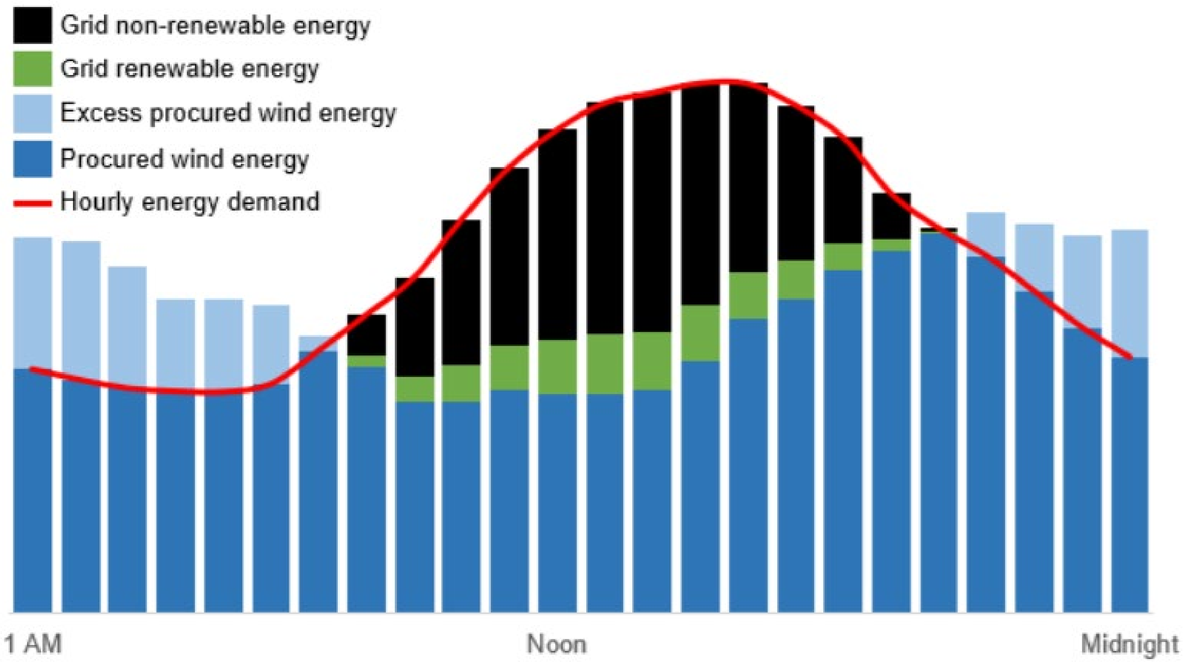
Wall Embedded Multi-Functional Heat Pump with Energy Storage systems For Grid-Responsive and Weather-Transactive Controls



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Project Overview

Timeline:
Start date: 08/01/2019
Planned end date: 02/28/2022
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

Budget:

	DOE funds	Costed	Cost share
FY20	200K	200K	0K
FY21	300K	50K	100K

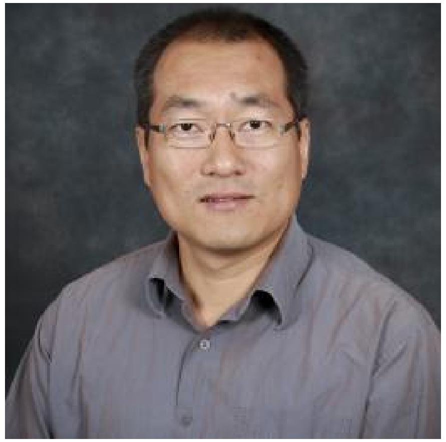
Partners:

- Emerson Climate Technologies
- University of Oklahoma

Project 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 IPLV > 19.0; HSPF > 11.0 and annual water heating COP > 4.0, operate down to -10F.
3. **Grid-responsive energy storage** to maximize use of renewable energy, shift peak load > 2 hours.

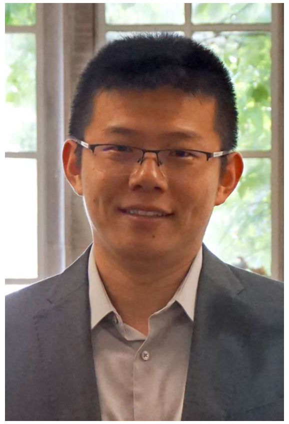
Team



Dr. Bo Shen (PI)
- System design
- Building energy simulation

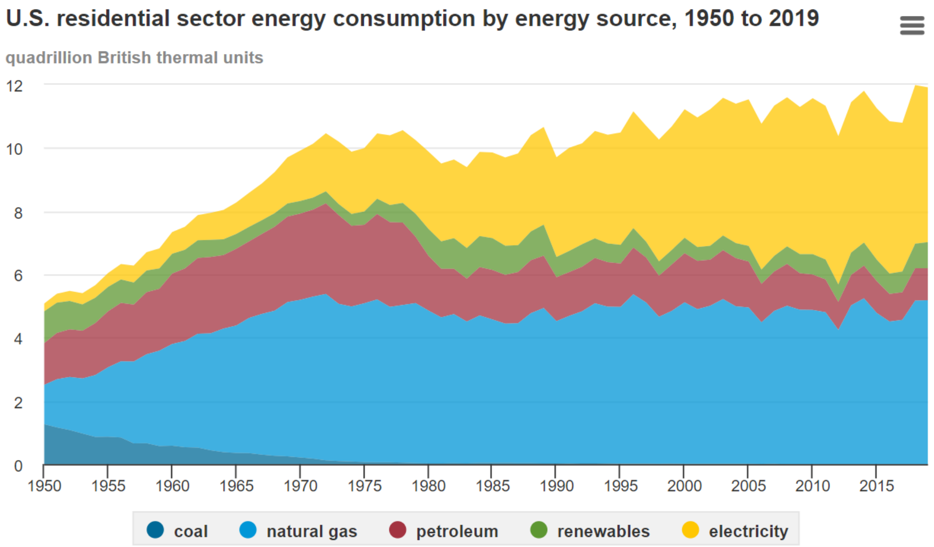
Dr. Zhenning Li
- Model and optimization
- Laboratory investigation

Drew Welch
Senior Lead HVAC Systems Engineer
- Develop 3-stage compressors for multi-family buildings
- Liquid desiccant latent storage



Dr. Jie Cai
Assistant professor at University of Alabama
- Develop grid-responsive,weather-transactive supervisory control

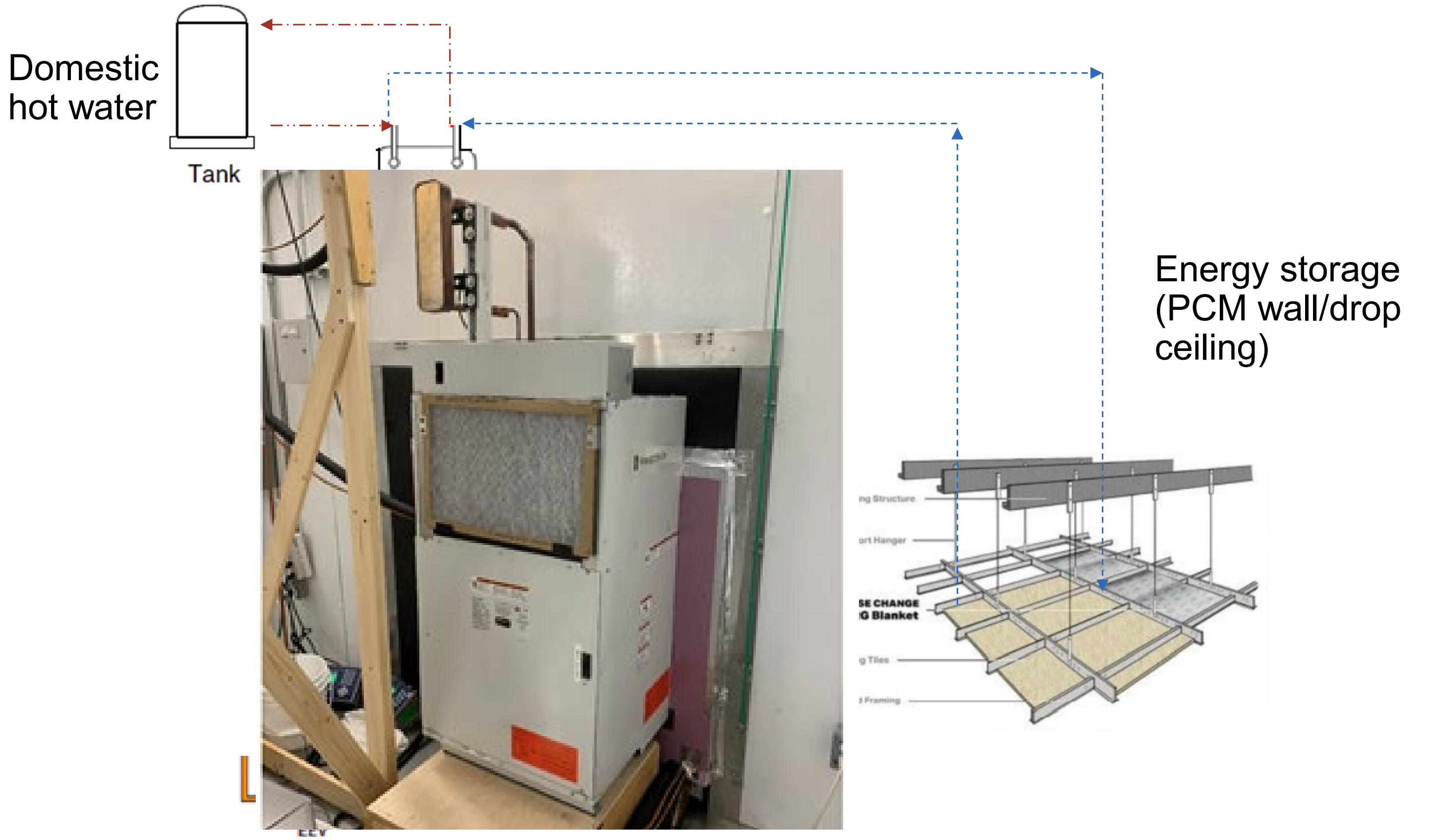
Challenge - Energy, Emissions and Equity (E3) Initiative



- 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.

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

The proposed project will develop an innovative wall embedded air-source integrated heat pump (WAS-IHP) solution capable of space cooling, space heating, water heating (WH), ventilation, and dehumidification. 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, with a two-level controller for weather-forecast transactive control.

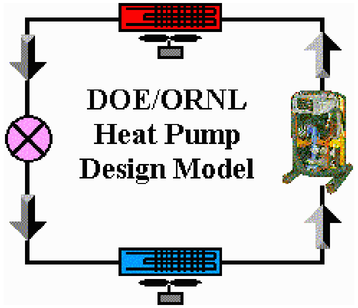


Five Modes:

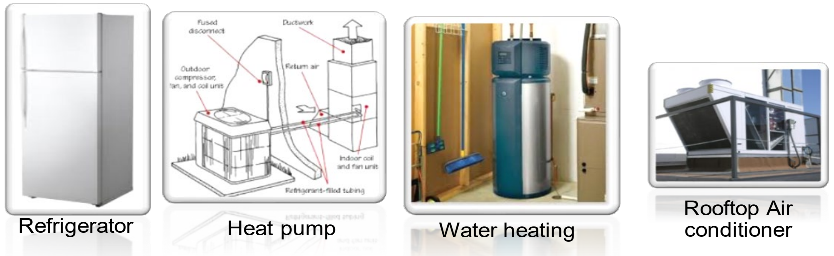
- Space cooling
- Space heating
- Cooling energy storage
- Water heating with outdoor air source
- Water heating with indoor air source

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

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

Consider phase change

$\dot{m}_{a,k}, h_{a,k,o}$

$\dot{m}_{r,k}, P_{r,k,i}, h_{r,k,i} \rightarrow$ kth segment $\rightarrow \dot{m}_{r,k}, P_{r,k,o}, h_{r,k,o}$

$\dot{m}_{a,k}, h_{a,k,i}$

Dry Coil Analysis Heat Transfer

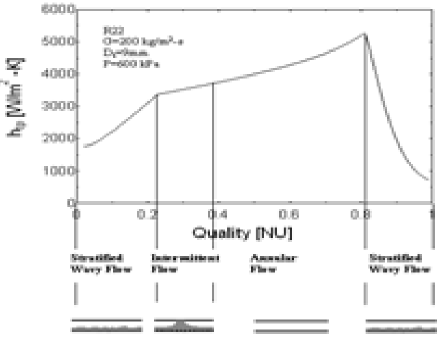
$$\dot{Q}_{max} = C_{min}(T_{h,i} - T_{c,i})$$

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

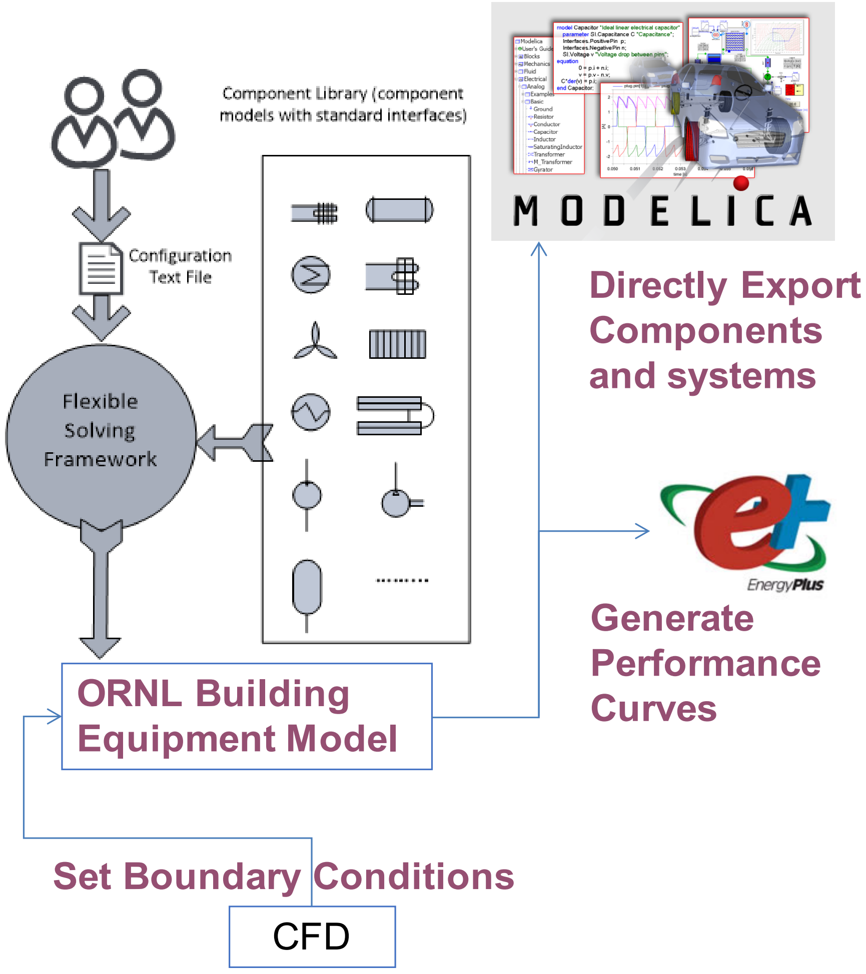
Wet Coil Analysis Heat & Mass Transfer

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

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



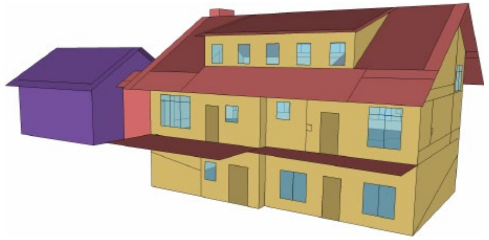
Refrigerant side local flow-pattern-specific heat transfer and pressure drop calculation

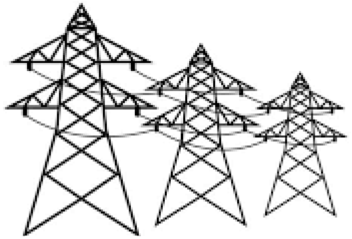


All connected.

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

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



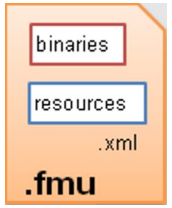


Grid signals

Weather forecast

Building Envelope + ASIHP

FMU Export of EnergyPlus



EnergyPlus fmu

Zone temperature + ASIHP operation status

PCM-to-room HX rate + control commands

Predictive Controller + PCM ceiling

Functional Mock-up Interface

PCM model:
- Multi-node enthalpy method
- Piece-wise linear map between enthalpy and temperature
- Natural convection for room-to-PCM HX
- Effectiveness-NTU method for ASIHP charging rate calculation

Controller design
- Mixed-integer convex programming algorithms for control optimization
- Data-driven control models for ASIHP, PCM and building loads

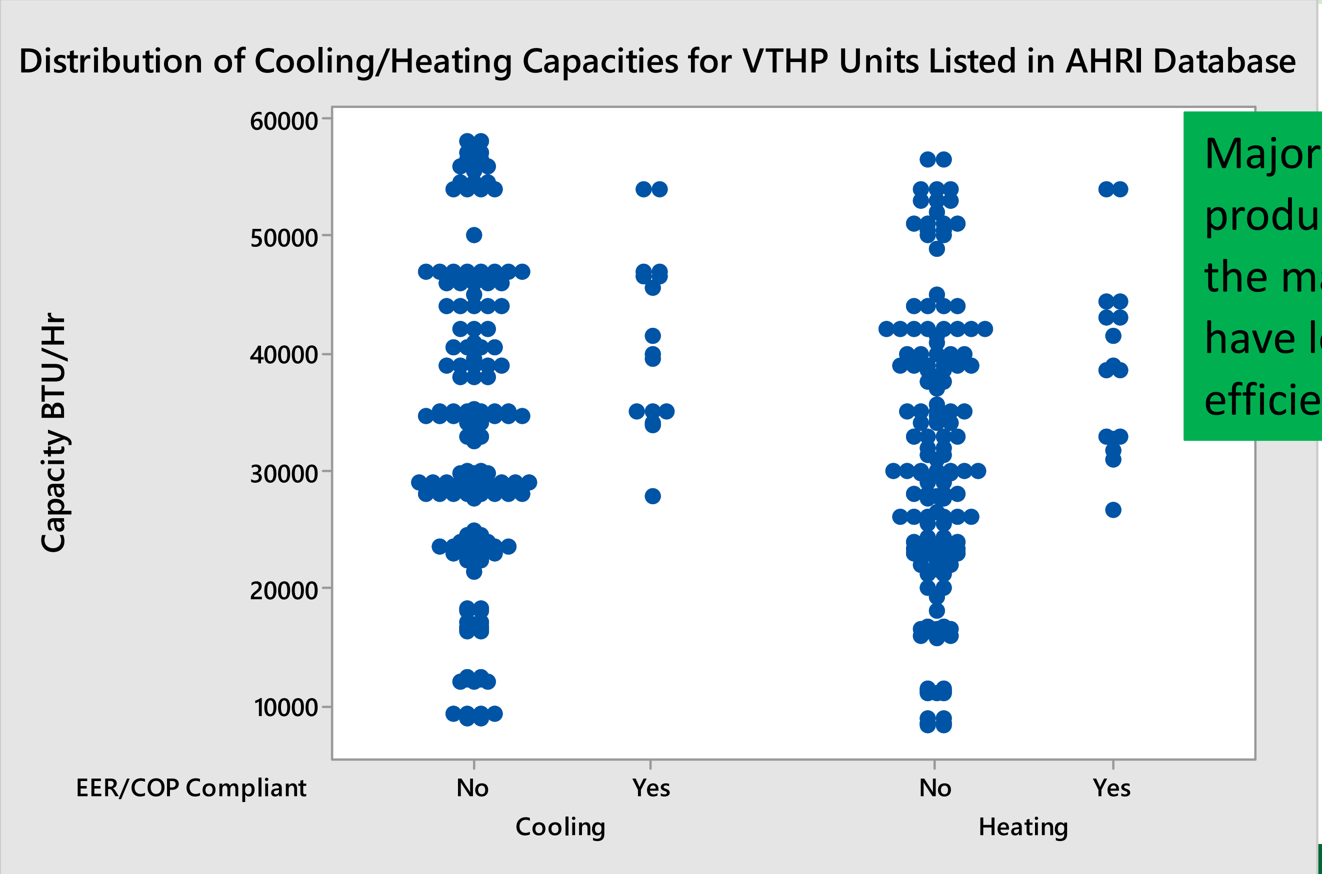
Project impact

- Develop high end, cost-effective packaged heat pump: Achieve IPLV > 19.0 (versus 14.0 mainstream products) and HSPF > 11.0, and integrated water heating annual efficiency > 4.0, to save annual energy up to 40%, than a baseline suite of equipment
- Multifunctional unit as the charging station for grid-responsive control and active PCM energy storage strives to carbon free buildings.
- 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.

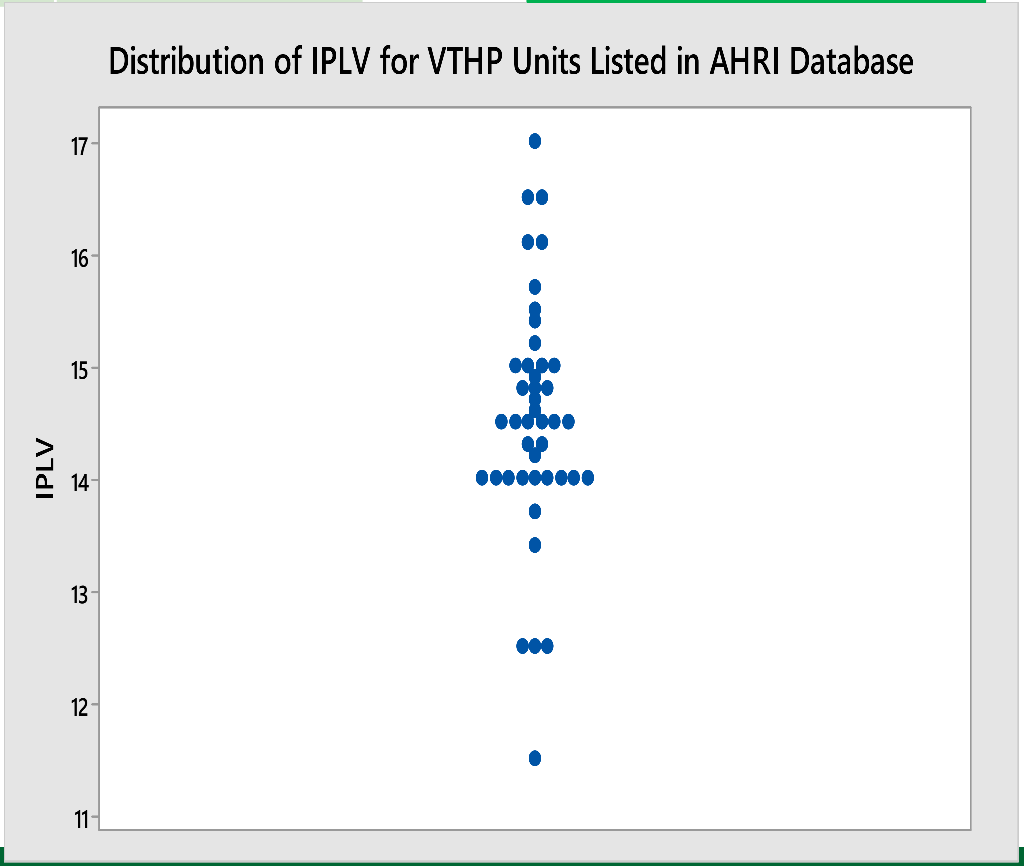
Progress: Complete technology assessment- Efficiency and Capacity Requirements of Single Packaged, Vertical Terminal AC/HP (VTHP)

Equipment Type	Cooling Capacity	Sub-Category	Efficiency Level	Compliance Date
Single package vertical air conditioners and single package vertical heat pumps single-phase and three-phase	< 65,000 BTU/hr	AC	EER = 11.0	Sept 23, 2019
		HP	EER = 11.0 COP = 3.3	

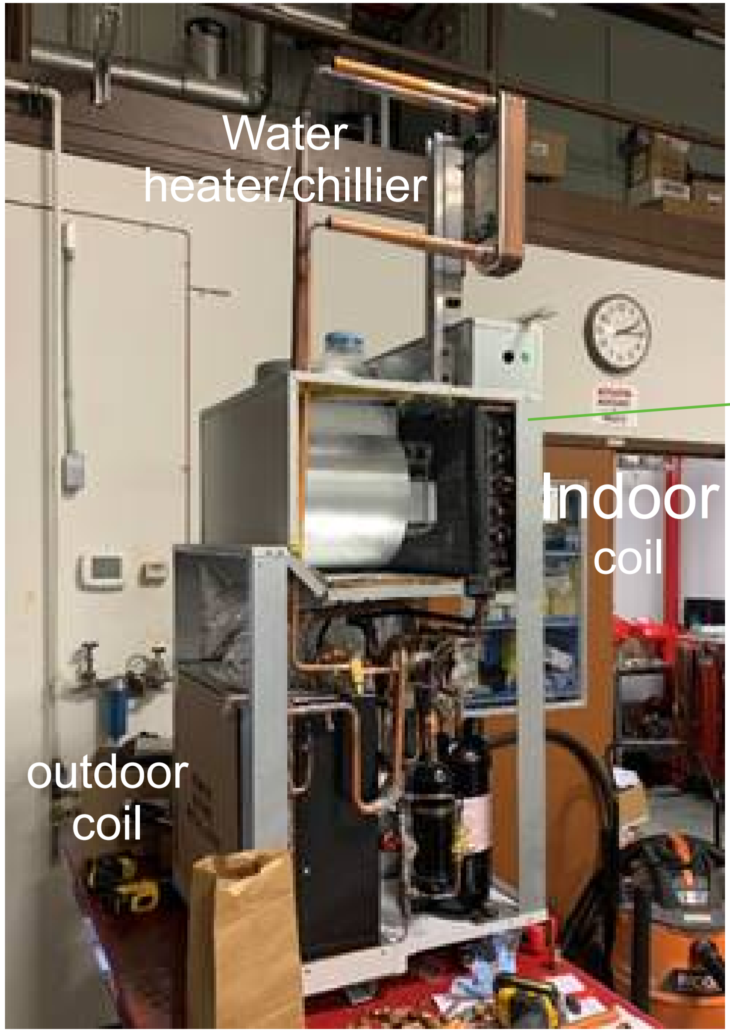
- Highest available IPLV is 17.0
- Majority have IPLVs around 14.0 to 15.0



Majority of products on the market have low efficiency



Progress: Complete the first prototype –vertical packaged multi-functional heat pump

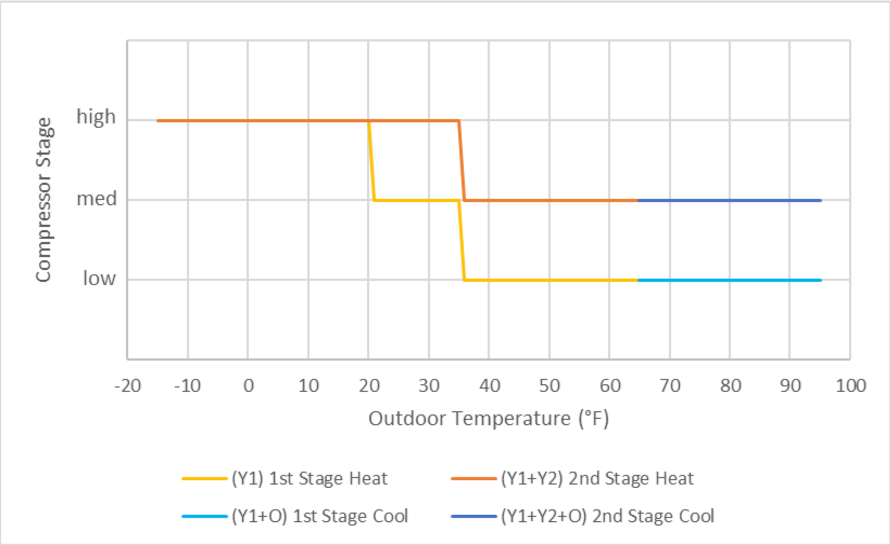


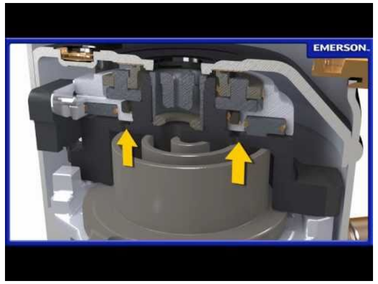
Ideal for building retrofit

Reconfigure a vertical packaged unit on the market (Friedrich)

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



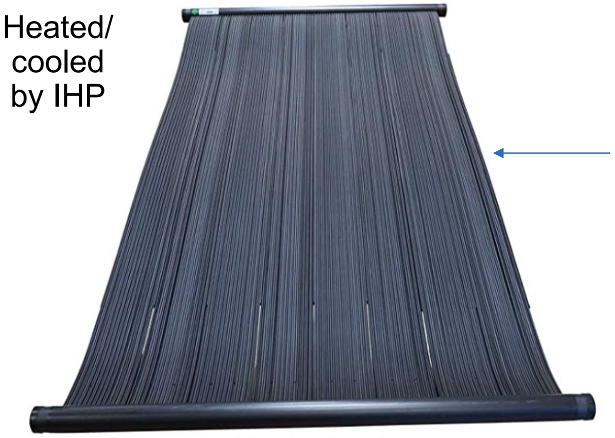


Mechanical capacity modulation

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

Progress: Fabricate a phase change heat exchanger in wall/drop ceiling

Heated/
cooled
by IHP



Bio PCM blanket

- 1-ton unit conditions 600 ft^2 living area
- 55 BTU/ft^2 * 600 = 33000 Btu
- Shift 2.75 peak heating hours

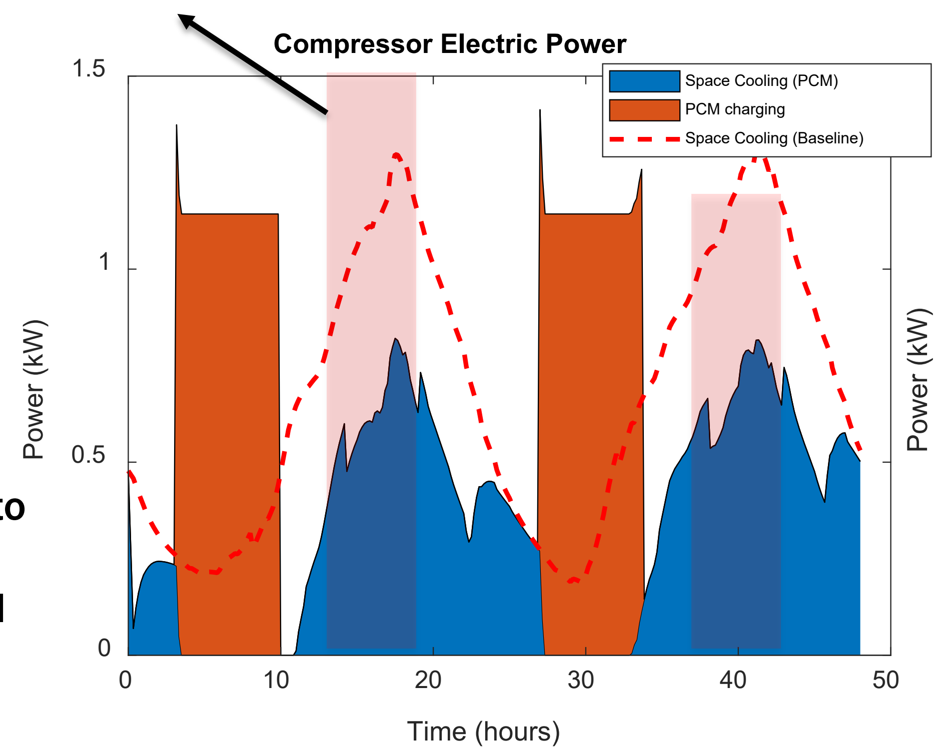
https://phasechange.com/enrgblanket/

Progress: significant savings and carbon reductions proven by EnergyPlus Simulations

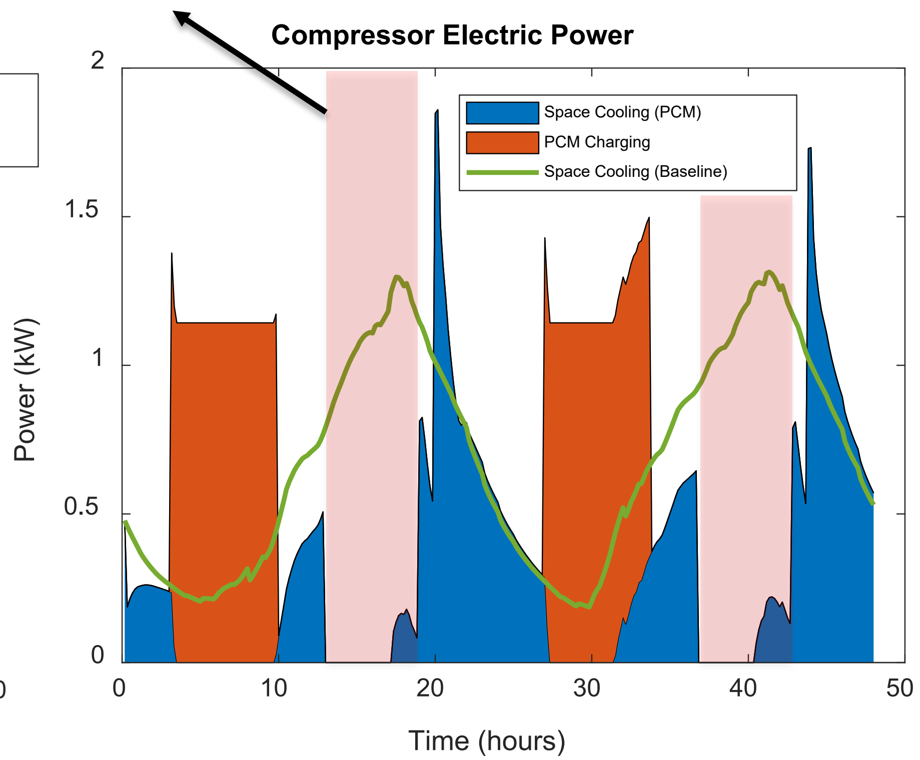
TOU rate schedules
- Georgia Power: Time of use – residential without demand
- Energy Charge
  - ✓ On Peak (2 PM to 7 PM) – $0.203 per kWh
  - ✓ Off Peak (7 PM to 2 PM) – $0.05 per kWh

PCM control schedule
- 4 kW PCM charging from 3 AM to 10 AM
- Constant COP of 3.5 during PCM charging

Baseline case
- Constant zone temperature setpoint (75˚F) without PCM ceiling
- 2-ton single-speed DX cooling coil



Case I: control constant 75˚F
-Achieve 23% cost reduction via reducing consumption during on-peak hours



Case II: allow rising to 80˚F during on-peak hours
-Achieve 52% cost reduction via eliminating consumption during on-peak hours

Progress: Laboratory set up in environmental chambers

Indoor Side

Outdoor Side

- Three power meters
- A thermostat to turn ON/OFF unit
- An EXV controller
- Two relays to control a four way valve and a liquid line solenoid valve

Labview (National Instrumentations INC)
Data Acquisition Cart

Stakeholder Engagement – Close Collaboration with Emerson

- Emerson is keen to enter their 3-stage scroll compressors into the market of multi-family buildings.
- Funded for Phase II by lab CRADA 2021: Emerson will develop a liquid-desiccant based latent energy storage technology, which will be integrated to the packaged system, in addition to the sensible PCM energy storage.

Remaining Project Work

- Validate the first laboratory prototype.
- Apply improvements and verify the improved prototype towards the project goals.
- Develop supervisory control responding to grid signals and weather forecast.
- Conduct a field demonstration in 2023.

Thank you

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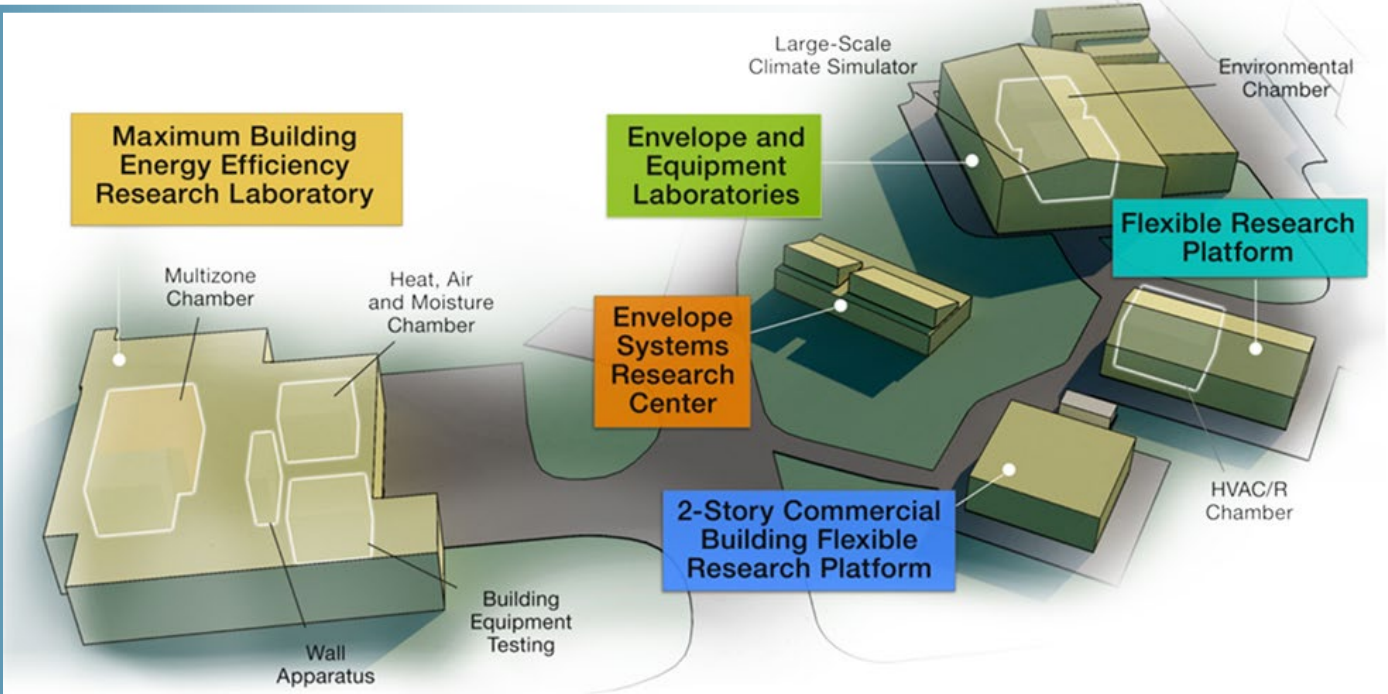

ORNL's Building Technologies Research and Integration Center (BTRIC) has supported DOE BTO since 1993. BTRIC is comprised of 50,000+ ft^2 of lab facilities conducting RD&D to support the DOE mission to equitably transition America to a carbon pollution-free electricity sector by 2035 and carbon free 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: $200K
Additional Funding: NONE

Budget History					
08– FY 2020 (past)		FY 2021 (current)		FY 2022 – 02/2022	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$200K	0	$300K	$100K	0	0

Project Plan and Schedule

Task	Subtask		Assigned to	Q1	Q2	Q3	Q4	Q5	Q6
1		Simulation-driven design and optimization, market assessment							
	1.1	Market assessment and technologies survey	Emerson						
	1.2	Building energy simulations	ORNL						
	1.3	Component performance and cost modelling	ORNL						
	1.4	System design and optimization	ORNL						
	1.5	Structure design	ORNL						
Milestone 1		Complete system design report	ORNL			Go/No-Go			
2		Development of technologies at component level							
	2.1	Develop a phase separation mechanism in combined space heating and water heating mode	ORNL						
	2.2	Develop an innovative defrosting mechanism	ORNL						
	2.3	Pretreat outdoor coil surface with super hydrophobic costing or chemical etching to slow frost growth	ORNL						
	2.4	Develop PCM panels with better heat conduction and capacity	ORNL						
Milestone 2		Verify component level improvements	ORNL						
3		Develop multi-objective, grid-responsive and weather-forecast based transactive control							
	3.1	Lower-level controller design and implementation	U Oklahoma						
	3.2	Supervisory-level control synthesis and validation	U Oklahoma						
Milestone 3		Complete development of lower-level control strategy	U Oklahoma						
Milestone 5		Complete development of supervisory-level control strategy	U Oklahoma						
4		Construct Proposed System							
	4.1	Component Specification and Purchase	Emerson						
	4.2	Prototype WAS-IHP system construction	ORNL						
	4.3	Data acquisition system and control implementations	ORNL						
Milestone 4		Construct the first lab prototype	ORNL						
5		Performance Testing in various modes	ORNL						
6		System Design Evaluation							
	6.1	Design evaluation and system improvements	ORNL						
	6.2	System modifications	ORNL						
	6.3	Test improved system	ORNL						
Milestone 6		Complete system tests and verify performance metrics	ORNL			Go/No-Go			
7		Final Report (phase I)							
Milestone 7		Submit the final report (Phase I) to the DOE sponsor	ORNL						