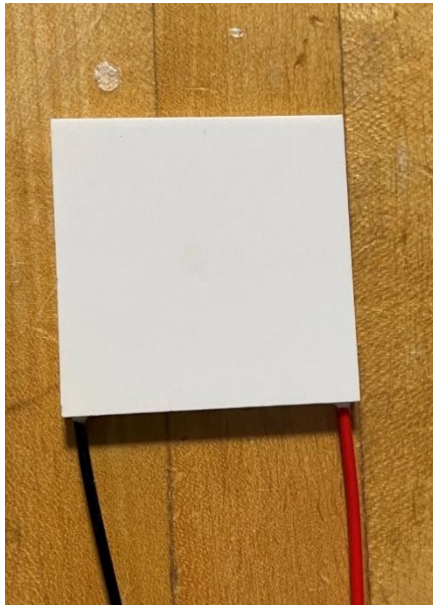
Cold Climate Heat Pump using Vapor Compression Cycle Cascaded with a Thermoelectric Heat Pump



Electric Power Research Institute, Oak Ridge National Laboratory
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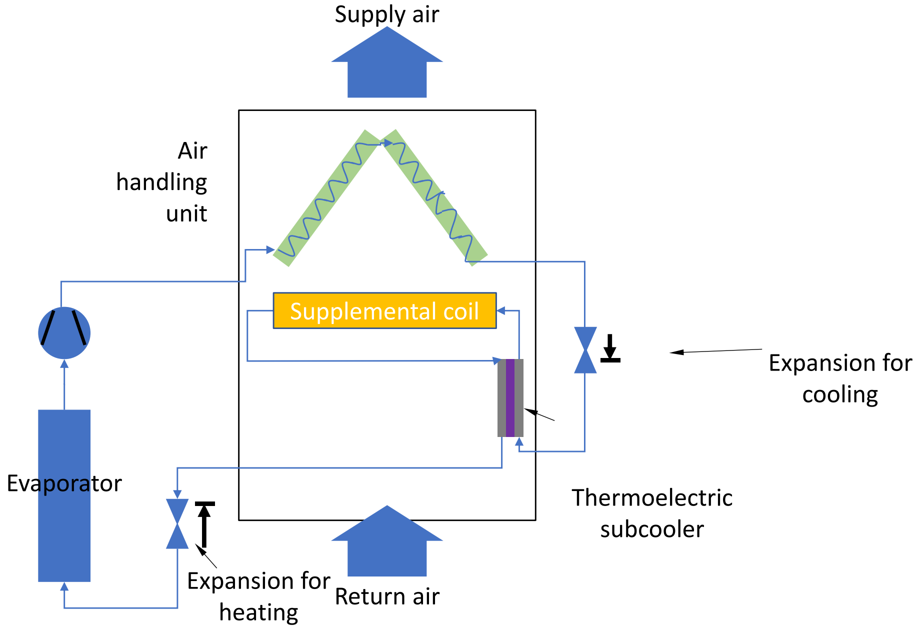
DOE BENEFIT 2020 Project: DE-EE0009687

Project Summary

Objective and outcome

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



Team and Partners

ELECTRIC POWER RESEARCH INSTITUTE

Principal Investigator: Sreenidhi Krishnamoorthy

OAK RIDGE National Laboratory

Point of Contact: Bo Shen

Stats

Performance Period: October 2021 – September 2024

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 cascade heat pump

Milestone 3: Successful field verification completion at three field sites

The Challenge of Low-Temperature Operation

Conventional Residential Air-Source Heat Pumps are unable to operate effectively at cold outside air temperatures

Reduced heating capacity

\+

Degraded efficiency

\+

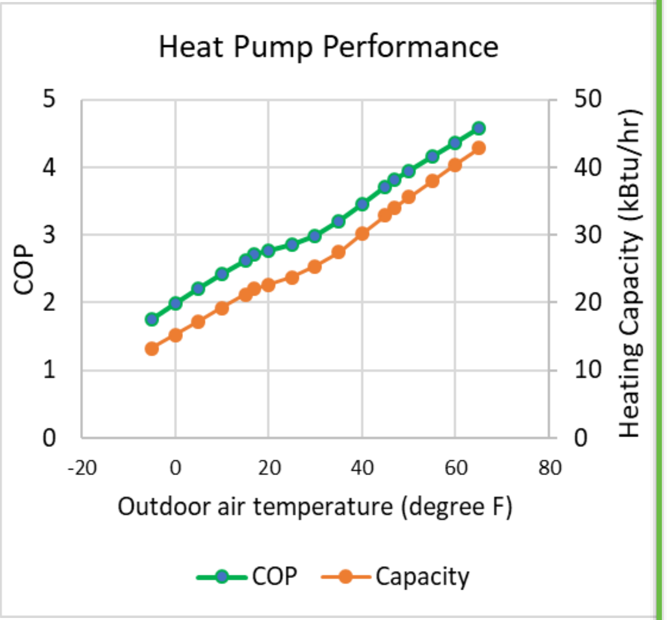
High discharge temperature

→

Heat Pumps are oversized

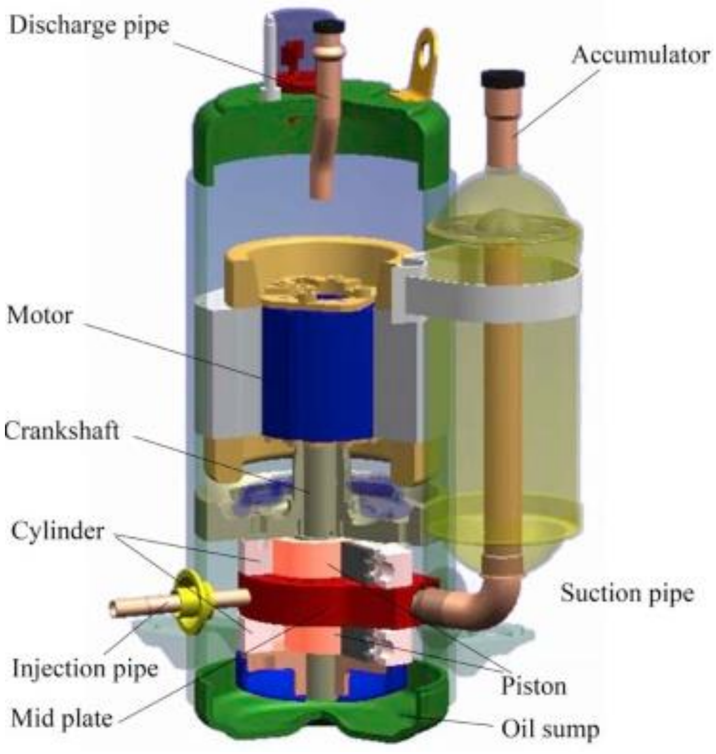
OR

Backup Heat Source needs to be used



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

More efficient heat pumps exist but have financial and installation challenges



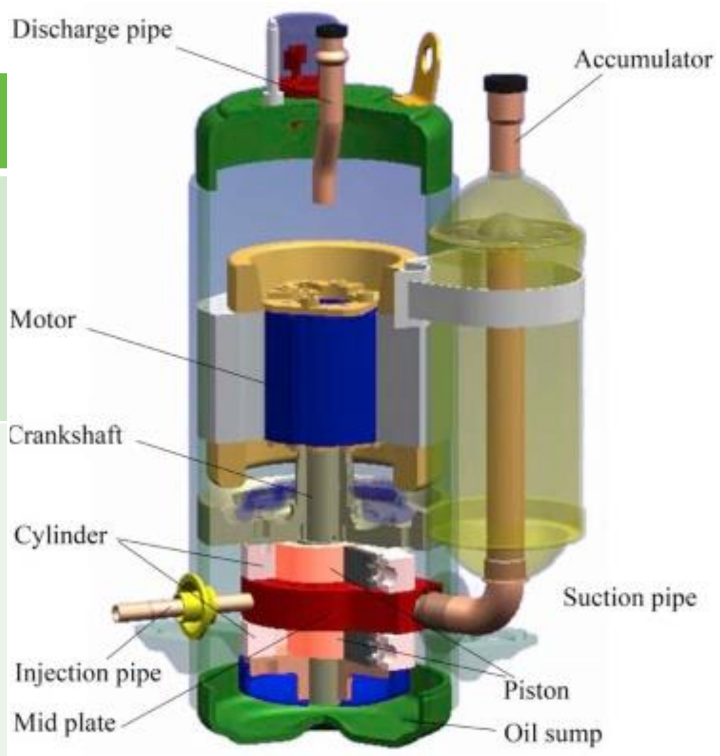
Vapor Injection Compressors that provide higher heating capacity in cold climates tend to be bulky and extremely expensive

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

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
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
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 proposed in the current research

The Proposed System and Benefits

The project intends to develop a thermoelectric cascaded hybrid heat pump for residential and small-commercial building applications with the following features:

- ✓ Provide additional heating capacity at high efficiency in extreme winters
- ✓ Potentially eliminates supplemental heating needs for moderate winters
- ✓ Provides dehumidification in summer

Measure	Currently available Heat Pumps (Baseline)	TE Cascaded Cold Climate Heat Pump (Proposed System)
Energy/Efficiency	14 SEER, 8.2 HSPF (Basic models) >9 HSPF (Advanced Models)	16 SEER, 12 HSPF, 10% annual energy savings
Occupant comfort	N/A	Prevent overcooling and excessive cycling during cooling
Affordability	Currently available cold climate heat pumps have payback period > 10 years	Payback: <5 years

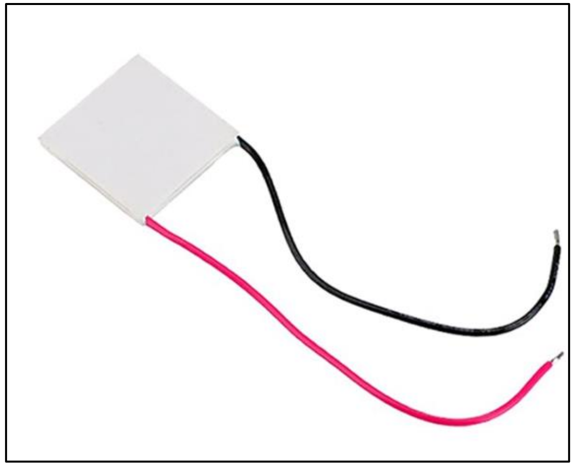
*** HSPF = Heating Season Performance Factor**
SEER = Seasonal Energy Efficiency Ratio (Cooling)

The project will research and develop non-vapor compression technology for space heating and demonstrate potential for significant **energy savings, affordability, occupant comfort and demand flexibility.**

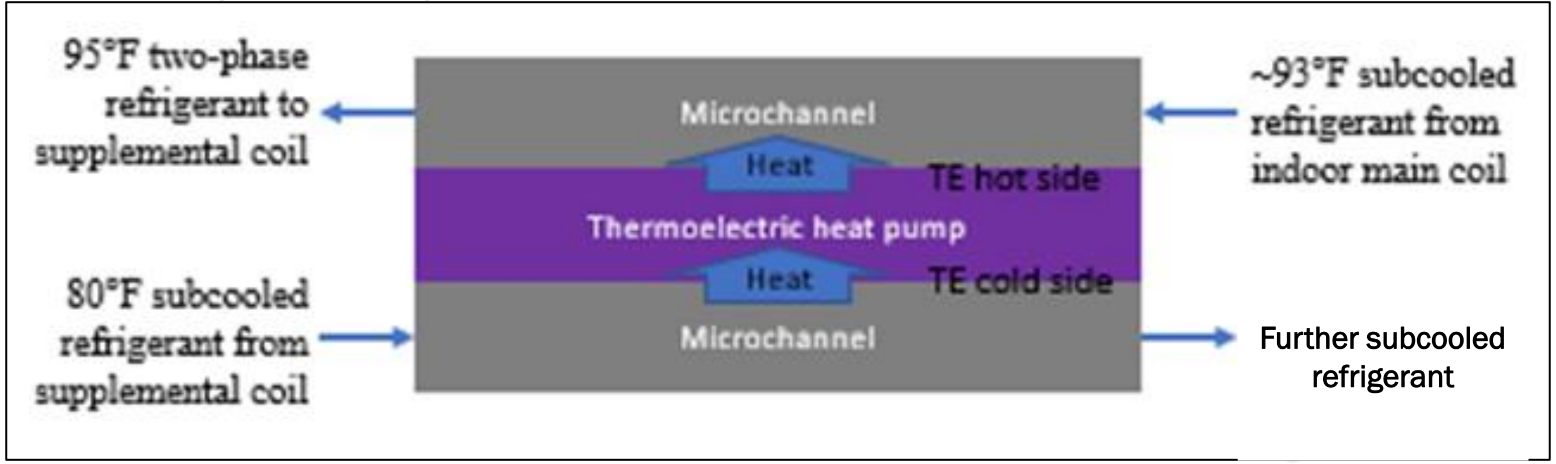
Innovation in Proposed Concept

Use of a compact thermoelectric (TE) heat pump device having microchannel tubes on both sides.

- 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 sandwiched between microchannels for increased heat transfer
- Can tolerate high refrigerant pressures up to 500 psi.



A 150W capacity thermoelectric module, 40mm x 40mm x 3.2mm



Details of thermoelectric heat pump arrangement

Fabricated TE Heat Pump Subcooler

Wood panel

Tube bundles

Thermal paste

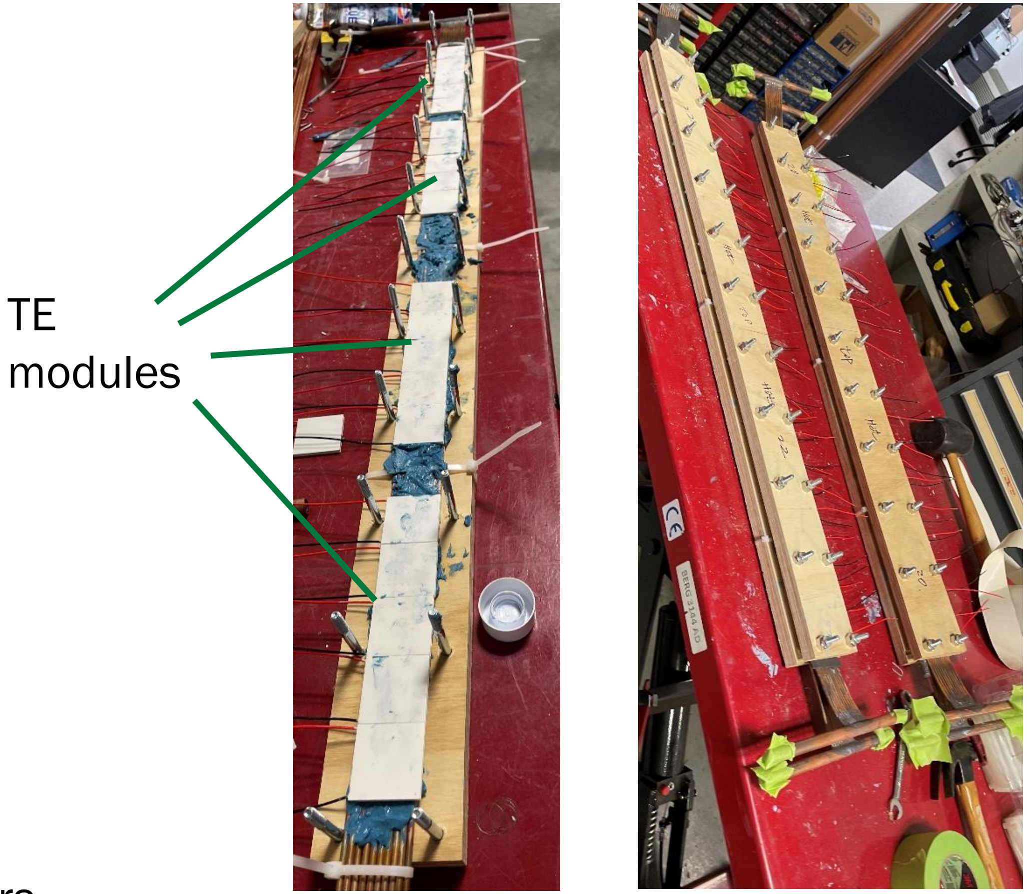
TE modules

Thermal paste

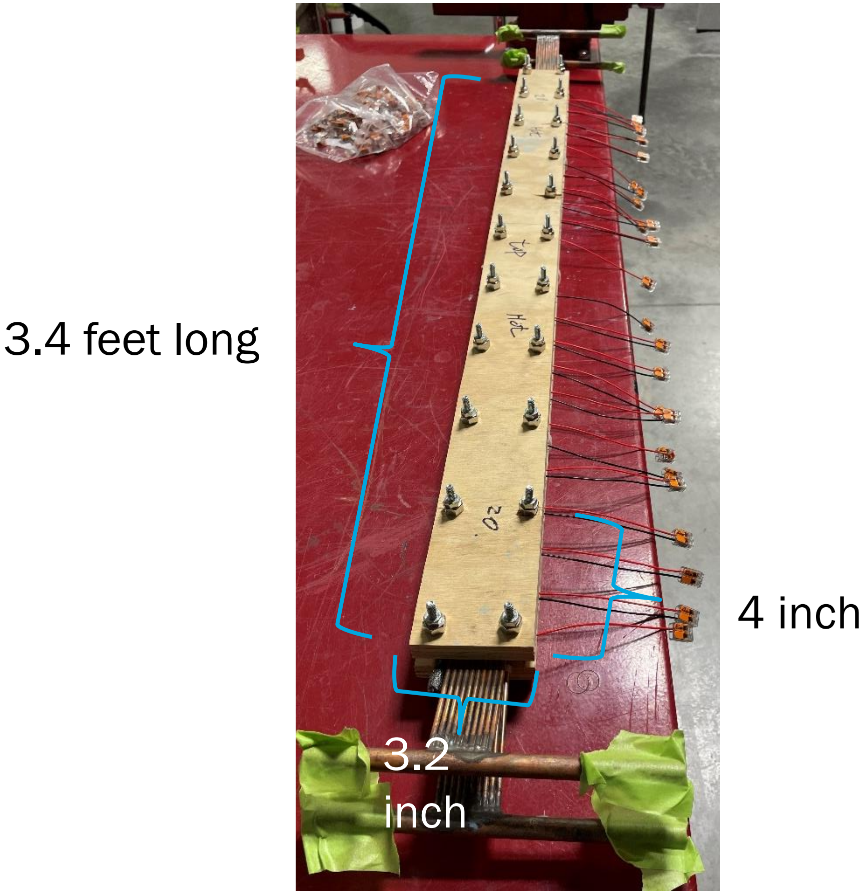
Tube bundles

Wood panel

TE subcooler layers



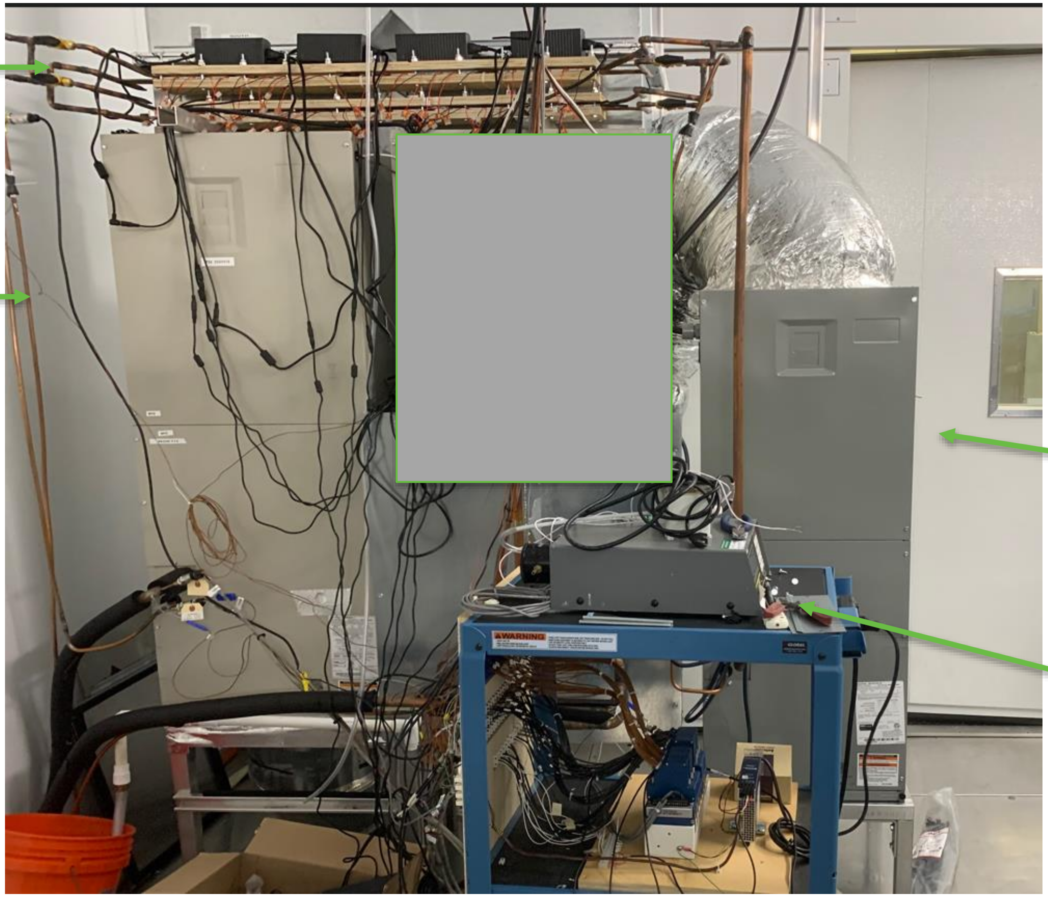
TE heat pump subcooler prototype; two TE subcoolers in parallel ON/OFF individually to study impacts of pressure drop.



Schematic arrangement of TE modules in a TE heat pump subcooler

The TE heat pump subcooler prototype contains two layers, each layer has twenty (4x5) 8-W TE modules

Integration of a TE refrigerant-to-refrigerant (R-to-R) Heat Pump with a Conventional Heat Pump



- Combined system offers heating energy benefits in any climate
- Can work down to -25°C (-13°F) with an integral COP > 2.0*

*Note: COP = Coefficient of Performance

Plan for Delivering the Intended Outcomes

Budget Period 1: FY 2022
(COMPLETED)

Budget Period 2:
FY 2023
(IN PROGRESS)

Budget Period 3:
FY 2024
(NOT STARTED)

Simulation based modeling

- TE Heat Pump Performance Curves
- Building Energy Simulations

Laboratory Testing

- Prototype Validation
  - R-to-R heat pump
  - W-to-W heat pump

Field Demonstration and Market Evaluation

- Cold Climate
- Humid Climate
- Commercialization and Tech Transfer

Major Accomplishments Till Date

- Completed simulation-driven design and optimization of thermoelectric integrated heat pump with 4 operating stages
- Fabricated refrigerant-to-refrigerant TE heat pump that consists of a 3-speed heat pump and a TE subcooler component
- Developed a test plan to laboratory test the heat pump that includes AHRI rating conditions as well as cold weather outdoor conditions (5°F)
- Completed the lab testing of the refrigerant-to-refrigerant prototype
- Two conference papers have been published and presented

Key Findings and Conclusions from Simulations

- Thermoelectric integrated heat pump with up to 4 stages of operation was modeled

ENERGY SAVINGS

- **Proposed design harvests ~12% heating energy savings annually vs. conventional single-speed HP**
  - Meets project goal of 10% energy savings

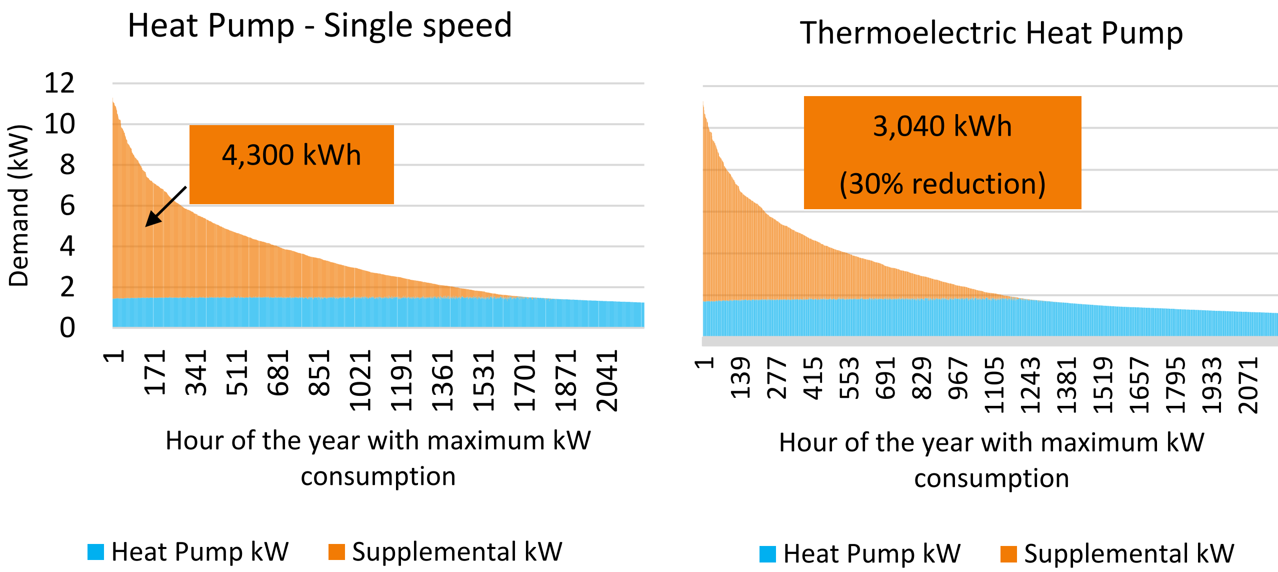
SUPPLEMENTAL HEAT USAGE

- **TE HP eliminates/reduces use of supplemental heat for 200-400 hours annually**

HEAT PUMP EFFICIENCY

- **Total Heating COPs of TE Heat Pump are 12-15% greater depending on climate**

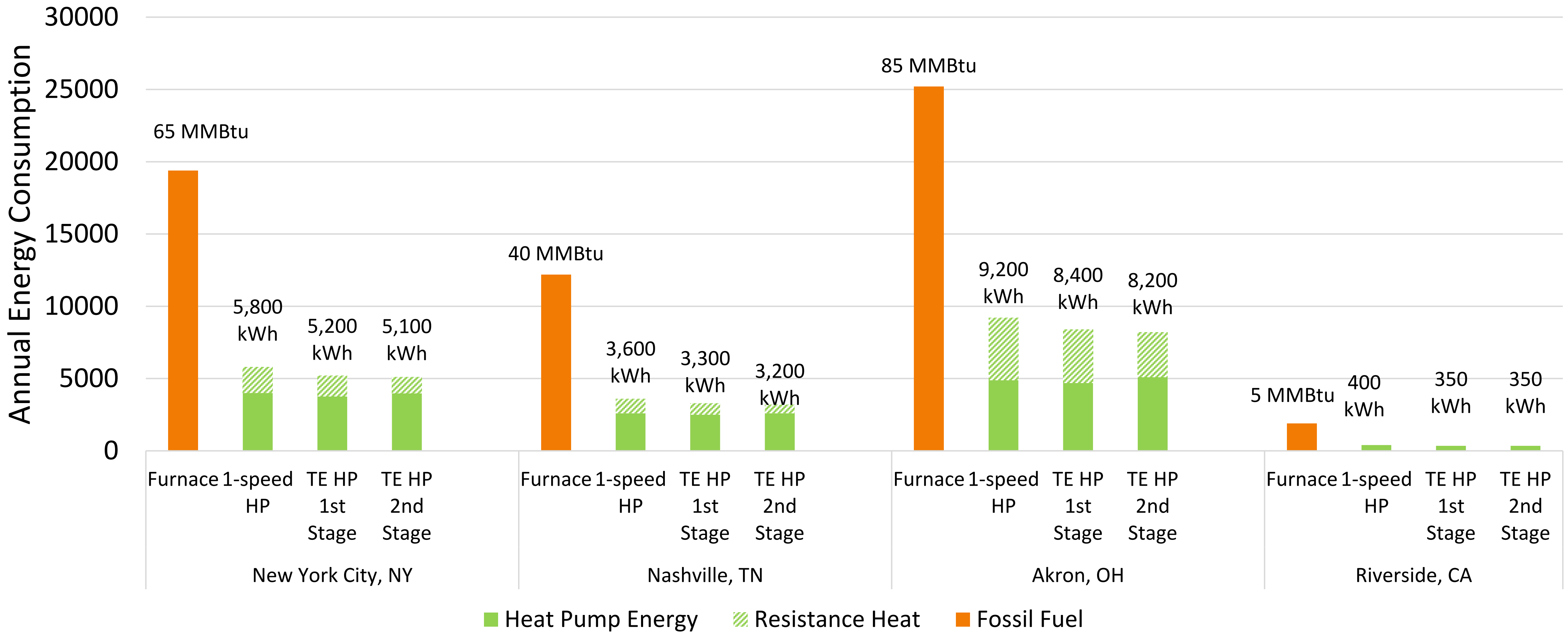
PEAK DEMAND IMPACTS



Climate/City	Modeled efficiency ranges for TE Heat Pump (HSPF) *
New York City, NY	10.5-12.4
Nashville, TN	10.4-12.1
Akron, OH	8.4-11.4
Riverside, CA	~14.0

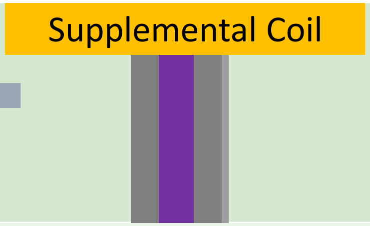
Annual Energy Consumption Simulation Results

- TE HP meets the proposed project goal of ~10% energy savings



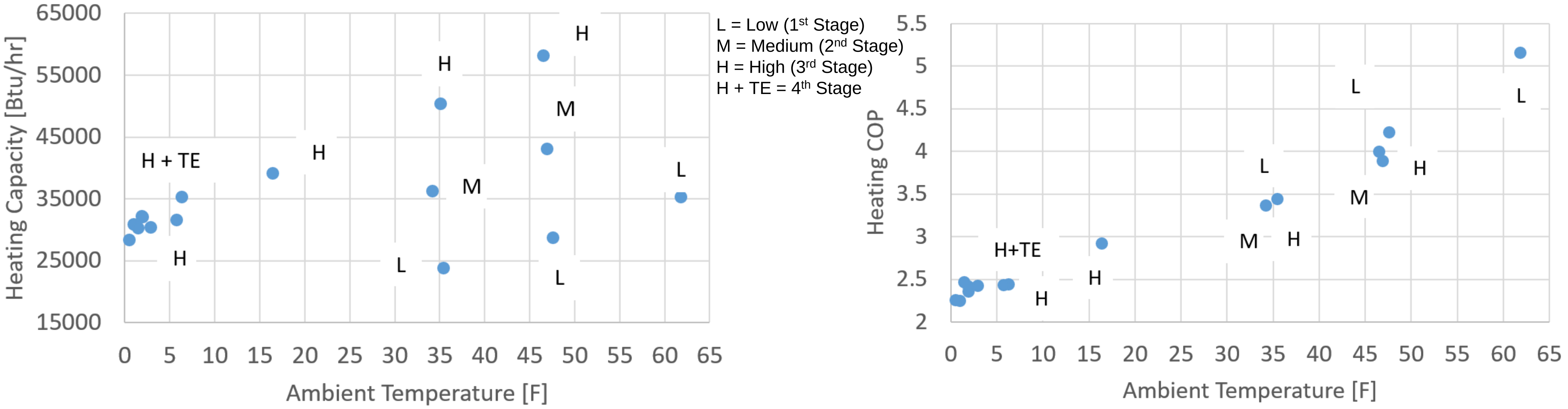
Annual Heating Energy Savings from a TE HP is up to 12% compared to a Conventional Single-Speed HP

Control Sequence for TE Integrated Heat Pump Operation

	Description of Stage	Compressor Speed	Supplemental Coil	TE heating, ΔT= 20°F
	Low Stage of 3-speed heat pump with supplemental coil	Low +	 Supplemental Coil	
	Medium Stage of 3-speed heat pump with supplemental coil	Medium +		
3	High Stage of 3-speed heat pump with supplemental coil	High +	 Supplemental Coil +	

The TE Integrated heat pump was laboratory tested with 4 stages of operation

Laboratory Testing Results



- **Thermoelectric Integrated R-to-R heat pump increases the capacity and COP of the system than a conventional heat pump due to two major reasons:**
  - Supplemental coil increases heat transfer area of the condenser side
  - TE modules provide additional heating capacity at a COP > 1.6
- **At 0°F, the heat pump increased the total capacity by 12% at a COP of 2.25**
- **Performance improvements were validated with repeatability through laboratory tests**

Major Project Milestones and Status

Milestone	Success Criteria	Estimated Date of Completion
Successful modeling of cascaded heat pump	*Simulated performance indices meet energy, demand, and cost goals*	March 31, 2022
Successful laboratory validation of R-to-R TE cascade heat pump	*Laboratory tests for capacity and efficiency at standard rating conditions for heating validate model results within 5% accuracy and reproducibility.*	April 30, 2023
Completion of field prototype installations at three U.S. sites	*install and instrument the heat pump prototypes in the selected host sites, ready for field testing*	November 30, 2023
Successful field verification completion at three field sites	*Complete field data collection and analysis of installed heat pump prototypes to show targeted energy savings*	July 31, 2024

Status : 🟩 =Completed ⬜ =Not Completed

Plans for the Rest of the Project

Task	Description of Task	Planned Timeline
Laboratory investigation of Water-to-Water TE heat pump	Validate dehumidification features of the cold climate heat pump to achieve energy savings, cost and demand reduction goal	July 2023
Field Demonstration	Install the heat pump at field test site and validate performance and functionalities built-in to the new technology.	August 2023 – June 2024
Commercialization and Market Potential Evaluation Assessments	Examine the market impact of the heat pump in terms of energy savings, expected number of installations and carbon emission reduction.	June 2024 – August 2024

Technology Transfer and Commercialization Planning

- Commercial viability/scalability will be evaluated for different U.S. regions
  - Realistic potential for electrification and number of installations in the next 20 years

- **Potential for 10% reduction in energy consumption could lead to short payback periods**
  - Manufacturing cost increment will be from TE component and heat exchanger

- **Approach commercial partners for further technology development**
  - Leverage EPRI's and ORNL's network to interview potential HP and TE partners
  - Socialize with strategic alliances or partnerships (ASHRAE, HARDI, NAHB, BEL, etc.)
  - Educate them on advantages that this HP will bring to the market
  - Identify future research and technology licensing

Thank You

Electric Power Research Institute and Oak Ridge National Laboratory
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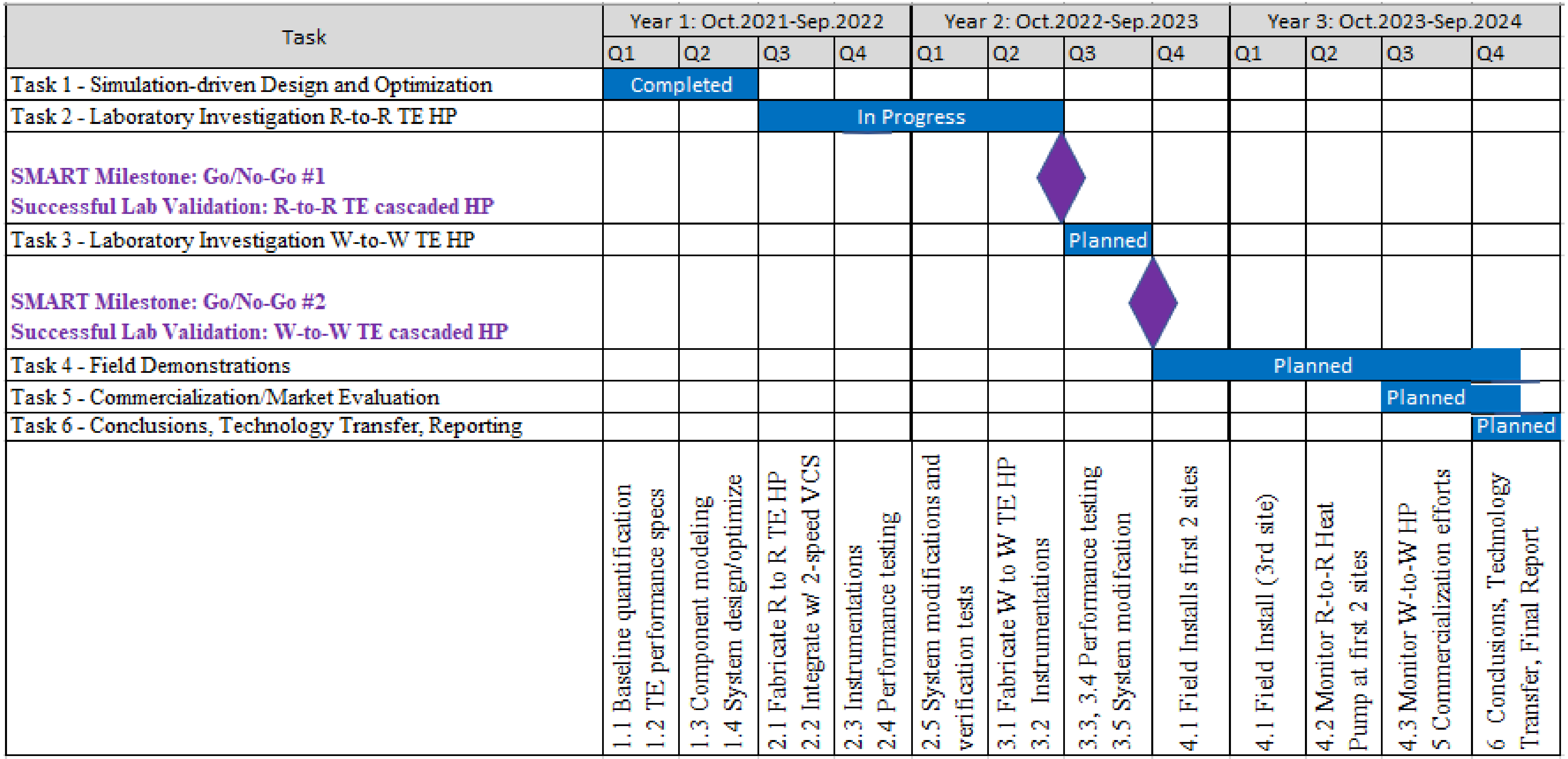
DOE BENEFIT PROJECT AWARD : DE-EE0009687

Project Execution



Task	Year 1: Oct.2021-Sep.2022				Year 2: Oct.2022-Sep.2023				Year 3: Oct.2023-Sep.2024			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1 - Simulation-driven Design and Optimization	Completed											
Task 2 - Laboratory Investigation R-to-R TE HP			In Progress									
SMART Milestone: Go/No-Go #1 **Successful Lab Validation: R-to-R TE cascaded HP**						◆						
Task 3 - Laboratory Investigation W-to-W TE HP							Planned					
SMART Milestone: Go/No-Go #2 **Successful Lab Validation: W-to-W TE cascaded HP**							◆					
Task 4 - Field Demonstrations								Planned				
Task 5 - Commercialization/Market Evaluation											Planned	
Task 6 - Conclusions, Technology Transfer, Reporting												Planned
	1.1 Baseline quantification 1.2 TE performance specs	1.3 Component modeling 1.4 System design/optimize	2.1 Fabricate R to R TE HP 2.2 Integrate w/ 2-speed VCS	2.3 Instrumentations 2.4 Performance testing	2.5 System modifications and verification tests	3.1 Fabricate W to W TE HP 3.2 Instrumentations	3.3, 3.4 Performance testing 3.5 System modification	4.1 Field Installs first 2 sites	4.1 Field Install (3rd site)	4.2 Monitor R-to-R Heat Pump at first 2 sites	4.3 Monitor W-to-W HP 5 Commercialization efforts	6 Conclusions, Technology Transfer, Final Report

Key Team Members and Stakeholders

Organization	Team member	Role
EPRI	Sreenidhi Krishnamoorthy	Project PI
		Lead Researcher
	Baskar Vairamohan	Advisory Role
		Primary Lead at ORNL

EPRI's Utility Partners

FirstEnergy

conEdison

TVA TENNESSEE VALLEY AUTHORITY

SOUTHERN CALIFORNIA EDISON
Energy for What's Ahead™

HVAC Manufacturing Partner

Heat Pump manufacturer

NORTEK
GLOBAL HVAC

EERE/BTO goals

(Not a template slide – for informational purposes only)

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

Support rapid decarbonization of the U.S. building stock in line with economywide net-zero emissions by 2050 while centering equity and benefits to communities

Increase building energy efficiency

Reduce onsite energy use intensity in buildings 30% by 2035 and 45% by 2050, compared to 2005

Accelerate building electrification

Reduce onsite fossil -based CO_2 emissions in buildings 25% by 2035 and 75% by 2050, compared to 2005

Transform the grid edge at buildings

Increase building demand flexibility potential 3X by 2050, compared to 2020, to enable a net-zero grid, reduce grid edge infrastructure costs, and improve resilience.

Prioritize equity, affordability, and resilience

Ensure that 40% of the benefits of federal building decarbonization investments flow to disadvantaged communities

Reduce the cost of decarbonizing key building segments 50% by 2035 while also reducing consumer energy burdens

Increase the ability of communities to withstand stress from climate change, extreme weather, and grid disruptions

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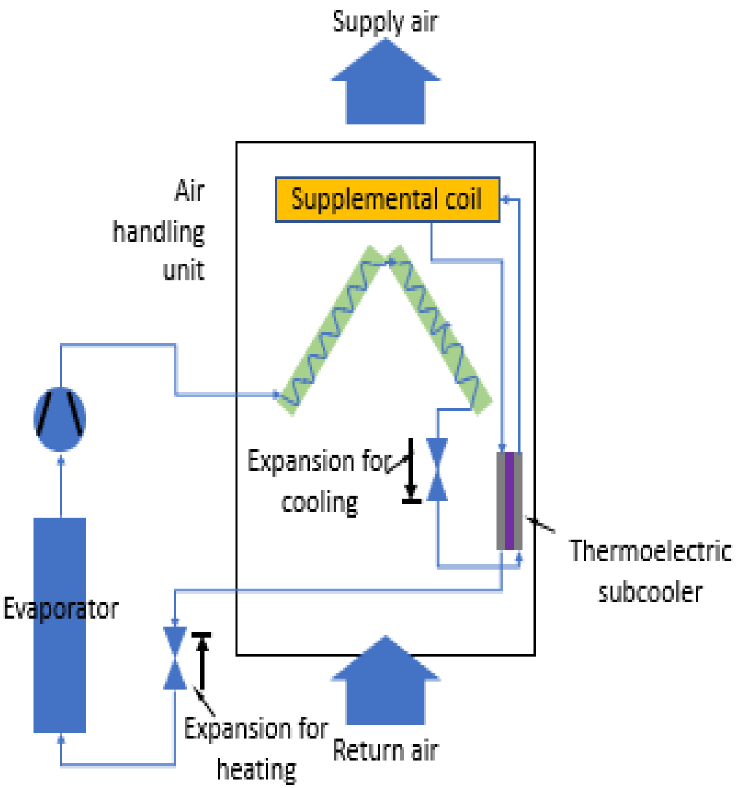
APPENDIX

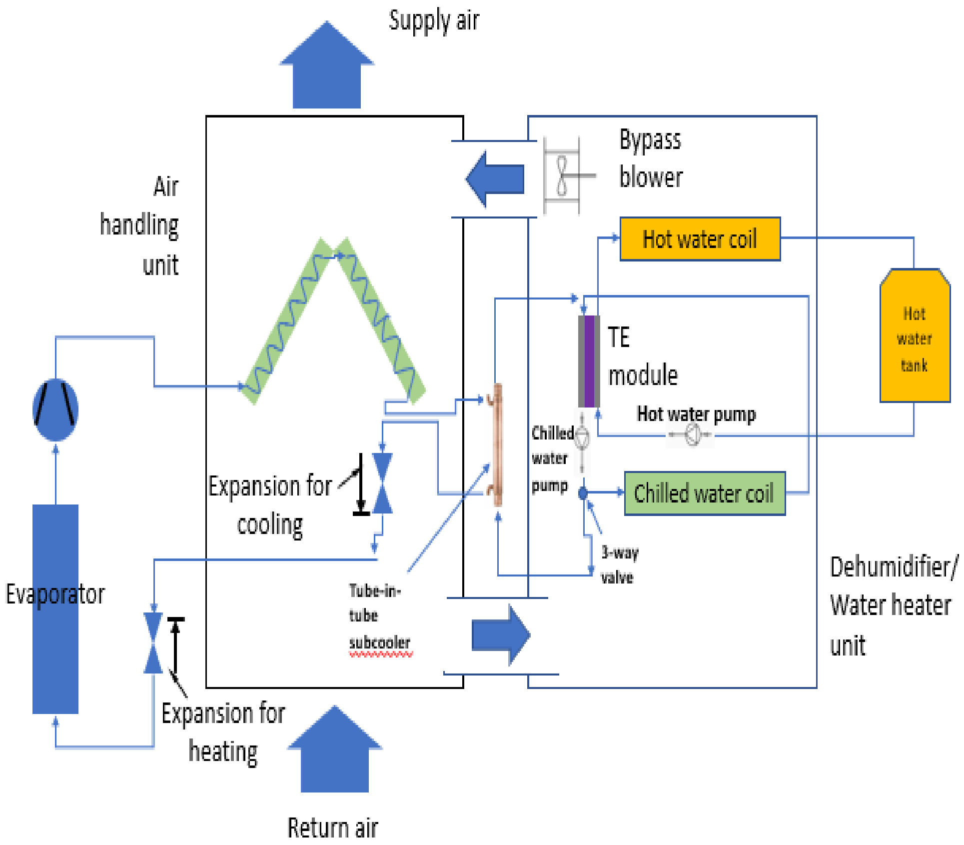
Two Heat Pump Configurations Based on Innovation

Configuration 1: Integration of a TE refrigerant-to-refrigerant (R-to-R) heat pump with a conventional heat pump



- Combined system offers heating energy benefits in any climate
- Can work down to -25°C (-13°F) with an integral COP > 2.0*

Configuration 2: Integration of a TE water-to-water (W-to-W) heat pump for heating and summer dehumidification



- System can be used as a heat pump in winter
- As a whole-building dehumidifier in summer
- Built-in hot water storage allows for demand flexibility

*Note: COP = Coefficient of Performance

Detailed List of Project Tasks

Task #	Task Name	Task Details
1	Simulation Based Cascaded Heat Pump Modeling	Obtain accurate baseline assessment of current heat pump technology and model performance improvement in new heat pump.
2	Laboratory investigation of Configuration #1 (Refrigerant-to-Refrigerant) TE heat pump integrated with a two-speed heat pump	Validate model results through laboratory testing. Develop optimum control strategy for cascaded heat pump.
3	Laboratory investigation of Configuration #2 (Water-to-Water) TE heat pump integrated with 2-speed heat pump	
4	Field Demonstration	Install the heat pump at field test site. Testing will validate and demonstrate the performance and functionalities built-in to the new technology.
5	Commercialization and Market Potential Evaluation Assessments	Examine the market impact of the heat pump in terms of energy savings, expected number of installations and carbon emission reduction.
6	Conclusions, Technology Transfer and Final Report	Summarize conclusions from project findings and tech transfer via final report, conference presentation, etc.