2024 PROJECT PEER REVIEW

U.S. DEPARTMENT OF ENERGY
BUILDING TECHNOLOGIES OFFICE

BTO Peer Review: Cold Climate Heat Pump using Vapor Compression Cycle Cascaded with a Thermoelectric Heat Pump

B.E.N.E.F.I.T. 2020 Award

DE-EE0009687

Project Summary

OBJECTIVE & OUTCOME

Develop, demonstrate, measure and verify the performance of a standard residential vapor compression system augmented with a solid-state thermoelectric (TE) heat pump (HP) to:

- Provide heating capacity at high efficiency throughout the heating season
- Greatly reduce or eliminate supplemental heating needs for both moderate and cold winters
- Provide superior dehumidification in summer

Integration of refrigerant-to-refrigerant TE HP

Integration of refrigerant-to-air TE HP

TEAM & PARTNERS

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Principal Investigator: Sreenidhi Krishnamoorthy

OAK RIDGE National Laboratory

Point of Contact: Bo Shen

STATS

Performance Period: October 2021 – September 2025

DOE budget: $1,800k, Cost Share: $450k

Milestone 1: Successful modeling of cascaded heat pump

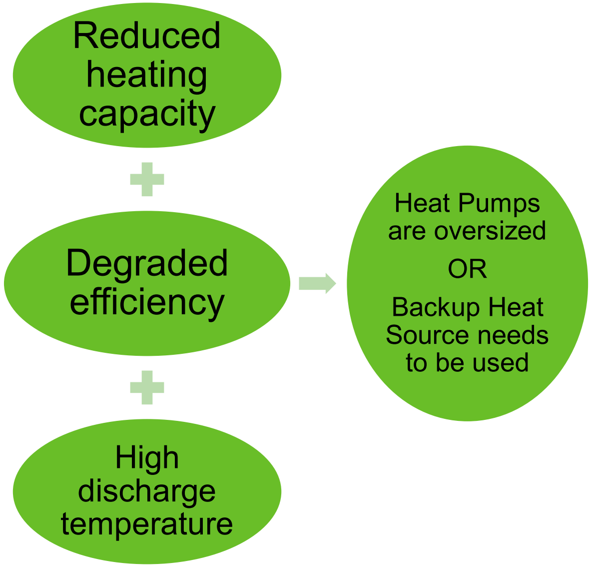
Milestone 2: Successful laboratory validation of R-to-R TE cascaded heat pump

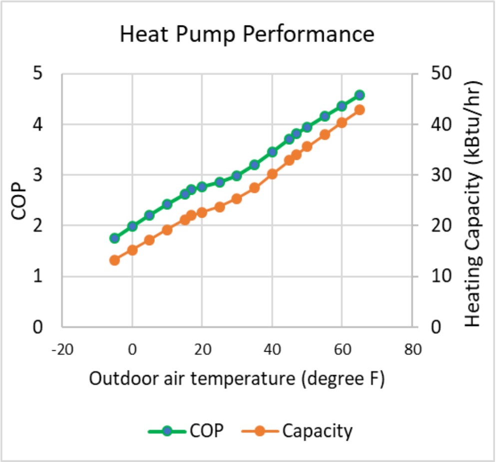
Milestone 3: Successful laboratory validation of R-to-Air TE cascaded heat pump

Milestone 4: Successful field verification completion at three field sites

The Challenge of Low-Temperature Operation

- Conventional Air-Source Heat Pumps are unable to operate effectively at cold outside air temperatures
- More efficient heat pumps exist but have financial and installation challenges



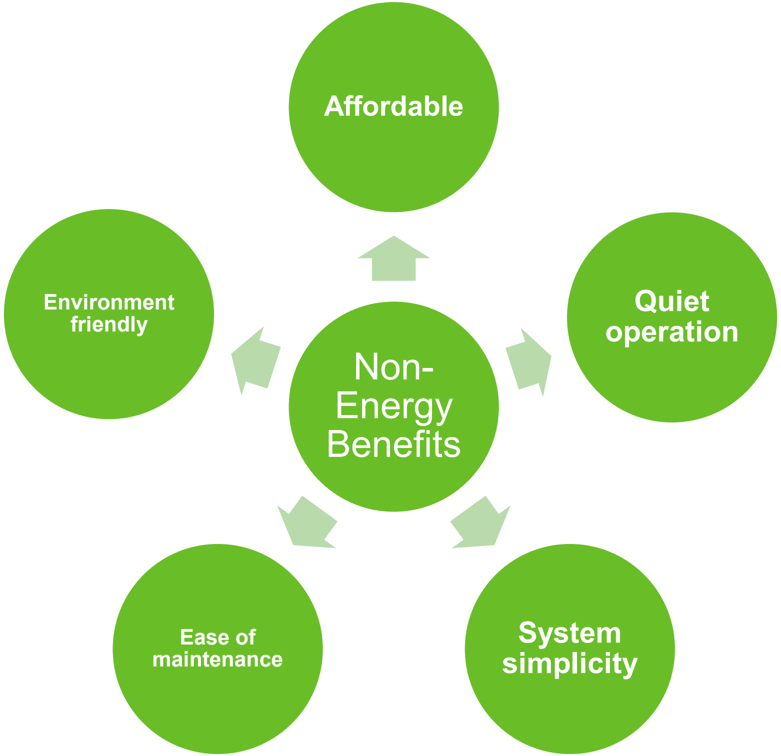


An example of Heat Pump Performance Degradation with Reducing Outside Air Temperatures

A simpler, quieter and cheaper cold climate heat pump is required to address this gap

Alignment and Impact

Measure	Quantitative Outcomes
Energy/Efficiency	10% annual heating energy savings compared to conventional heat pumps
Occupant Comfort	Prevent overcooling / excessive cycling during cooling
Affordability	Payback: <5 years

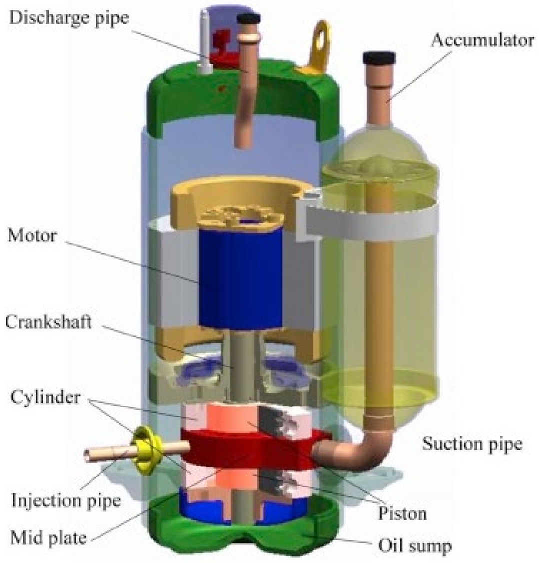


The project improves the TRL of non-vapor compression TE technology and demonstrates potential for significant energy savings, affordability and occupant comfort in space heating

Current State of the Art for Advanced Heat Pumps

Multiple solutions have been explored to address the challenges of low temperature operation of heat pump

Strategy	Details	Limitations
Variable Speed Heat Pumps	Certain models can overspeed the compressor to provide higher heating capacity in cold climates	Higher chances for compressor failure, and premium unit cost (+ $1000 to 2000/ton)
Vapor Injection	Uses an internal heat exchanger (HX) or flash tank to conventional vapor compression cycle	These systems tend to be bulky and incur a significant cost premium
Tandem Compressors	Two compressors are used instead of one, and programmed to turn on and off as needed	



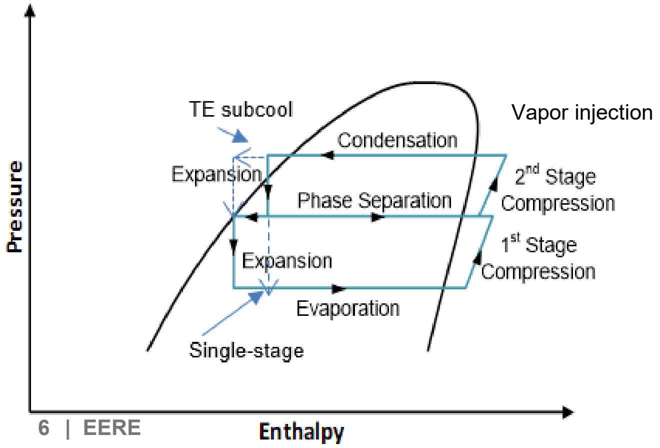
Cutaway view of a vapor-injection compressor

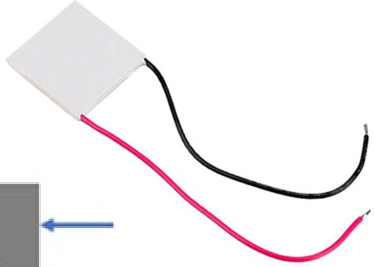
A simpler, quieter and cheaper solution is being developed in the current research

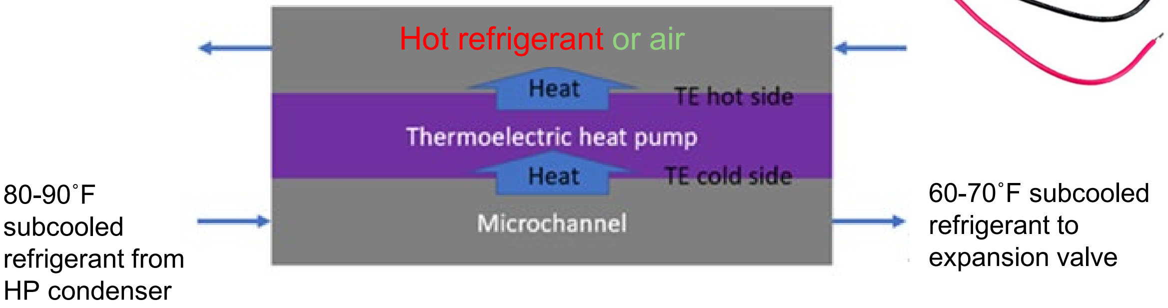
Innovation in the Current Concept

Use of a compact thermoelectric (TE) heat pump device having microchannel tubes
TE devices exhibit Peltier effect (DC current passed through a circuit of two semi-conductors creates a temperature difference)

- TE devices are simple, cheap, and quiet
- In this innovation, TE modules are attached to microchannels for increased heat transfer
- Can tolerate high refrigerant pressure up to 500 psi.







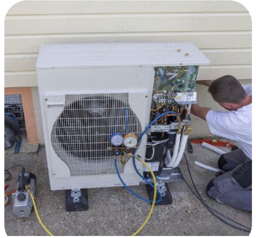
Details of thermoelectric heat pump arrangement

Plan for Delivering the Intended Outcomes

Budget Period 1: FY 2022 (Completed)

Budget Period 2: FY 2023 (Completed)

Budget Period 3: FY 2024 (In Progress, extended to FY 2025)



Simulation based modeling

- TE Heat Pump Performance Curves
- Building Energy Simulations

Laboratory Testing

- Prototype Validation
  - Heating Operation
  - Cooling Operation

Field Demonstration and Market Evaluation

- Cold Climate
- Humid Climate
- Commercialization and Tech Transfer

Configuration 1: Refrigerant-to-Refrigerant TE Subcooler Heat Pump

Wood panel

Tube bundles

Thermal paste

TE modules

Thermal paste

Tube bundles

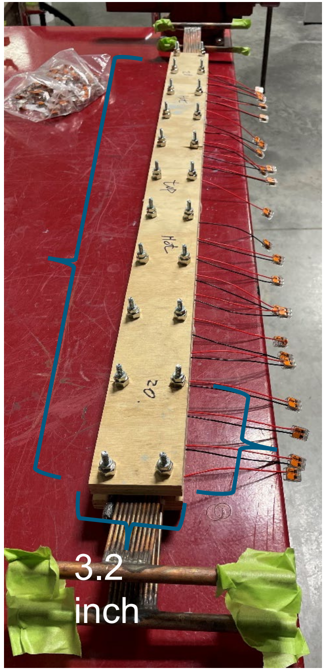
Wood panel

TE subcooler layers

TE modules

TE heat pump subcooler prototype; four TE subcoolers in parallel ON/OFF individually to study impacts of pressure drop, power inputs, etc.

3.4 feet long

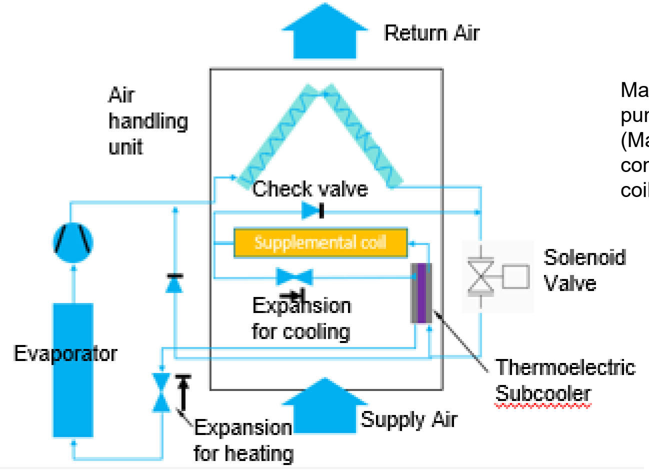


4 inch

Schematic arrangement of TE modules in a TE heat pump subcooler

TE heat pump subcooler contains 98 TE modules in 4 subcooler bundles arranged in a parallel configuration

Integration of a R-to-R TE Subcooler Heat Pump into a Conventional Residential Heat Pump

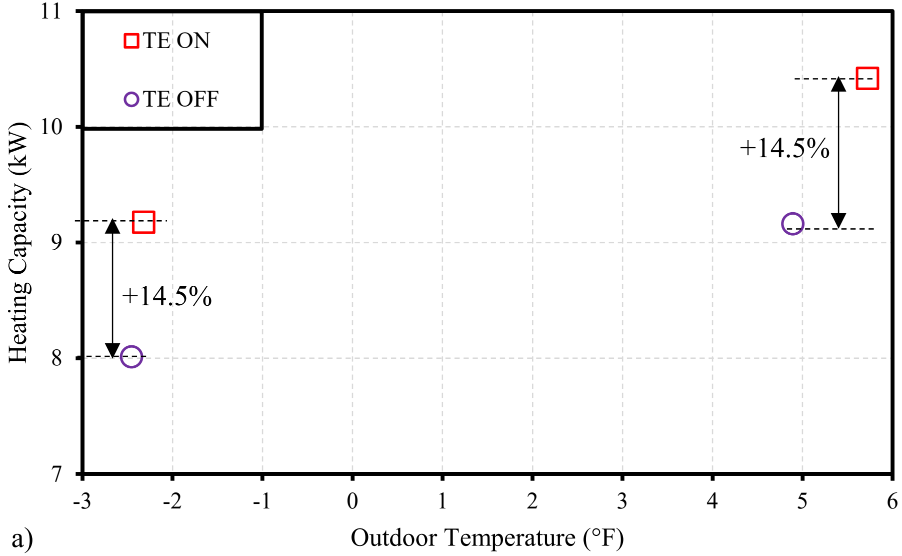


Front View

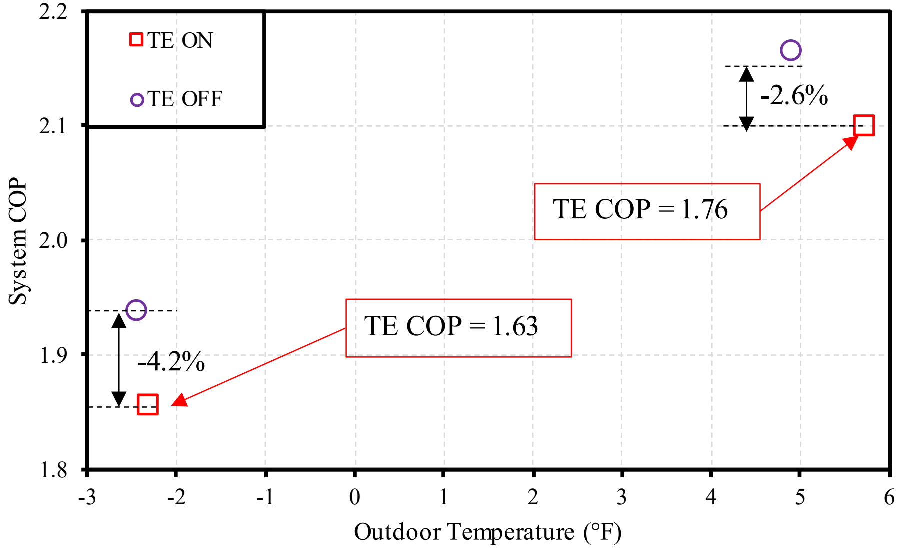

Back View

The unit consists of a)TE heat pump subcooler, b)Supplemental coil that augments heat transfer area

Configuration 1: Results of R-to-R TE Subcooler Integration



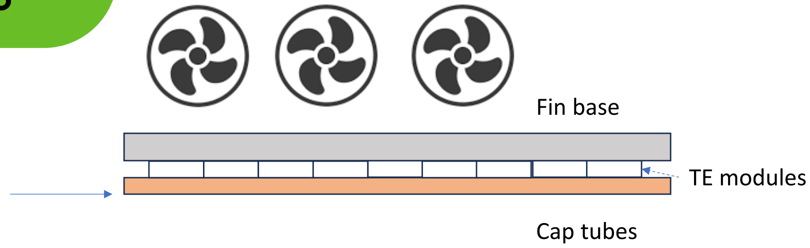
a)

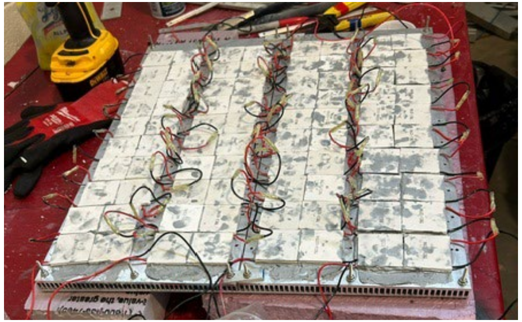


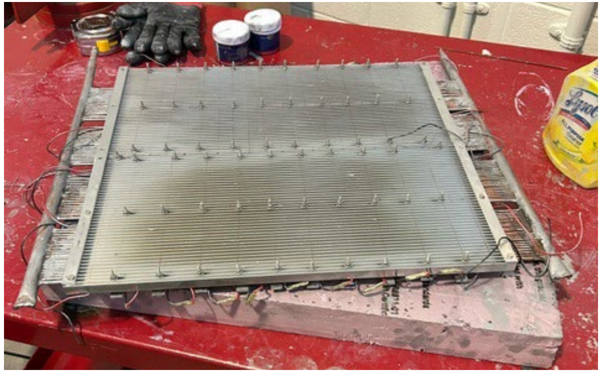
Baseline: Single-speed, 4.5-ton, Nortek HP, 16 SEER/8.0 HSPF, R-410A

a)TE subcooler HP holds a near constant COP, b) At extremely low ambient temperatures, the TE integration augmented 14% capacity with negligible impact on heat pump COPs.

Configuration 2: Refrigerant-to-Air TE Subcooler Heat Pump







80 pieces TE

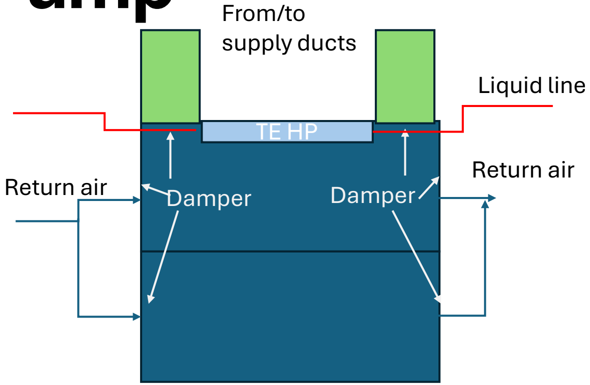
Modular and retrofittable, add-on to any existing HPs, with installing a TE subcooler/HP to the liquid line.

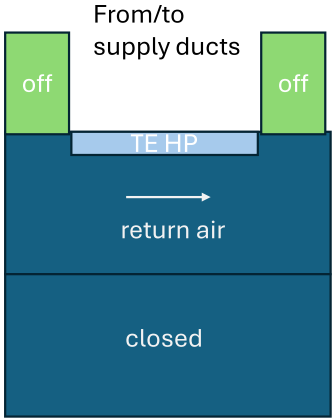
Integration of a R-to-Air TE Subcooler into a Conventional Residential Heat Pump

Place at return side in heating mode

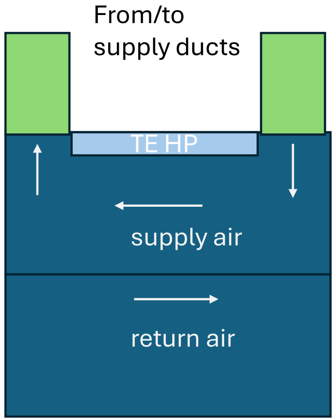
Place at supply in cooling mode

Field duct assembly





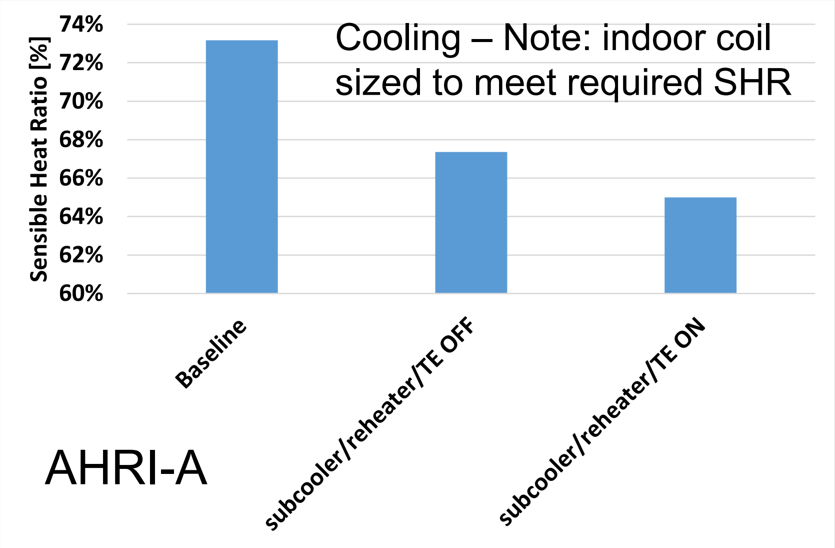
Air flow in heating

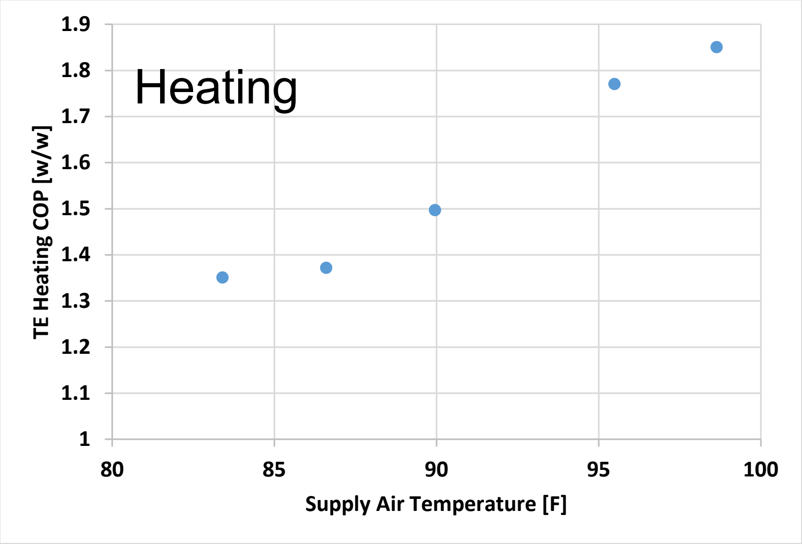


Air flow in cooling

Configuration 2: Impacts of TE

Baseline: Coleman, 2-ton outdoor unit (THE2B24T21S)+ 2-ton indoor air handler (JHETB24) (AHU)
Lab prototype: Coleman, 2-ton outdoor unit + 3-ton AHU (JHETB36) + TE subcooler HP

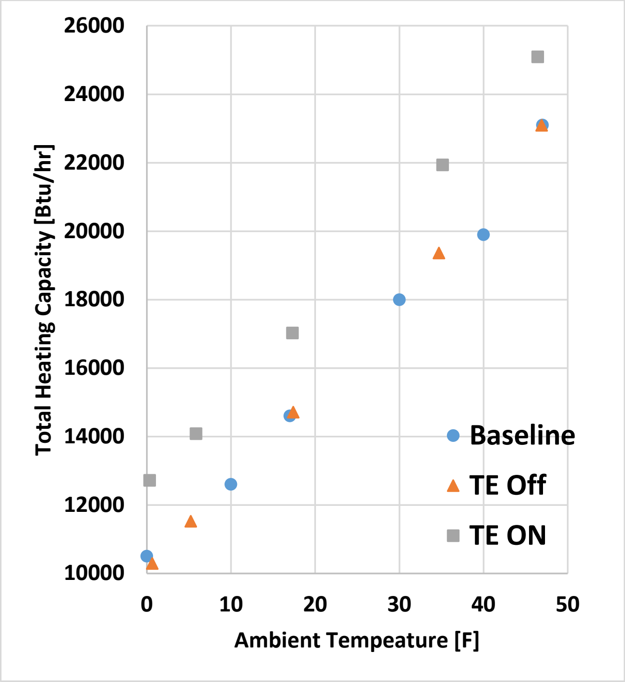


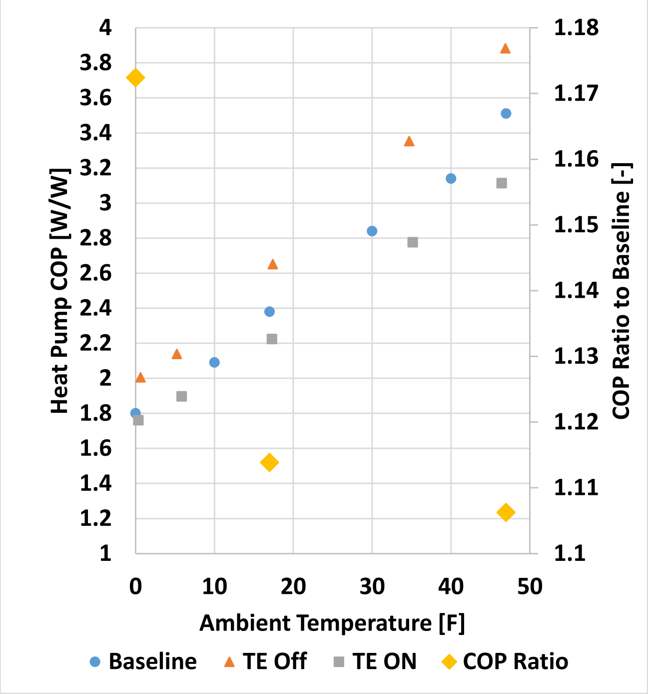


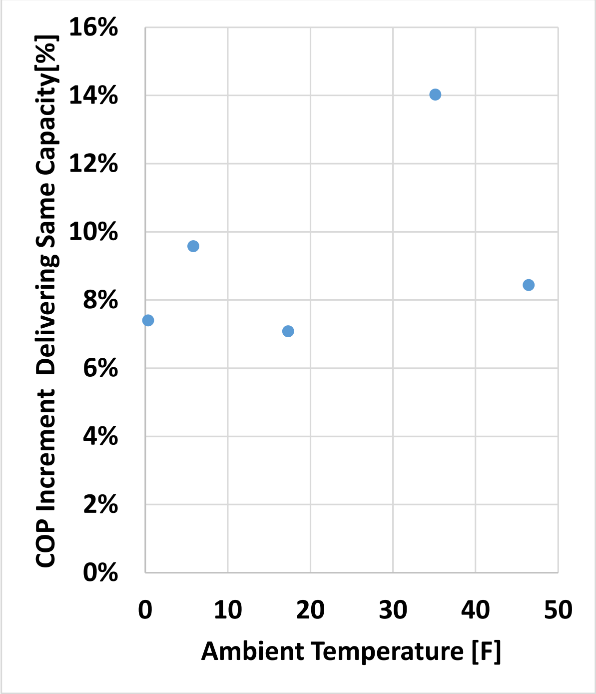
Baseline performance from https://www.tfehrhart.com/media/docs/THE2_HP_Technical_Guide.pdf

a) TE subcooler reheating supply air, leads to > 3% higher moisture removal than baseline; b) Enhanced dehumidification allows "oversize" AHU; c) TE integration benefits higher supply air temperature, i.e. cold climate HPs

Configuration 2: Heating System Performance







TE ON increased total capacity, 13% to 26%

Larger condenser surface area + TE subcooler augments HP COP 11% to 17%

TE ON boosts the total COP, 7% to 14%, than HP + resistance heat, to deliver the same capacity

Factors Resulting in > 10% Annual Heating Saving

- TE subcooler reheating enhances dehumidification and facilitates use of larger indoor coil (<$200 cost increment for AHU).
- Larger indoor coil + TE subcooler (no power input) leads to > 10% heat pump COP increments in the whole ambient temperature range
- TE HP ON (570 W power input), leads to > 10% higher total heating COPs, than HP + supplemental resistance heating, to deliver the same total capacity

- ***10% annual heating saving resulted by TE integration and the related system optimization***
- ***Subcooler reheating →better dehumidification; larger indoor coil →higher HP COPs; TE ON to replace supplemental resistance heating →higher total COPs***

Field Demonstrations

COMPLETED WORK

- Two of three field sites have been finalized
- Constructed and lab tested the field prototype
- Submitted prototype details for UL safety standards review

TO BE COMPLETED

- Identify HVAC Contractor to install HP
- Coordinate site visit for UL approval
- Install M&V and perform monitoring
- Remove prototype after field tests

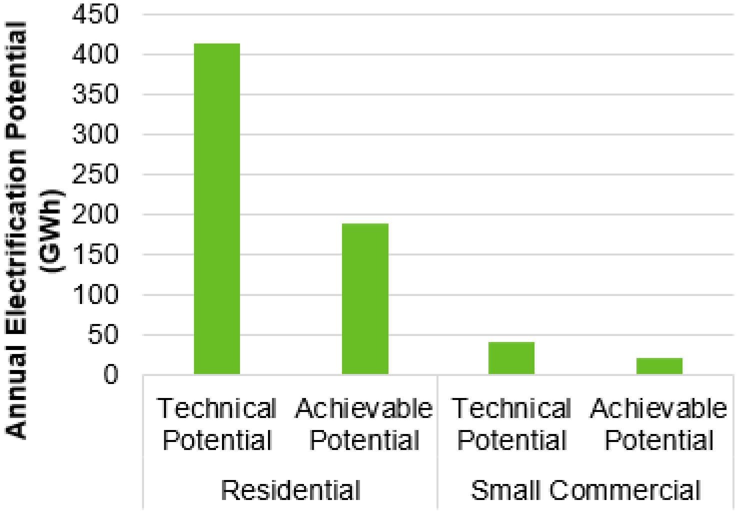
Site 1: Nashville, TN

Site 2: Long Island, NY

EPRI is working with member utilities to identify the third field site

Key Highlights from Market Potential Assessment

TE Heat Pump Electrification Potential in U.S. Buildings by 2050



Achievable Electrification Potential = 200 GWh by 2050
Associated reduction in CO_2 emissions = 35 MMT

COST ANALYSIS	
Additional components that add to system cost	
Item	**Cost Estimate**
TE modules	\$200-\$300 per ton
AC to DC converter	\$20-\$100 (standard single-phase 24V DC, 5A)
Larger indoor coil	<\$200 per ton

- **20% upfront cost increment estimated than conventional single speed heat pump**
  - \$100-\$150 per kW << \$400-\$650/kW extra for CCHPs

Bottlenecks for Industry Adoption	Mitigation Plans
Lack of awareness about TE	• **Collaborate with Utilities** • **Educate Key Account Reps** • **Develop Incentives** • **Highlight Novelty** • **Highlight Energy and Non-Energy Benefits**
Acceptance by customers & distribution channels	
Cost parity between vendor/ contractor costs	

Summary of Major Accomplishments Till Date

- **Completed simulation-driven design and optimization of thermoelectric integrated heat pump with 4 operating stages**
- **Fabricated two TE subcooler heat pumps, refrigerant-to-refrigerant and refrigerant-to-air.**
- **Completed laboratory testing of two TE integrated heat pumps in heating and cooling operations with promising results → over 10% saving in heating season**
- **Finalized 2 out of 3 sites for field demonstration of the heat pump, and built the field prototype**
- **Four conference papers, 2 journal paper and 1 poster have been published / presented**

Technology Transfer Activities

Conference Publications

- Shen, B., Gluesenkamp, K., Wan, H. "Integration of Thermoelectric Modules to Vapor Compression Systems", Purdue Conference 2022.
- Wan, H. Shen, B., Li, Z. "The Potential of Thermoelectric Heat Pumps in Cold Climate Buildings", ASHRAE Cold Climate Heat Pump Conference 2023.
- Krishnamoorthy, S., Shirey, D., Shen B. "Development and Testing of an Advanced Cascaded Thermoelectric Residential Heat Pump". ACEEE Summer Study, 2024.
- Hu, Y., Shen, B., Gluesenkamp, K.R., Yana Motta, S.F., Krishnamoorthy, S., Shirey, D., 2024. Experimental Investigation on Heating Performance of a Cold Climate Thermoelectric-Assisted Heat Pump. 20th Int. Refrig. Air Cond. Conf. at Purdue, Paper 2266, July 15-18, West Lafayette, IN, USA.

Journal Publications

- Wan, H., Gluesenkamp, K. R., Shen, B., Li, Z., Patel, V. K., & Kumar, N. (2023). A thermodynamic model of integrated liquid-to-liquid thermoelectric heat pump systems. Int. J. of Refrig., 150, 338-348.
- Hu, Y., Shen, B., Wan, H., Gluesenkamp, K. R., Krishnamoorthy, S., & Shirey, D. (2024). Heating performance of a vapor compression heat pump cascaded with a thermoelectric heat pump. App.Therm. Eng., 249, 123397.
- **Poster Presentations**
- Krishnamoorthy, S., Shirey, D., Shen, B. "Advanced Cascaded Thermoelectric Residential Heat Pump". CEC Building Electrification Summit, Sacramento, Oct. 2023.

Thank you

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Project Execution

- Planned Date of Completion
- Actual Date of Completion
- Go/No-Go Milestone

	FY2022				FY2023				FY2024			
Planned budget	$ 523,000				$ 813,000				$ 913,000			
Spent budget	$ 482,000				$ 697,000				$ 260,000			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Q1 Milestone: Successfully identify list of design considerations												
Q2 Milestone: Successful modeling of cascaded TE heat pump												
Q3 Milestone: Fabricate TE heat pump system prototype												
Q4 Milestone: Test Plan finalized												
Q5 Milestone: Successful lab validation of TE HP in heating												
Q6 Milestone: Fabrication of TE HP prototype for cooling												
Q7 Milestone: Successful lab validation of TE HP in cooling												
Q9 Milestone: Commerlization and Market Potential Evaluation												
Current/Future Work												
Q8 Milestone: Completion of 1st and 2nd prototype field installs												
Q9 Milestone: Completion of 3rd field prototype installation							In progress work					
Q11 Milestone: Successful field verification completed all 3sites												

Project has been extended till end of FY2025 due to challenges in obtaining field test sites and due to additional time used for improving system design, control, etc.

Team

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