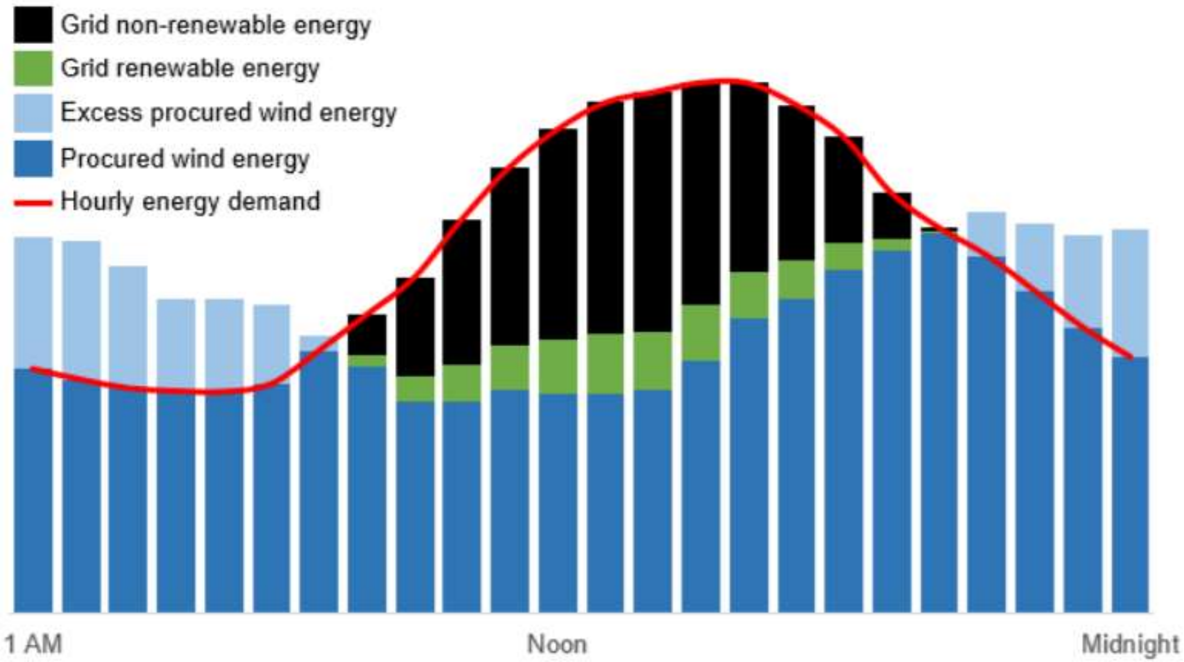
Wall Embedded Multi-Functional Heat Pump with Energy Storage systems For Grid-Responsive and Weather-Transactive Controls



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WBS# 02.02.02.123; ABC Benefit FOA

Project Summary

Objective and outcome

1. **Decarbonization,** i.e. space heating and water heating, via replacing resistance heating and fossil fuel heating.
2. Develop cost-effective multi-functional packaged heat pump for multi-family buildings, having a IEER > 17.0; HSPF > 10.0 and annual water heating COP > 4.0, 100% heating capacity and COP > 2.0 down to 5˚F.
3. **Grid-responsive energy storage** to maximize use of renewable energy, shift peak load > 2 hours, and utility cost reduction > 20%, corresponding to one Time-of-Use Profile

Team and Partners

- Emerson Climate Technologies
- University of Oklahoma

1st Two-Layer PCM HX

BioPCM blankets

Stats

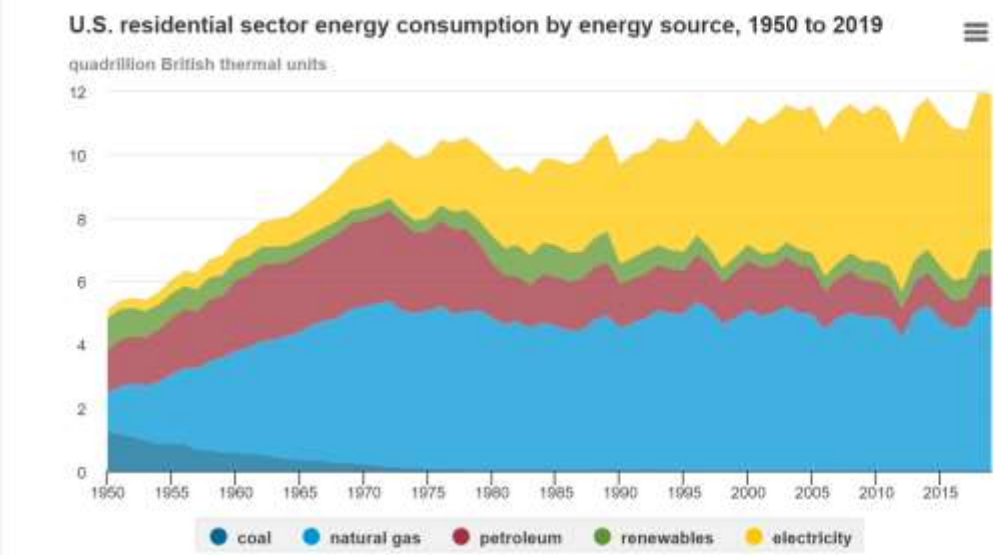
Start date: 08/01/2020; End date: 09/30/2022

Budget: DOE Total - $500K; Emerson: $120K

Key milestones

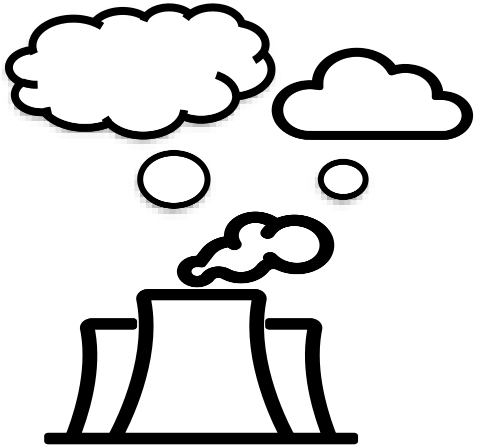
1. Complete system design– 11/2020
2. Development of technologies at component level – 04/2021
3. Develop multi-objective, grid-responsive and weather-forecast based transactive control – 07/2021
4. Construct 1st laboratory prototype – 09/2021
5. Laboratory verification of space cooling/heating performance – 03/2022
6. Verify water heating performance – 05/2022
7. Verify energy storage mechanism and performance – 07/2022

Challenges - Energy, Emissions and Equity (E3) Initiative



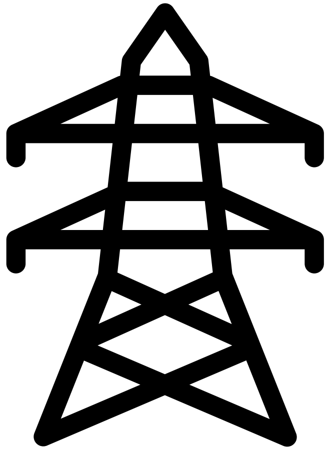
- E3 initiative challenges HPWH and CCHP.
- Majority of multi-family buildings still use electric resistance or low efficiency heat pumps for heating.
- Decarbonization and electrification: heat pumps are the most effective means to replace fossil burning. It should deliver the same functionalities with good efficiency and adequate capacity at low ambient temperatures.
- Grid-response: a multi-functional, packaged unit can actively charge/discharge building elements for energy storage and maximize the use of renewable energy.
- Multi-family building sector is a cost competitive market. A single-set of components provide all the home comforts, leading to good cost effectiveness.

Alignment and Impact



Greenhouse gas emissions reductions

High Efficiency: Develop high end, cost-effective packaged heat pump: Achieve IEER > 17.0 and HSPF > 10.0, enhanced heating at 5˚F to deliver 100% rated capacity @ COP > 2.0, and integrated water heating annual efficiency > 4.0.



Power system decarbonization

- Multi-functional heat pump for space heating and water heating, to replace natural gas
- Energy storage to shift peak load

Energy Justice

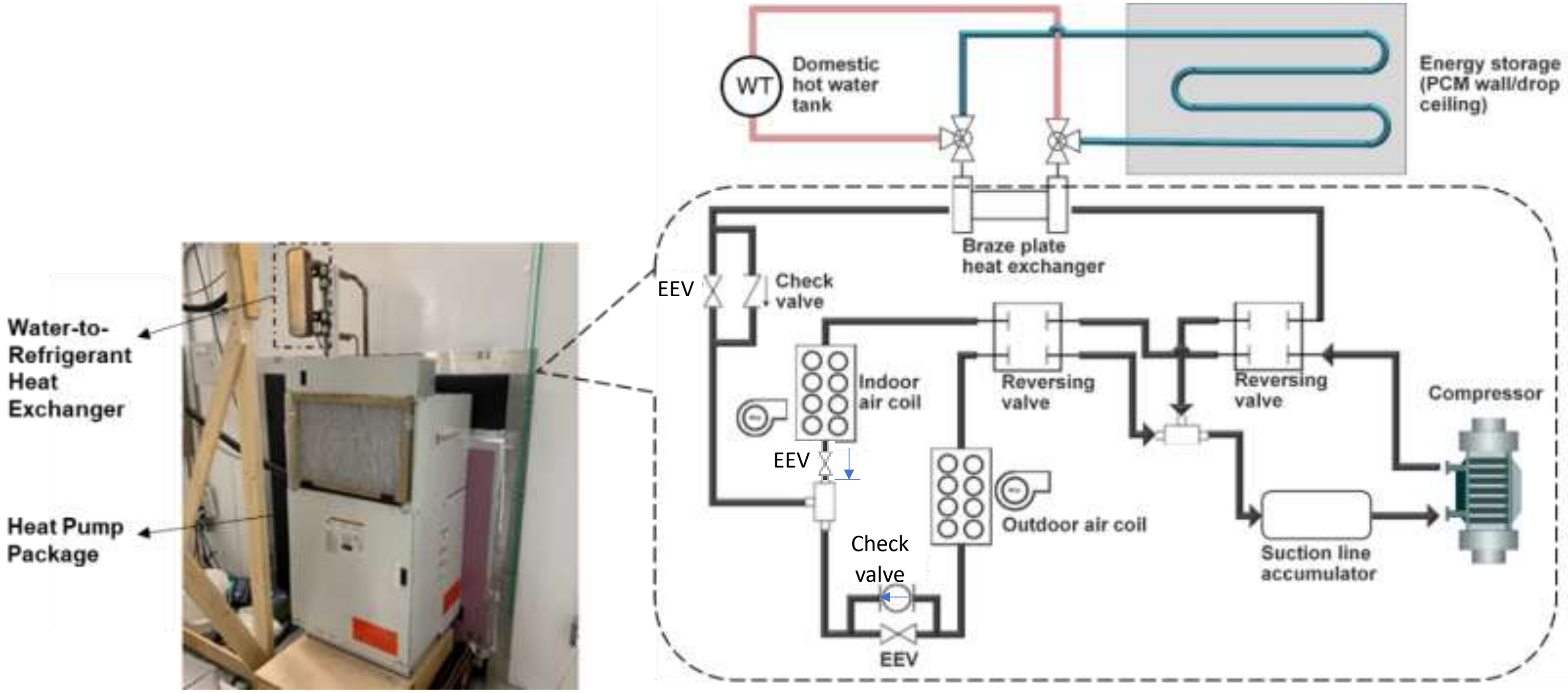
Increase competitiveness of US manufacturing --promote low-cost capacity modulation using 3-stage scroll compressors in multi-family buildings, to compete with variable-speed rotary compressors.

One equipment serves all home comforts

The nation's ambitious climate mitigation goals

Approach – Innovative Configuration to cover all the functions with a single-set of components

An innovative wall embedded air-source integrated heat pump (WAS-IHP) solution capable of space cooling, space heating, water heating (WH). Coupled with enhanced thermal storage elements—a water tank and phase change material (PCM) panels—the unit will respond to grid signals to shift peak load, for weather-forecast transactive control.



Six Working Modes:

- Space cooling
- Space heating
- Cooling energy storage
- Heating energy storage
- Water heating with outdoor air source
- <u>Water heating with indoor air source (combined space cooling and water heating)</u>

High efficiency, multi-functional terminal unit to satisfy all home comfort needs and grid-responsive energy storage.

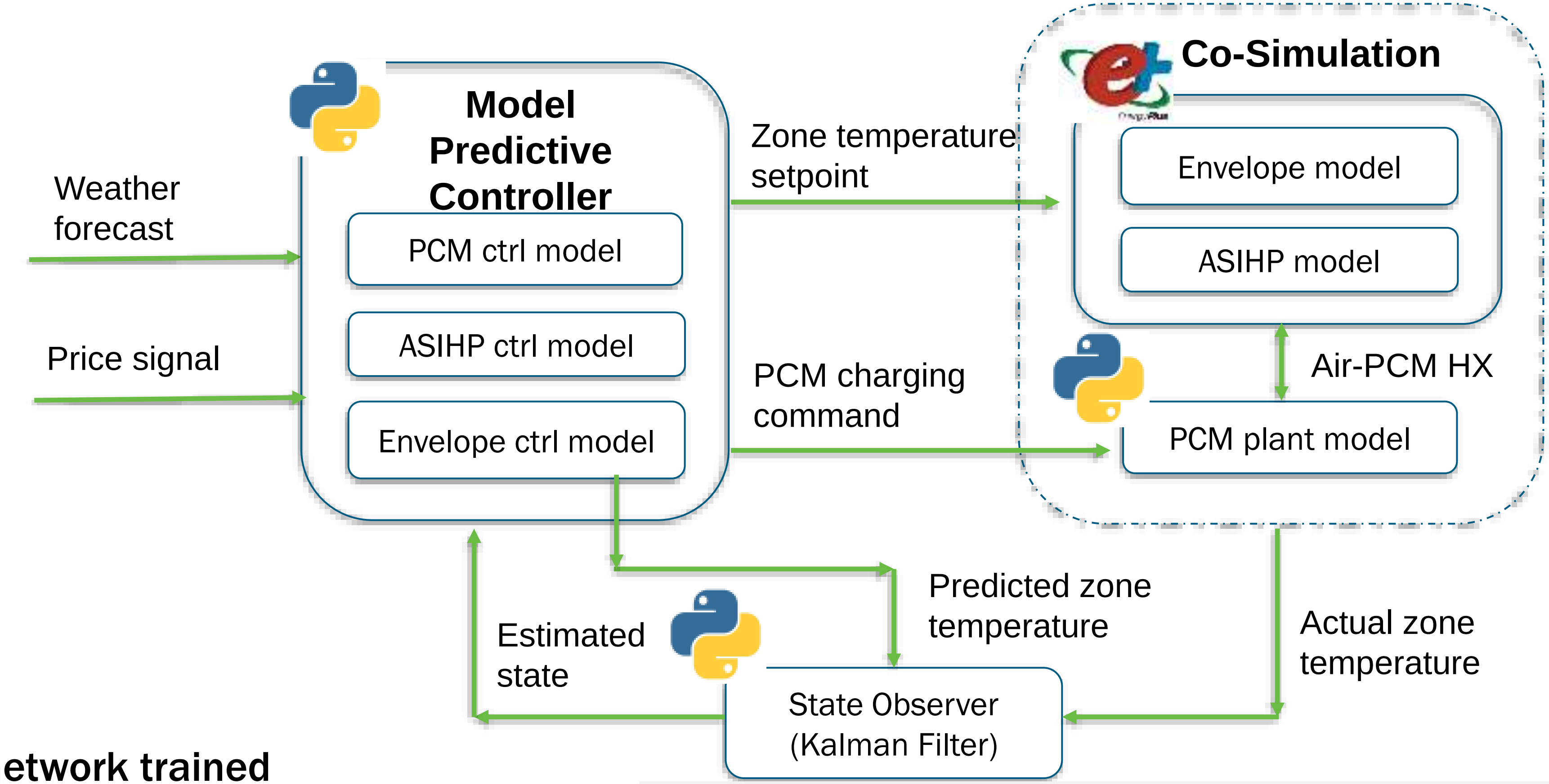
Approach: Co-simulation of Grid-Responsive Energy Storage and Weather-Transactive Control in Residential Template Buildings

Control algorithm
- Mixed-integer linear programming routine

PCM model:
- Multi-node enthalpy method
- Piece-wise linear map between enthalpy and temperature
- Identical control and plant models

Envelope control model:
- Resistance/capacitance network trained with E+ data

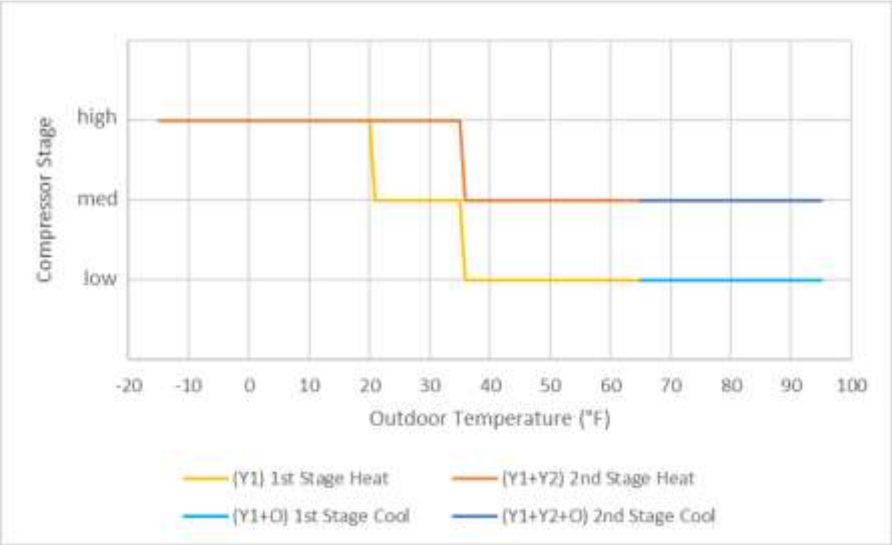
Air source integrated heat pump (ASIHP) control model:
- Performance curves with simplifying assumptions to ensure solvability



Predictor/corrector to estimate values for all state variables (all nodal temperatures in the thermal network). These estimated states are updated every hour and are used as initial states for predictive optimization of the 24-hr look-ahead time horizon.

Approach: Low-Cost Capacity Modulation Technique: Emerson 3-stage compressor sample having 2-ton capacity at the top speed

- **Single, 3-stage, scroll compressor**
  - Preliminary capacity levels of 100%, 67%, 45%
    - 67% is used for rated capacity of cooling mode, 100% capacity for enhanced heating at low ambient temperatures.
    - Compatible with 2-stage thermostat
  - 30% reduction in compressor cost per rated cooling ton, to compete with inverter-driven variable-speed compressors



Mechanical capacity modulation

In the AC/HP market having capacity < 2-ton, scroll compressors don't have cost advantage; lower cost capacity modulation will make scroll compressors win over inverter-driven rotary compressors.

Progress: Laboratory Prototype

Code tester to measure air flow rate

Separate power meters to measure total, compressor, condenser fan power

- Chilled mirror humidity sensor to measure supply air dew point
- T/RH probe to measure return air state
- A thermocouple probe to measure supply air temperature

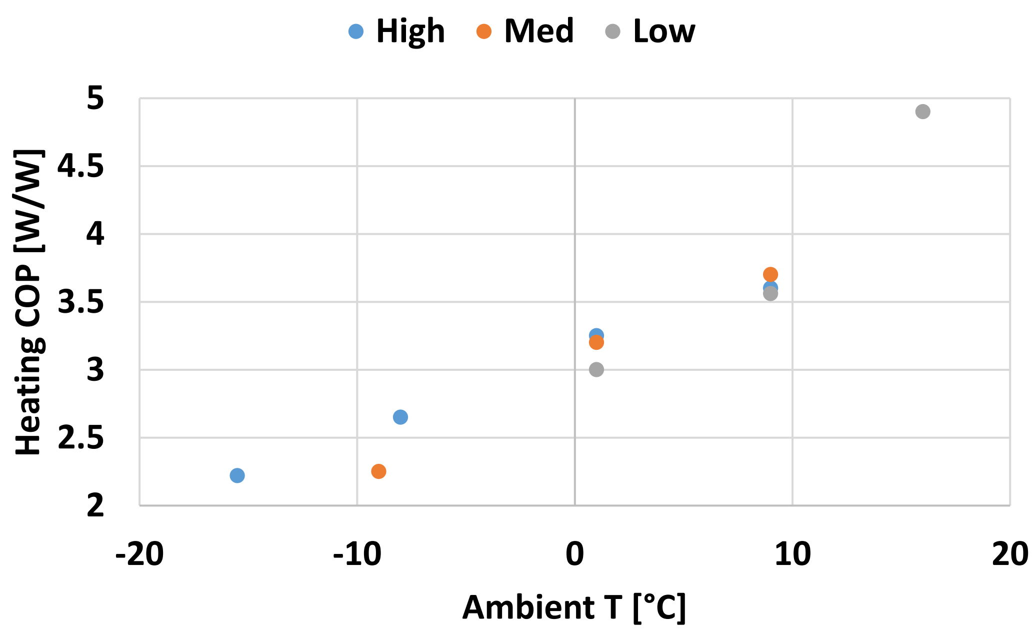
1st Two-Layer PCM HX

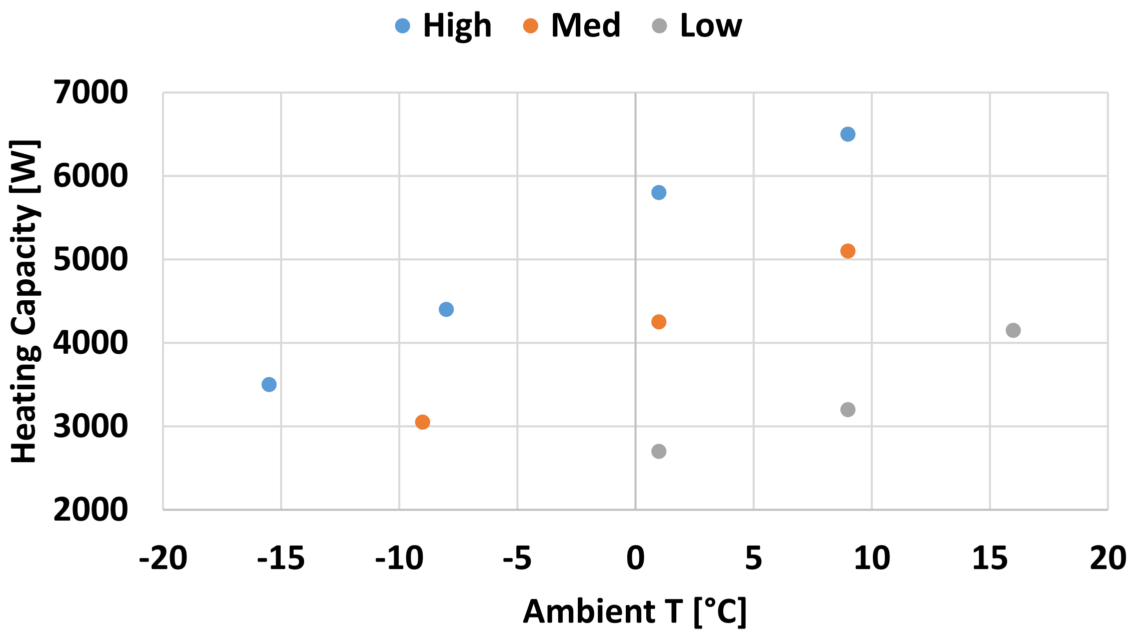
Heated/ cooled by IHP

BioPCM blankets

❑ **PCM melting temp = 24C**

Measured Space Heating Performance



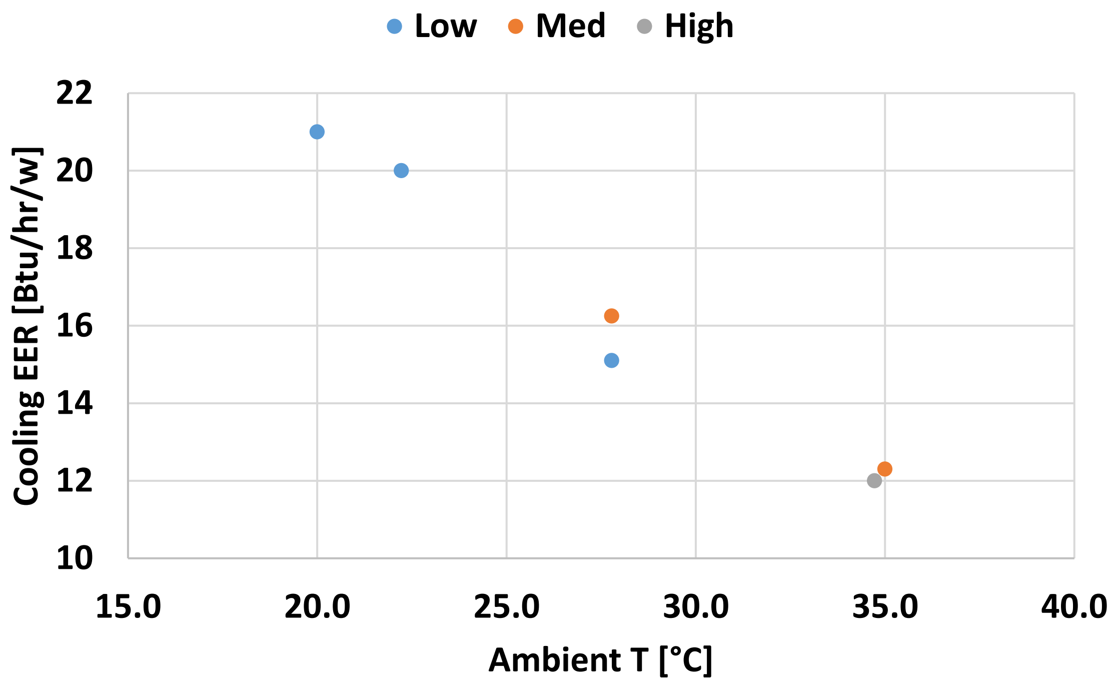


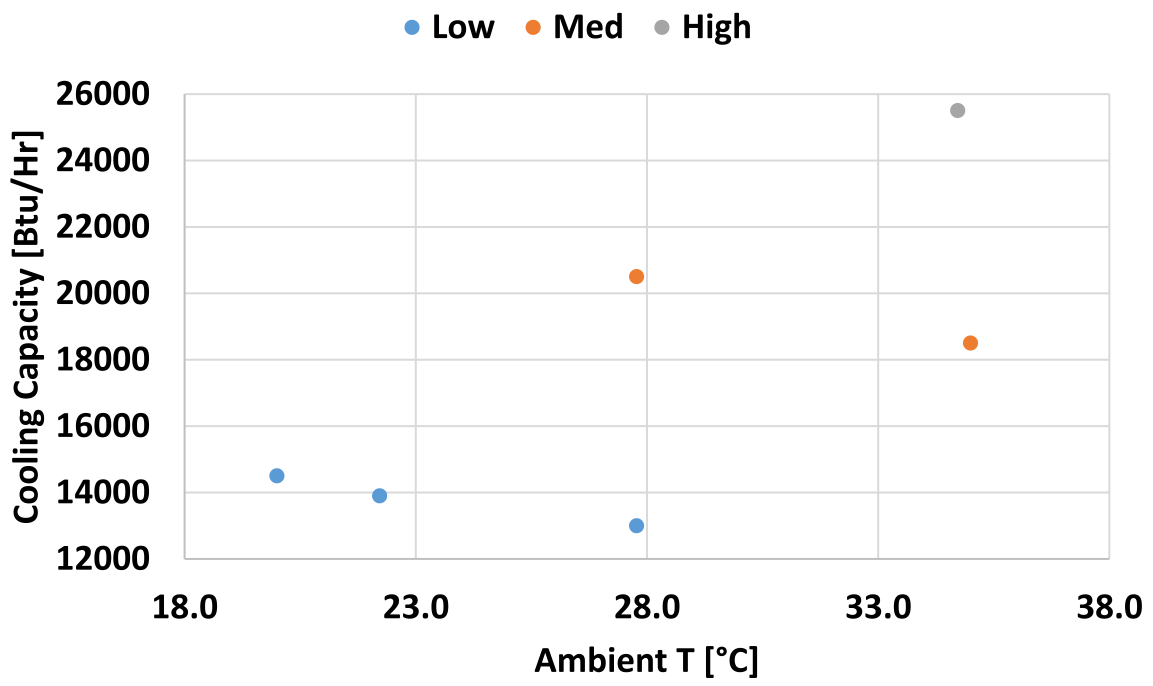
Heating COP > 2.2 down to -15˚C (5 ˚ F)

	Region (AHRI 210/240)	IV	V	I	II	III	VI
Size 17.5K, C_d=0.1	HSPF_DHRmin	9.99	8.76	12.47	11.49	10.94	11.89
	HSPF_DHRmax	8.95	7.40	12.69	11.79	10.56	12.26
Size 12K, C_d=0.1	HSPF_DHRmin	9.90	8.87	12.23	11.49	10.80	11.69
	HSPF_DHRmax	9.78	8.48	12.47	11.69	11.00	12.10

If rated at the compressor low stage, and two higher stages for enhanced heating, heating capacity@-15 ˚ C > 100% rated capacity

Measured Space Cooling Performance



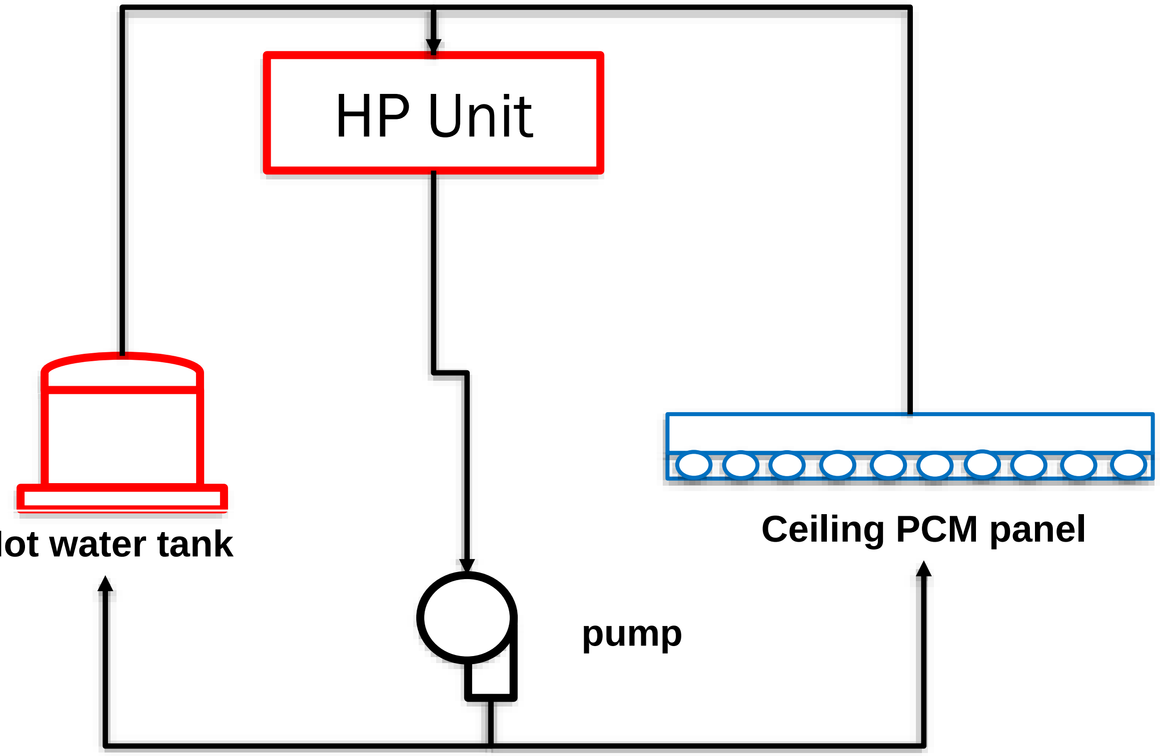


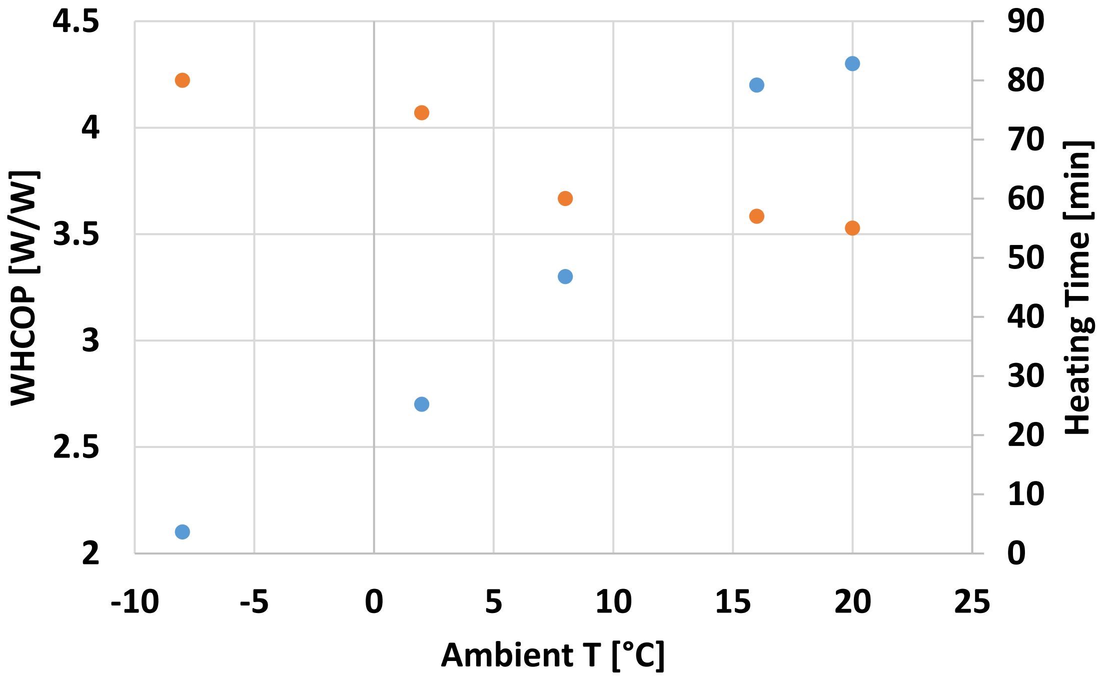
IEERs at different rated capacities.

	RatedCapacity [Btu/hr]	IEER [Btu/hr/W]
Rated@High	25000	18.07
Rated@Middle_Heat,47F	17500	17.30
Rated@Low	12000	16.05

Water Heating Energy Storage

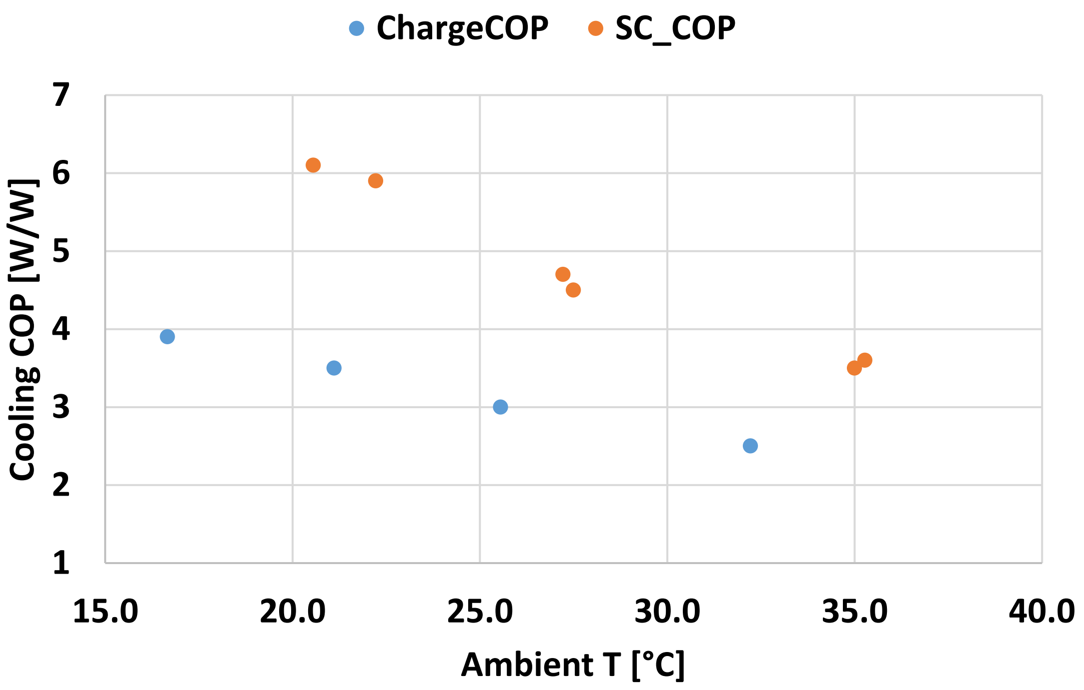
Hydronic Loop

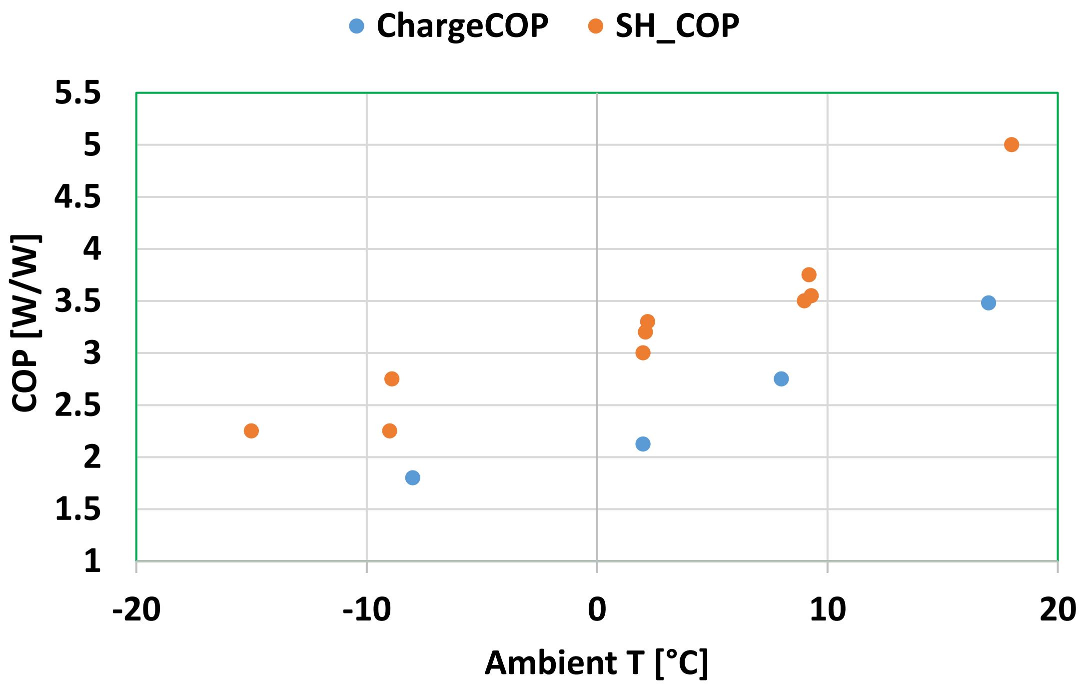




- Speedy heat-up of a 40-gallon water tank from 14˚C to 51.7˚C
- Efficient WH down to -8.3 ˚ C
- Most efficient combined space cooling and water heating – integrated COP >8.5

Phase change material energy storage



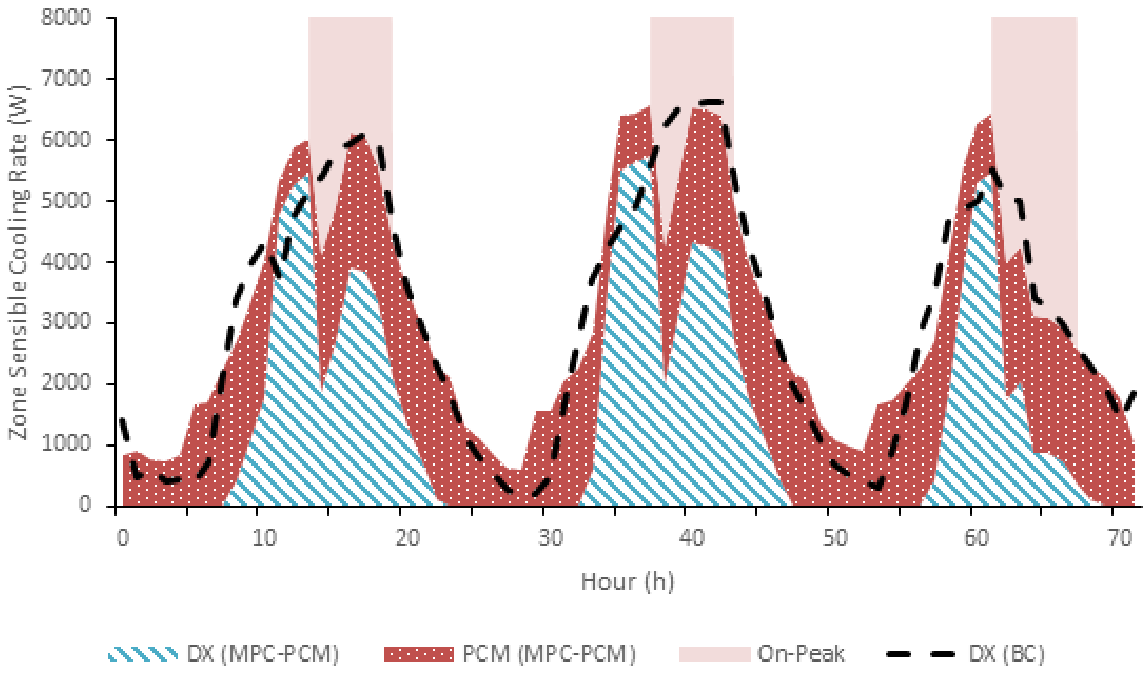


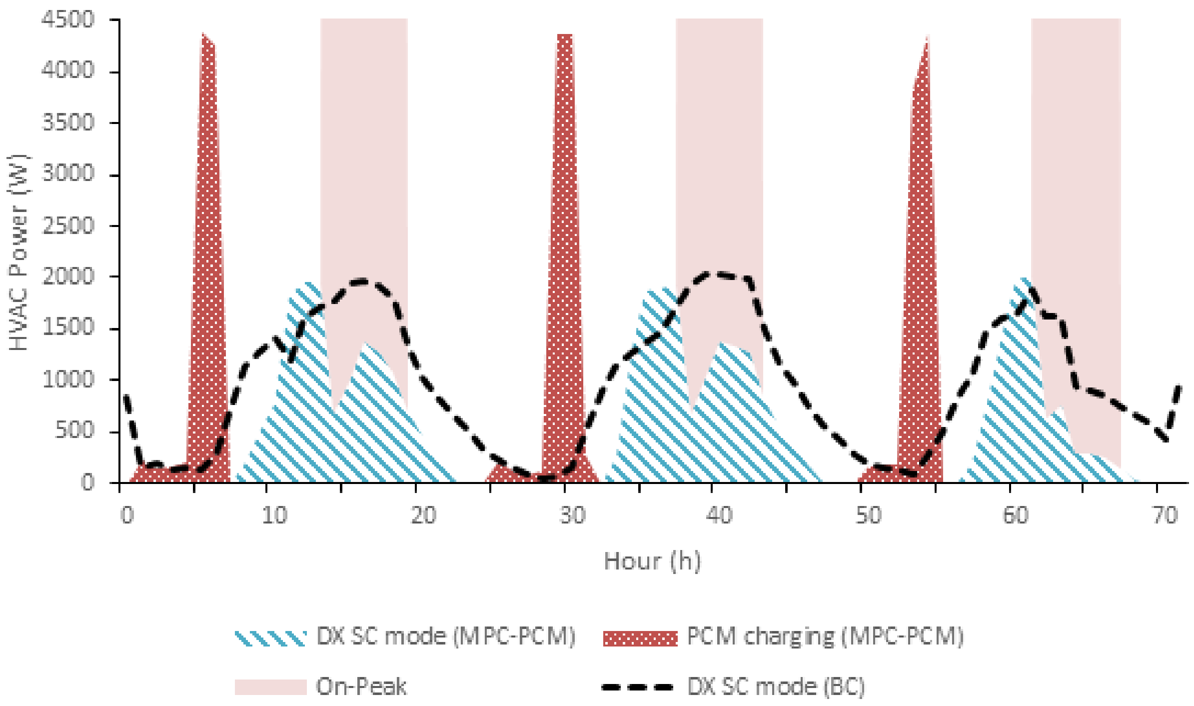
*charging terminated when chilled water out of the heat pump reached 3.3˚C

*charging terminated when hot water out of the heat pump reached 48.9˚C

PCM charging process COPs were 30% to 50% lower than the space cooling/heating COPs due to increased PCM thermal resistance during the charging processes

Results for three summer days – Single-family house, Atlanta, GE





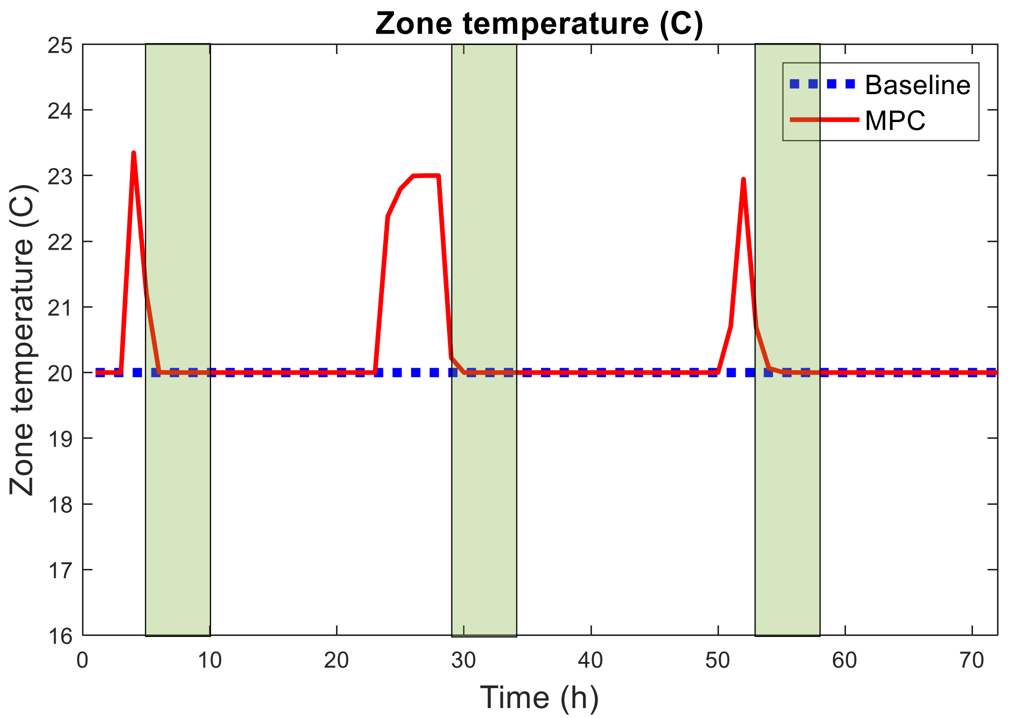
- ❑ Zone temperature setpoint: 23C
- ❑ Lower limit of precooling zone temperature: 20C
- ❑ PCM melting temp = 24C
- ❑ Peak hour = 5:00am-10:00am (Winter)
- ❑ Electricity price: peak hour = 0.2$/KWh
  off-peak hour = 0.05$/KWh

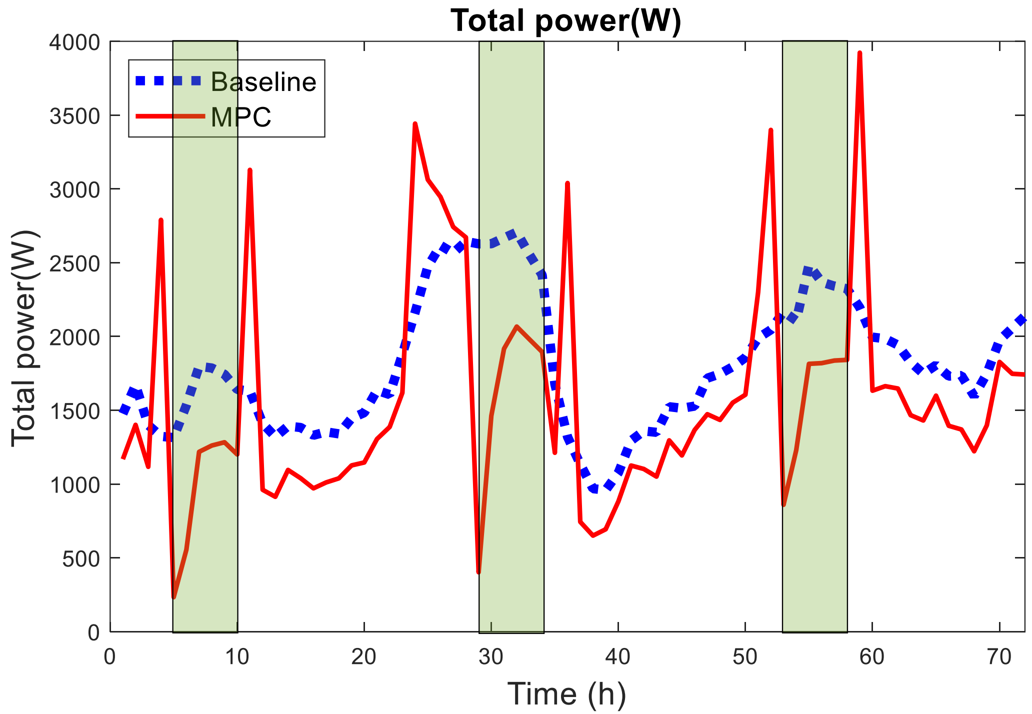
Cooling season of Utility structure of Georgia Power TOU-REO-12

- ❖ **Three-day electricity cost:**
  - ❑ MPC control with PCM ceiling:
    Electricity bill = $5.4 (27.1 % cost savings)
  - ❑ Baseline control:
    Electricity bill = $7.41

Cover the ceilings with PCM blankets.

Results for winter days - Indianapolis





- ❑ Zone temperature setpoint: 20C
- ❑ Upper limit of preheating temperature: 23C
- ❑ PCM melting temp = 24C
- ❑ Peak hour = 5:00am-10:00am (Winter)
- ❑ Electricity price: peak hour = 0.2$/KWh
  off-peak hour = 0.05$/KWh

❖ **Three-day electricity cost:**

- ❑ MPC control with PCM ceiling:
  Electricity bill = $9.3908 (24.19% cost savings)
- ❑ Baseline control:
  Electricity bill = $12.3878

Outcomes: The project completed in 2022, and a public final report released.

Publications:

- "Wall Embedded Multifunctional Heat Pump", Project Final Report, ORNL/TM-2022/2626
- "Model-based predictive control of multi-stage air-source heat pumps integrated with phase change material-embedded ceilings", P Hlanze, Z Jiang, J Cai, B Shen - Applied Energy, 2023
- "Cold Climate Integrated Heat Pump with Energy Storage for Grid-Responsive Control", Bo Shen, Kyle G, Zhenning Li , ASHRAE and SCANVAC HVAC Cold Climate Conference 2023.

Stakeholder Engagement – Close Collaboration with Emerson

- Emerson provided 3-stage sample compressor and controller
- Had weekly meetings with Emerson to monitor the work progress
- University of Oklahoma performed building energy simulation and control development

Thank you

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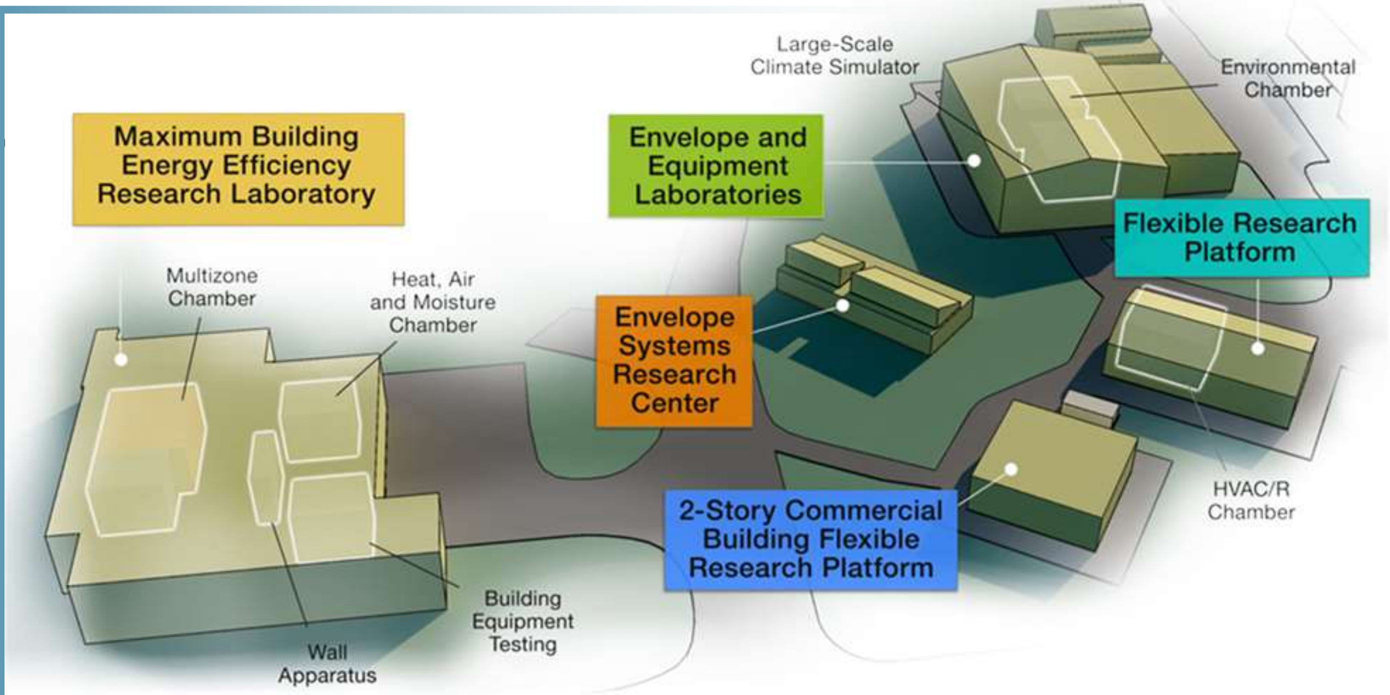


ORNL's Building Technologies Research and Integration Center (BTRIC) has supported DOE BTO since 1993. BTRIC is comprised of 50,000+ ft^2 of lab facilities conducting RD&D to support the DOE mission to equitably transition America to a carbon pollution-free electricity sector by 2035 and carbon free economy by 2050.

Scientific and Economic Results

238 publications in FY20
125 industry partners
27 university partners
10 R&D 100 awards
42 active CRADAs

BTRIC is a DOE-Designated National User Facility

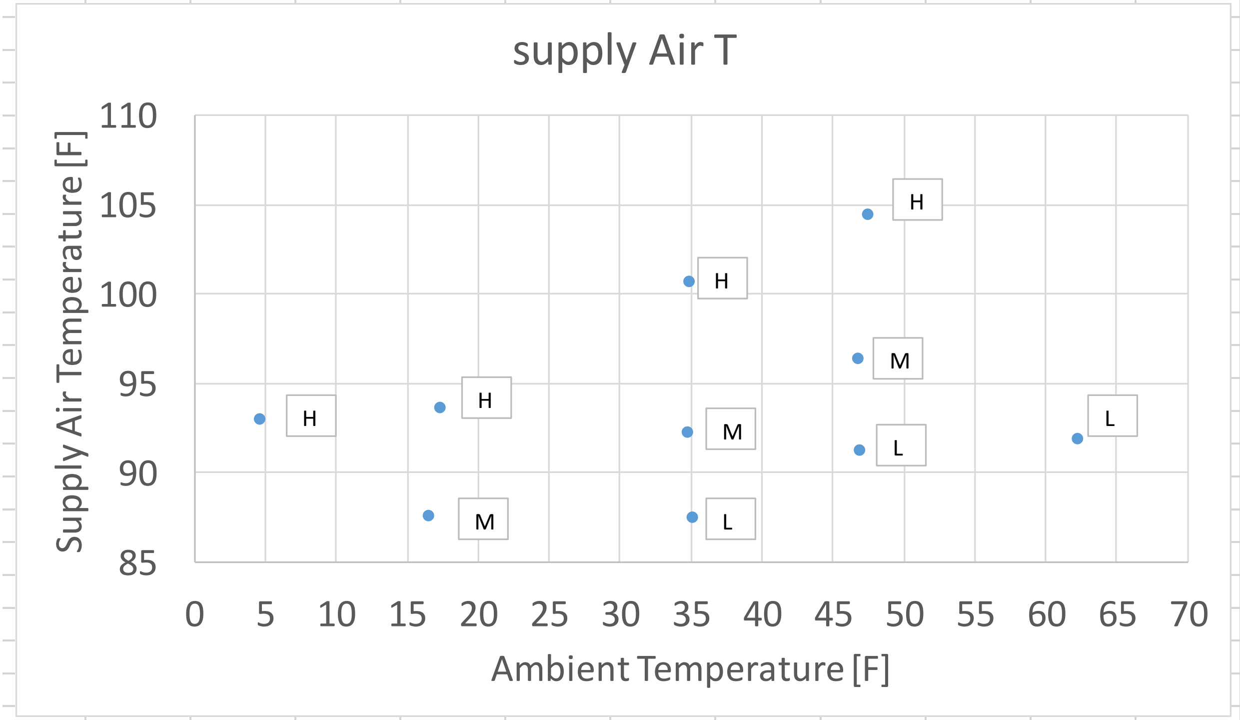
REFERENCE SLIDES

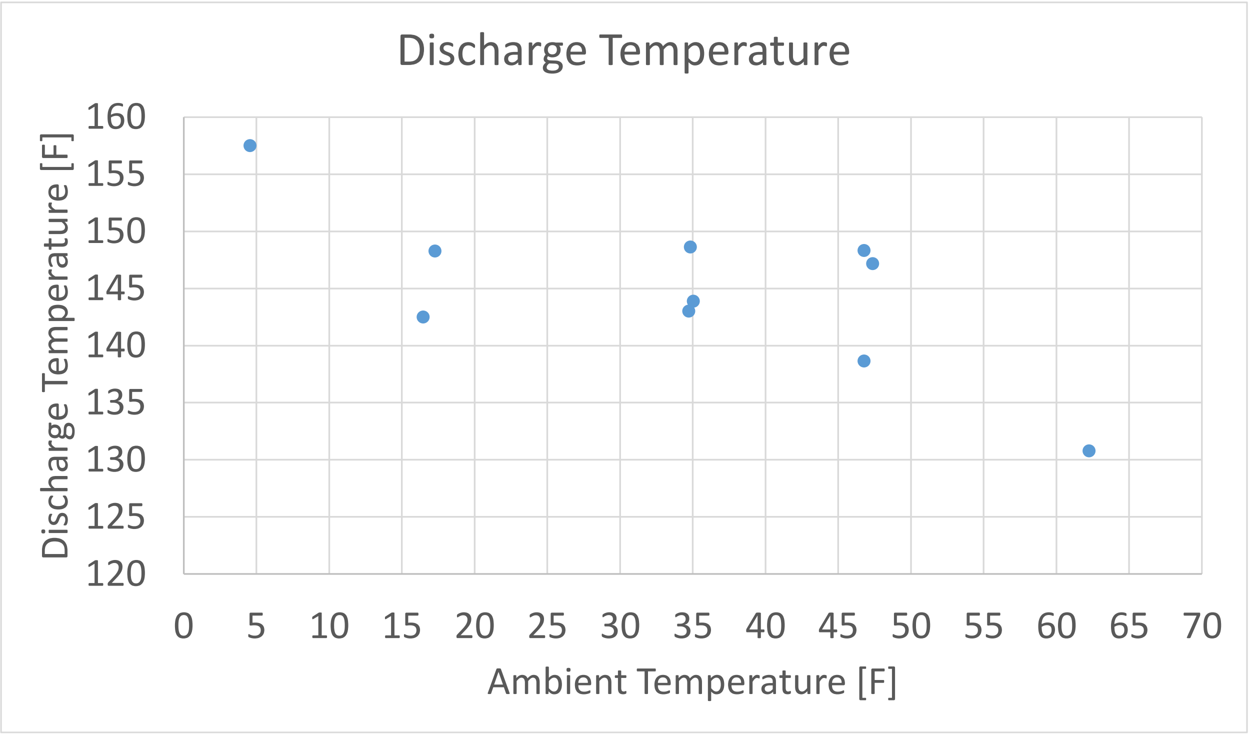
Project Budget

Project Budget: $500K (DOE)
Variances: NONE
Cost to Date: $120K
Additional Funding: NONE

Budget History					
FY 2021 (past)		FY 2022		FY 2023	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$200K	0	$200K	$100K	$100K	0

Measured Space Heating Performance -continued

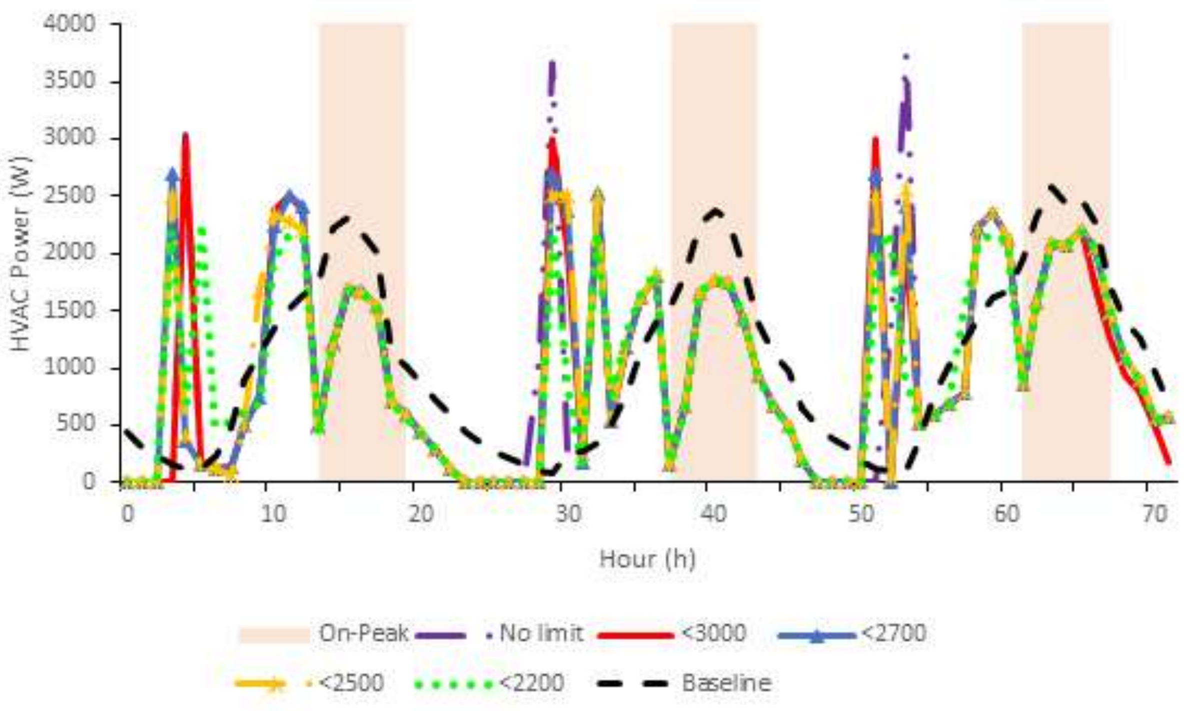




Supply air temperature > 90˚F (31 ˚ C) @-15 ˚ C

Discharge temperature is manageable, CCHP able to work down to lower outdoor temperatures.

Results of Peak Power Limiting in Summer



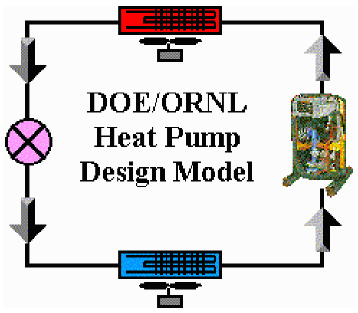
Peak power limiting avoids HVAC power spiking and slows down PCM charging – set the peak power threshold as a penalty upper limit of the MPC optimization.

	Baseline	No limit	<3000 W	<2700 W	<2500 W	<2200 W
Total Electricity Cost ($)	9.44	7.38	7.38	7.49	7.50	7.46
Cost Saving (%)	N/A	21.9	21.9	20.7	20.6	21.0
Peak Demand Reduction (%)	N/A	N/A	19.6	27.7	31.4	39.2

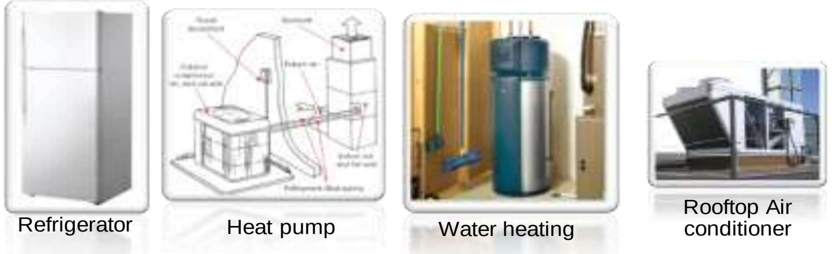
Conclusion

- Developed a multi-functional packaged vertical heat pump for multi-family buildings, capable of energy storage in PCM ceiling/wall to shift peak power consumption and reduce utility cost
- Demonstrated great potential for cold climate heating application; If rated at the compressor middle stage, having a rated capacity of 4.75 kW the resultant HSPF reached 10.0 (seasonal heating COP of 2.93); if rated at the compressor low stage, having a rated capacity of 3.52 kW, the packaged heat pump can provide > 100% rated capacity and a COP > 2.2 down to -15˚C ambient temperature.
- Extensively capable of water heating: in the most efficient simultaneous space cooling and water heating mode, the combined COP reached 8.79. The dedicated water heating mode, led to speedy water heating, worked down to -8.8˚C, faster and more efficient than stand-alone HPWHs.
- Developed a model-predictive supervisory control and conduct building energy simulations to predict energy savings and utility cost reductions.
- The control strategy has been tested using a co-simulation platform for a prototypical detached house in Indianapolis, IN. Test results showed that application of the proposed control strategy to the PCM-integrated heat pump could achieve cost savings of 24.2% in heating season, and 27.1% saving in cooling season.

Approach: Model-based equipment design and optimization– From Concept Design to Building Energy Simulation

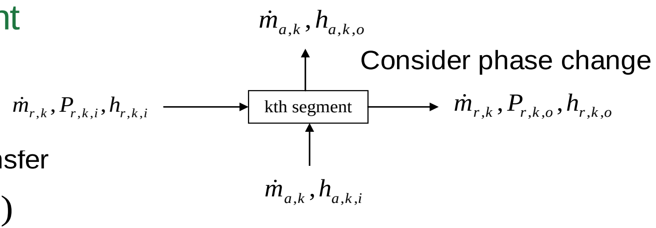


Extensive applications and complex system configurations in HVAC&R



Detailed Component Modeling

- Segment-to-segment modeling approach



Dry Coil Analysis Heat Transfer

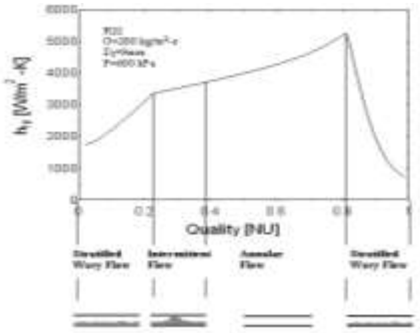
$$\dot{Q}_{max} = C_{min}(T_{h,i} - T_{c,i})$$

$$\varepsilon = 1 - \exp(-NTU)$$

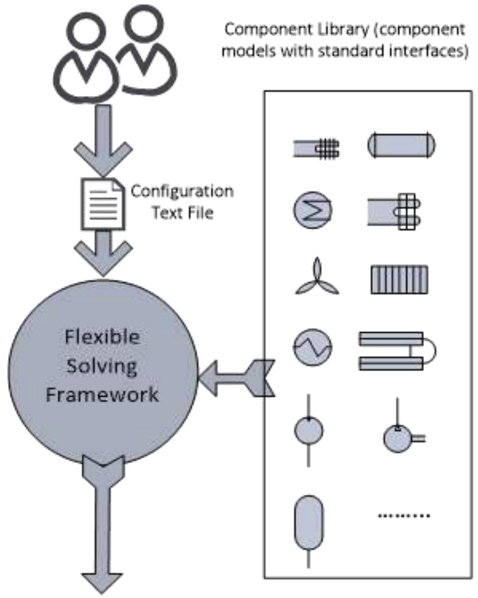
Wet Coil Analysis Heat & Mass Transfer

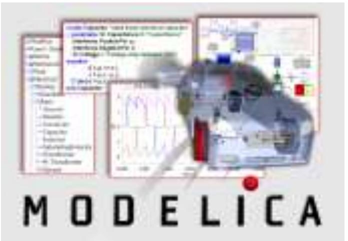
$$\dot{Q}_{max} = \dot{m}_a(h_{a,i} - h_{s,evap})$$

$$\varepsilon^* = 1 - \exp(-NTU^*)$$



Refrigerant side local flow-pattern-specific heat transfer and pressure drop calculation





Directly Export Components and systems

Generate Performance Curves

ORNL Building Equipment Model

Set Boundary Conditions

CFD

All connected.

Web interfaces – Google "ORNL HPDM" or "Heat Pump Design Model"