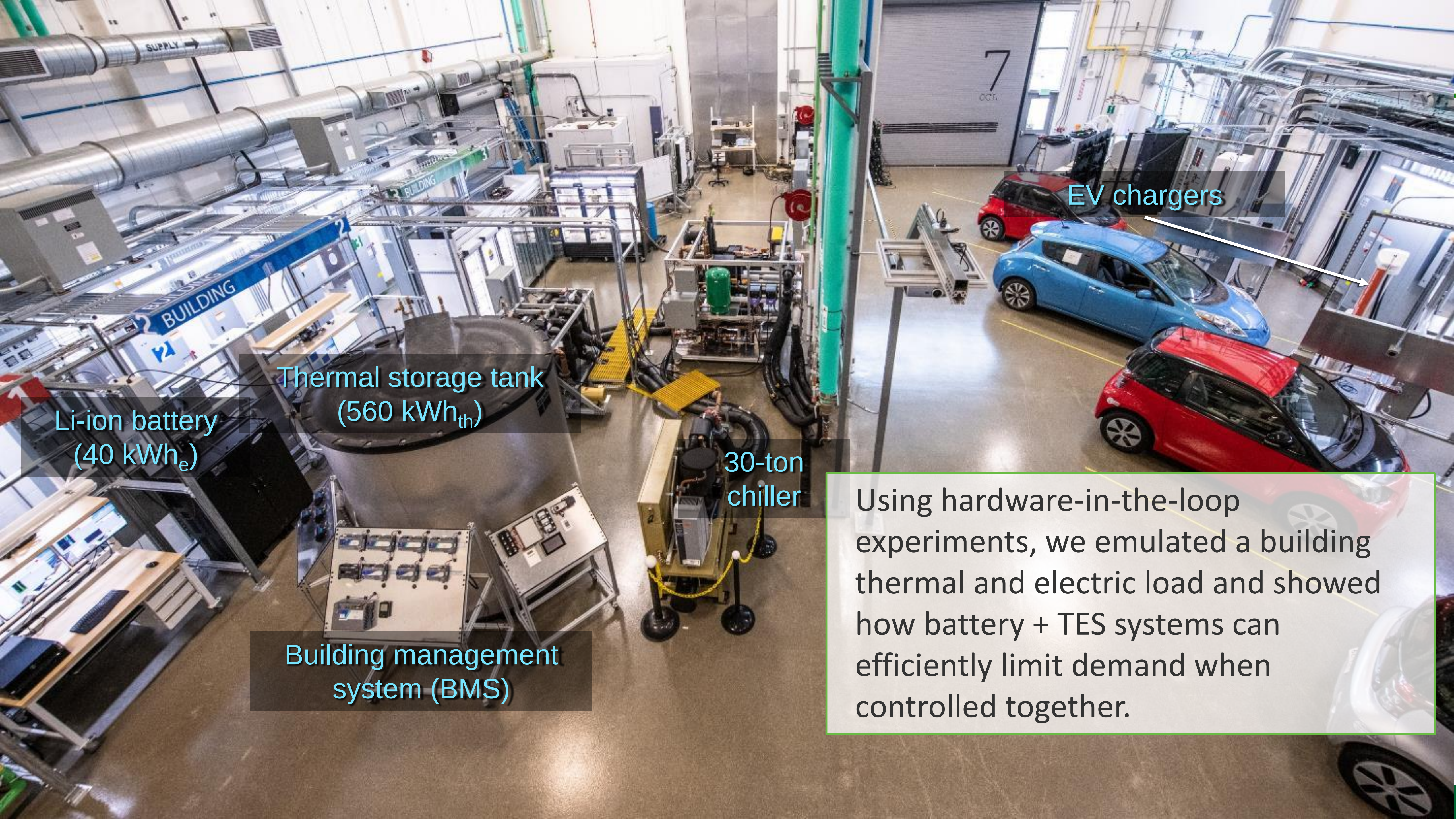
Annualized costs ($k/yr)



Hybrid systems provide the same utility savings as battery-only system

Hybrid systems minimize battery cycles, extending lifetime.

Hybrid systems offer cost optimal solutions



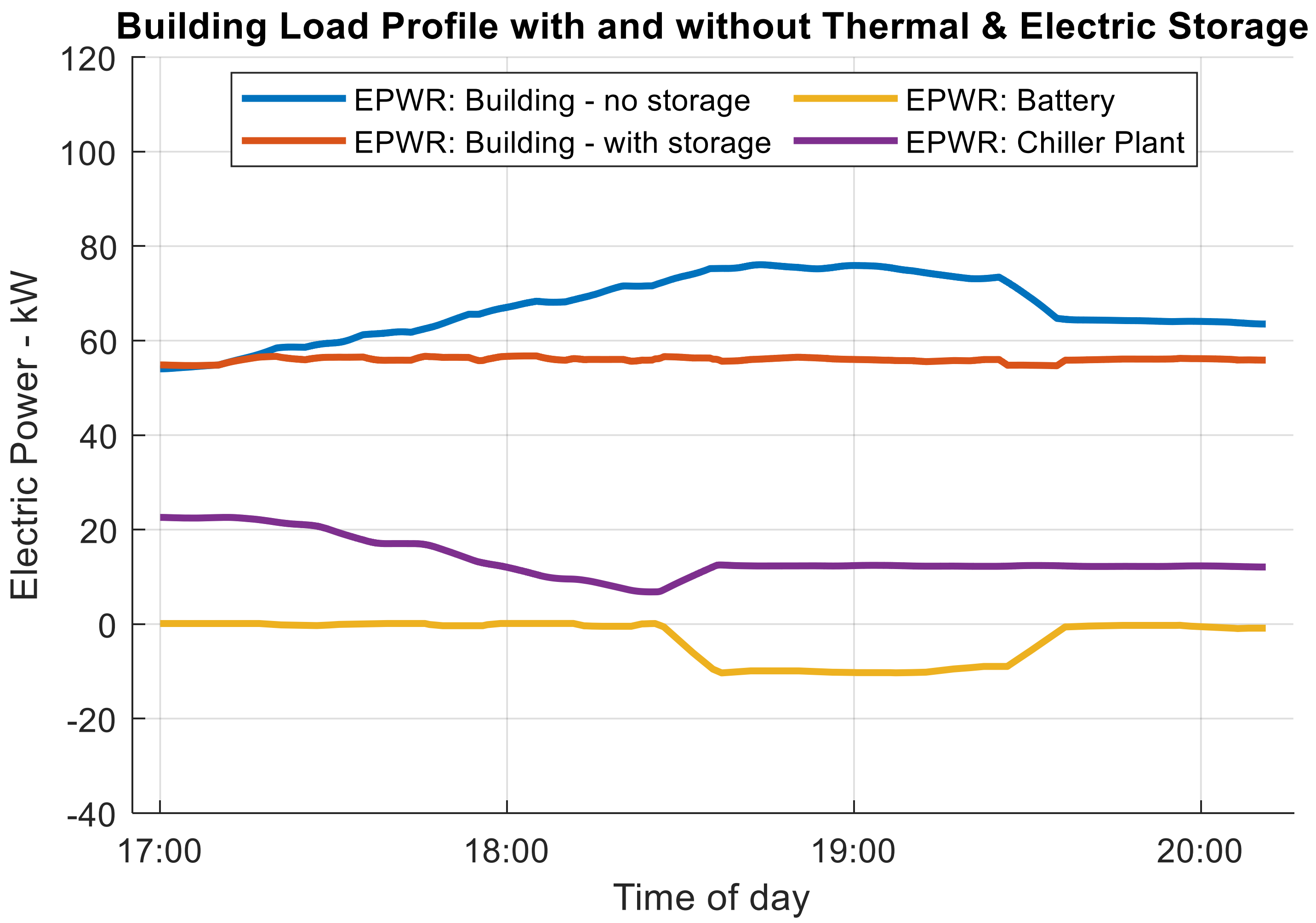
Using hardware-in-the-loop experiments, we emulated a building thermal and electric load and showed how battery + TES systems can efficiently limit demand when controlled together.

Controlling HVAC+TES with batteries can maximize efficiency

- Chiller modulation reduces electric load from 5-6:30pm. Battery provides additional load reduction from 6:30-7:30pm.

- Chiller efficiency improves by ~40% at part load.

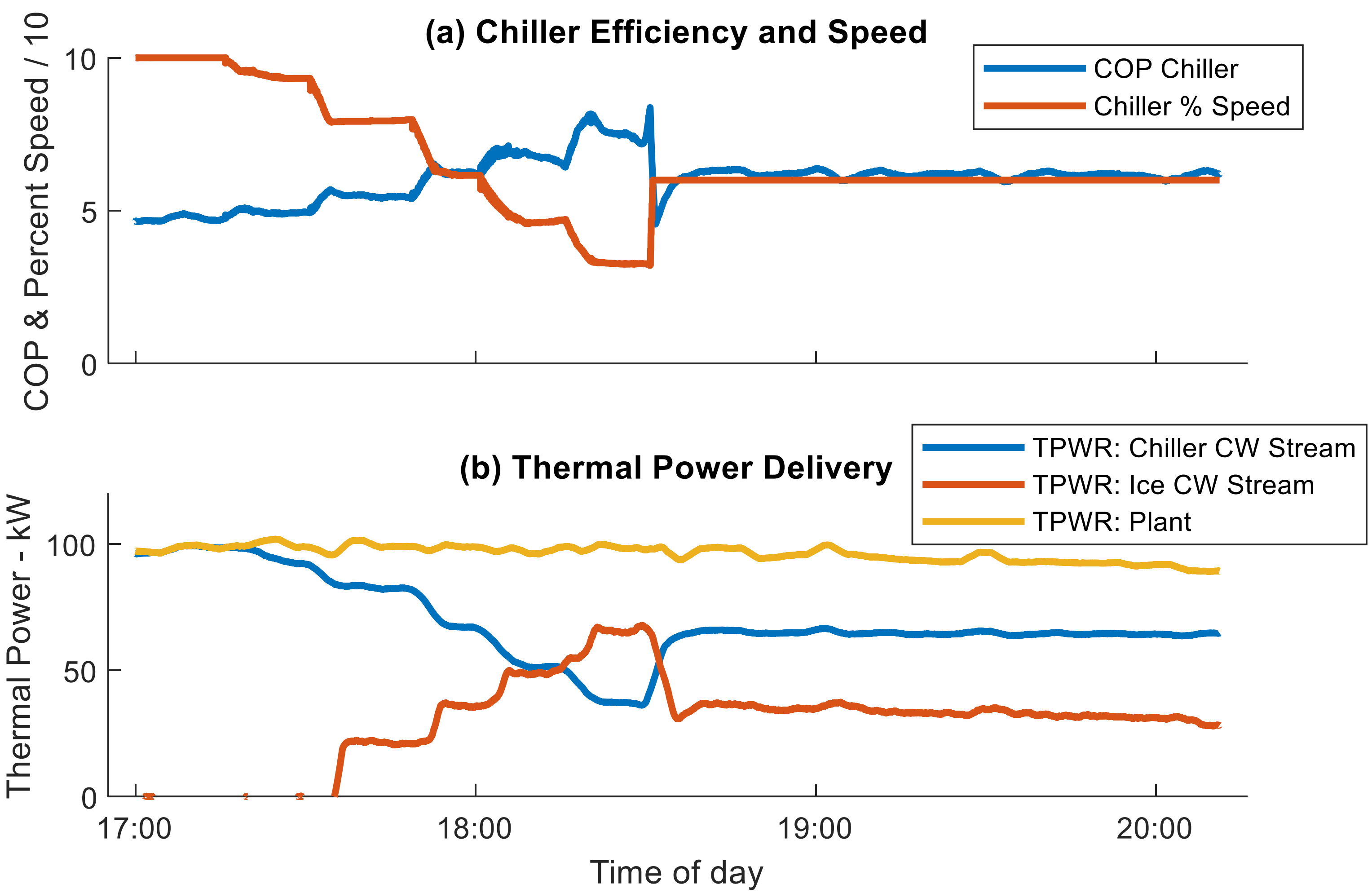
- 35.3 kWh of shaved energy
- 71% from TES
- 29% from BES



Controlling HVAC+TES with batteries can maximize efficiency

- Modulation of chiller increases efficiency by ~40%

- Compressor modulation limited to 60-100%, based on an internal Trane software limit.



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EERE/BTO goals

The nation's ambitious climate mitigation goals

Greenhouse gas emissions reductions

50-52% reduction by 2030 vs. 2005 levels

Net-zero emissions economy by 2050

Power system decarbonization

100% carbon pollution-free electricity by 2035

Energy justice

40% of benefits from federal climate and clean energy investments flow to disadvantaged communities

EERE/BTO's vision for a net-zero U.S. building sector by 2050