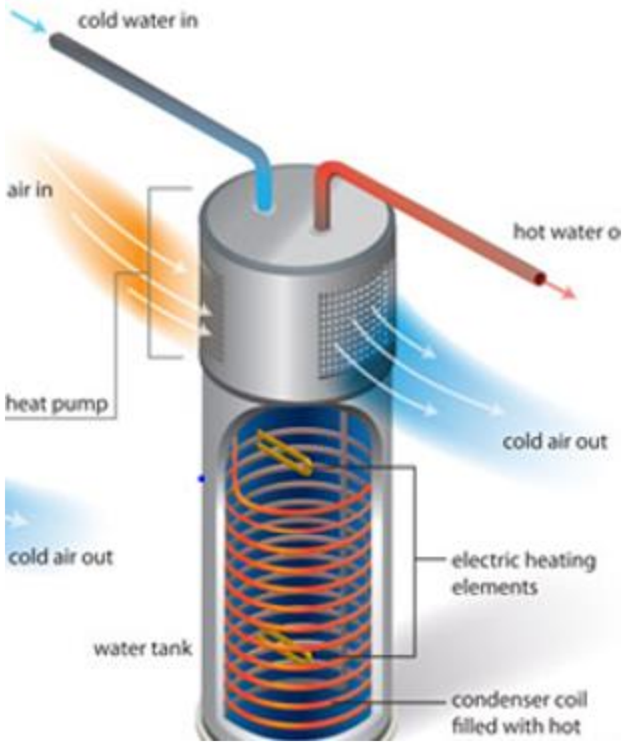
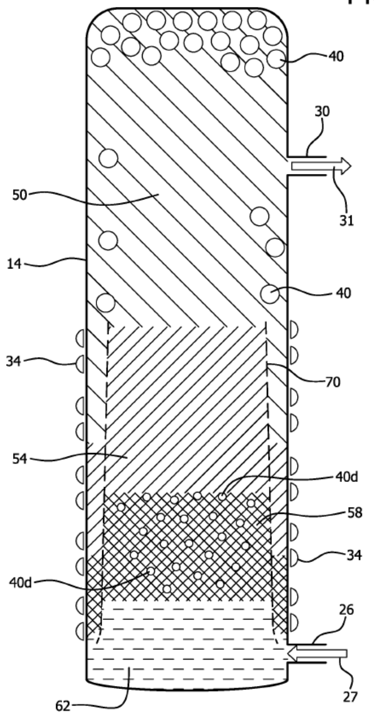
U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Flexible HP WH with embedded energy storage



Patent Application Publication Mar. 16, 2023 Sheet 5 of 17 US 2023/0082570 A1

FIG. 5

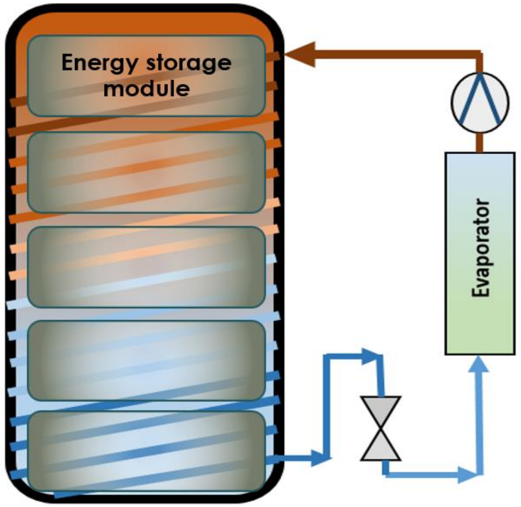


Oak Ridge National Lab
PI: Kashif Nawaz (Senior R&D Staff)
Presenter: Jian Sun (R&D Staff)
(865) 241-0972
WBS 03.02.02.36, FY 21 AOP Water Heating R&D

Project Summary

Objective and outcome

- The project is focused on the development and performance optimization for next-gen HPWH with embedded energy storage solution.
- Demonstration of cost-effective technology to enhance the performance through selection and deployment of energy storage medium.



OAK RIDGE National Laboratory

AO Smith Innovation has a name.

Team and Partners

Oak Ridge National Lab
Kashif Nawaz, Joe Rendall, Jian Sun, Ahmed Elatar, Jamieson Brechtl, Keju An, Xiaoli Liu

A.O. Smith

Steven Memory, Timothy Rooney

Stats

Performance Period: Dec 2020- June 2024

DOE budget: $300k/year, Cost Share: $250k

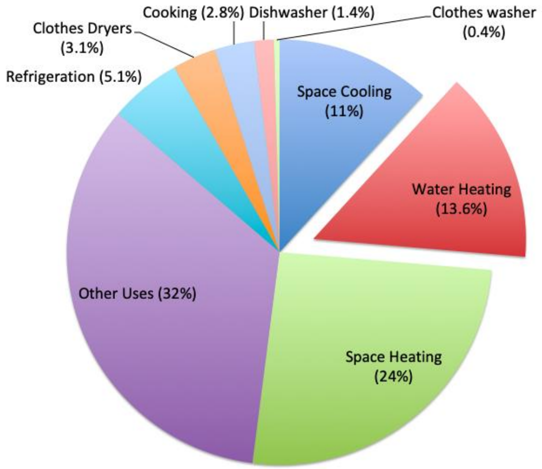
Milestone 1: Alpha prototype enables at least 20% higher capacity (Oct. 2021)

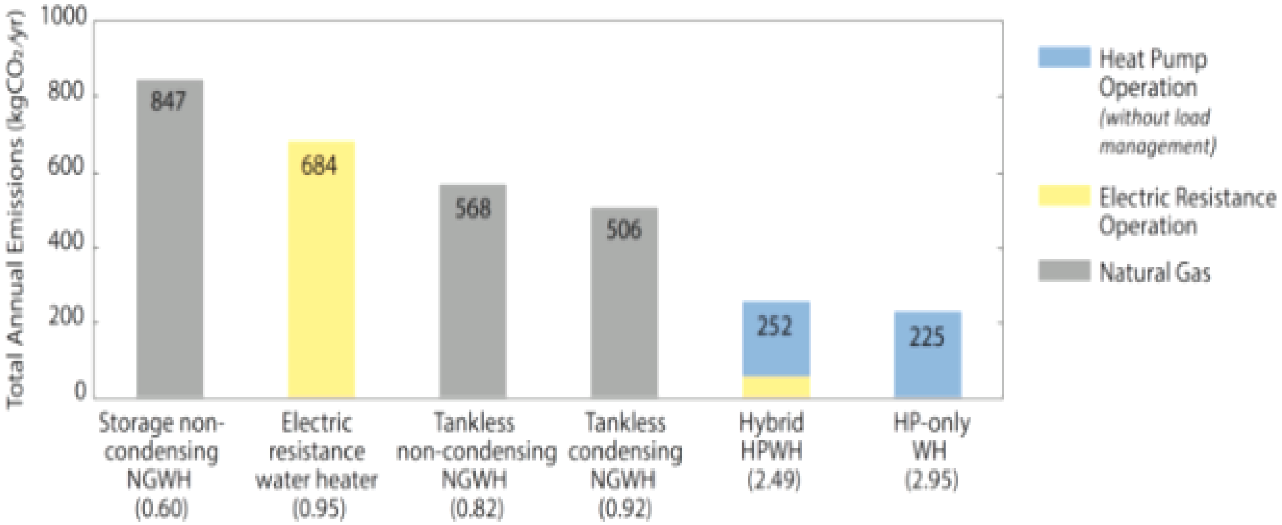
Milestone 2: Lab demonstration of Betha prototype with at least 5% improvement (Oct. 2022)

Milestone 3: Field demonstration of Epsilon prototype for more than 4 hours load shifting (Ongoing)

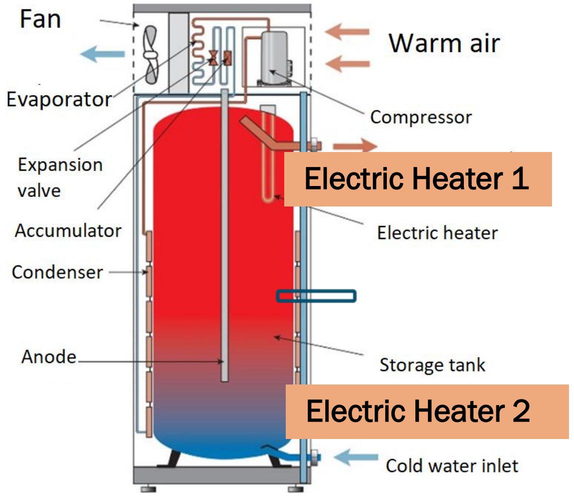
Problem

- Space constraints in some applicaitons
- HPWH are unable to meet the demand through the base-operation (HP) requiring ancillary heat through electric heaters (Hybrid configuration)
- Potential solutions through the deployment of suitable thermal energy storage medium are required for cost-effective load shifting.





Annual emissions from water heating technologies



https://www.nrdc.org/experts/pierre-delforge/electric-heat-pumps-can-slash-emissions-california-homes

Alignment and Impact

- A highly flexible water heating technology
  - Improved capacity (Higher FHR)- 20% higher capacity with same footprints
  - Reduced carbon emission (~60% compared to electric resistive and 10% compared to hybrid HPWH)
  - At least 30% cost saving compared to state of the art
- Enabling development for Grid-interactive Efficient Buildings
  - At minimum 4-hours of load shifting capability for medium and higher usage patterns
  - Embedded energy storage solution (no engagement of additional vendors)
  - Reduced required maintenance due to compact design
- Implications for additional processes
  - Residential air cooling/heating, refrigeration, Process water heating
- At least <u>250TBtu energy saving </u>in water heating technology.
  - Aligned with BTO goal to develop energy efficient technology to cause 45% energy saving by 2030 compared to 2010 technologies with at least 40% reduction in CO_2 emissions.

Approach

Phase 1
Market assessment

Phase 2
Preliminary evaluation

Phase 3
System optimization
& Demonstration

Phase 2- Preliminary evaluation

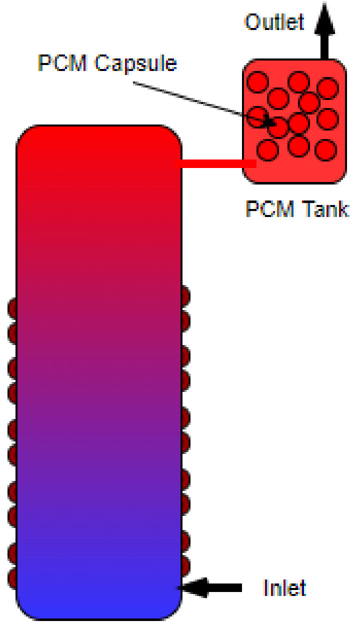
Platform selection → Selection of storage materials → Deployment strategies

Phase 3- System optimization and demonstration

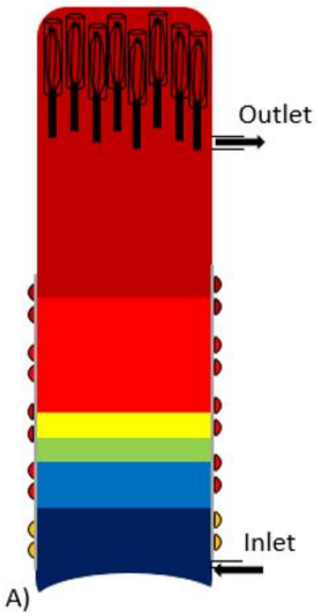
Alpha prototype-developments and testing → Process control and optimization → Beta prototype-development field evaluation

Approach

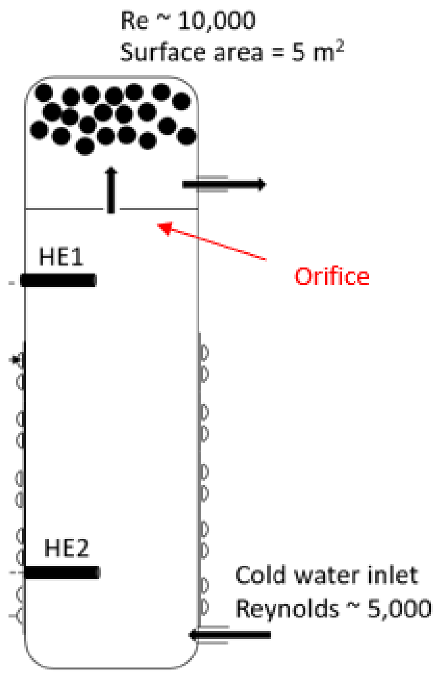
- Experimental validation of PCM heat transfer
- Prototyping to reduce component number while keeping heat transfer performance high



Alpha



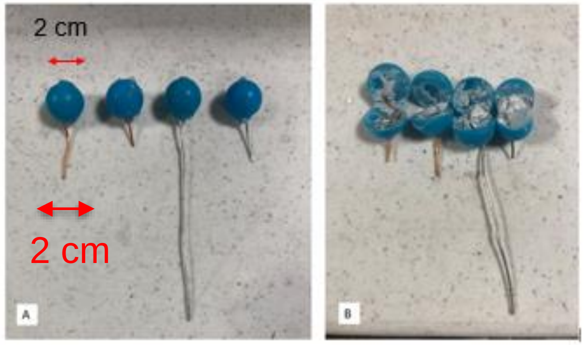
Beta

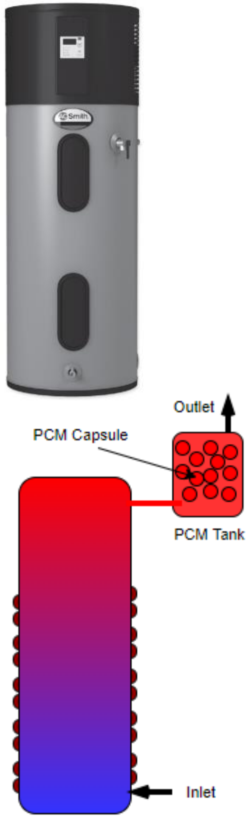


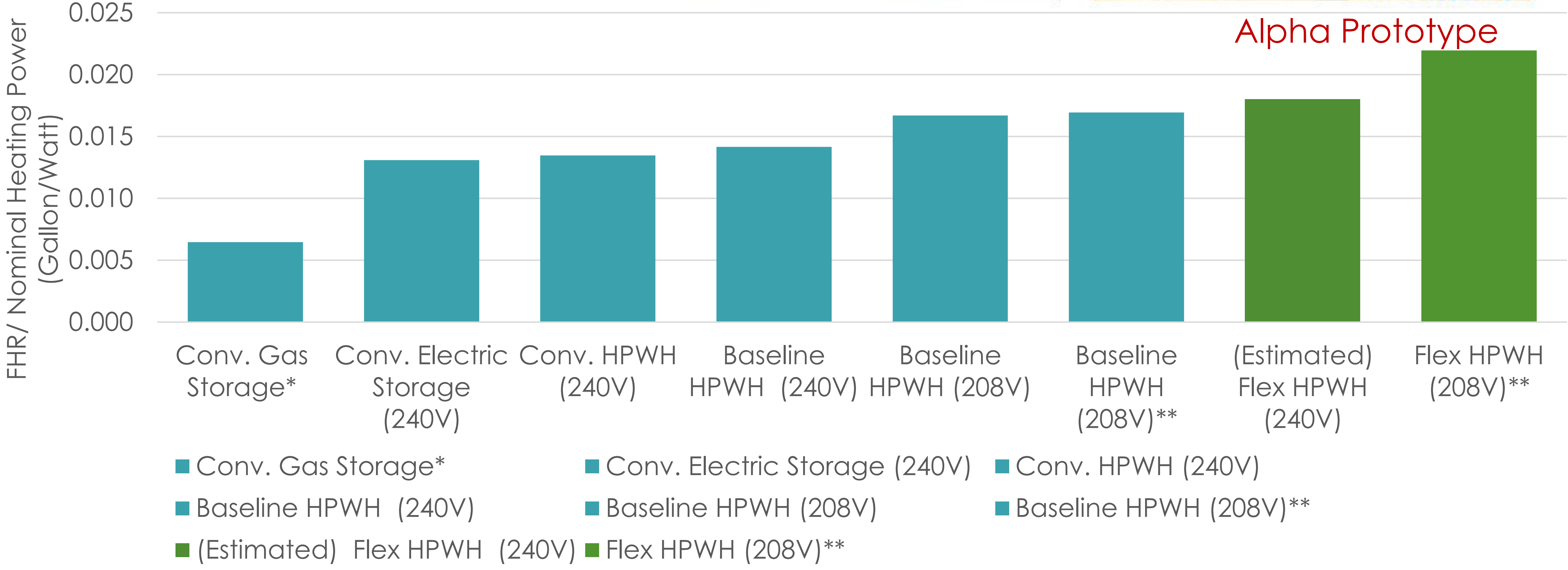
Epsilon

Progress: Experimental Prototype Alpha

- Higher FHR by 30%
- Best FHR/Nominal heating power
- Large Surface area on spheres
- Heat losses significant (UEF failed)

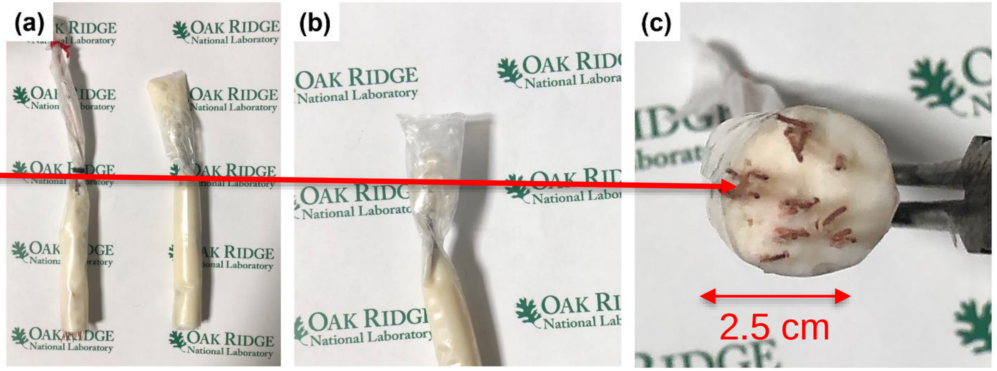


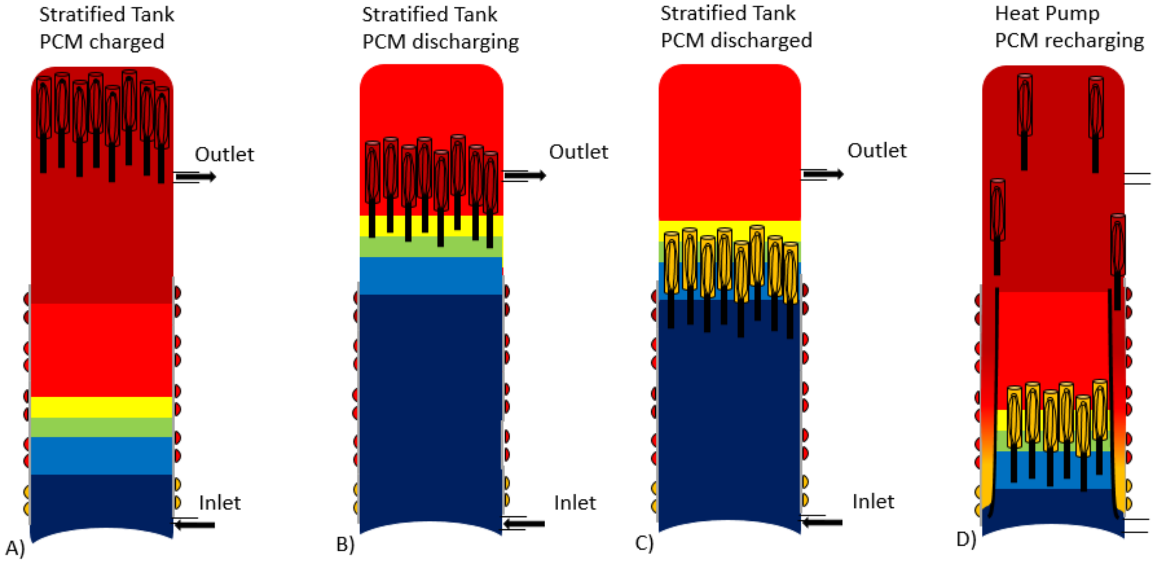


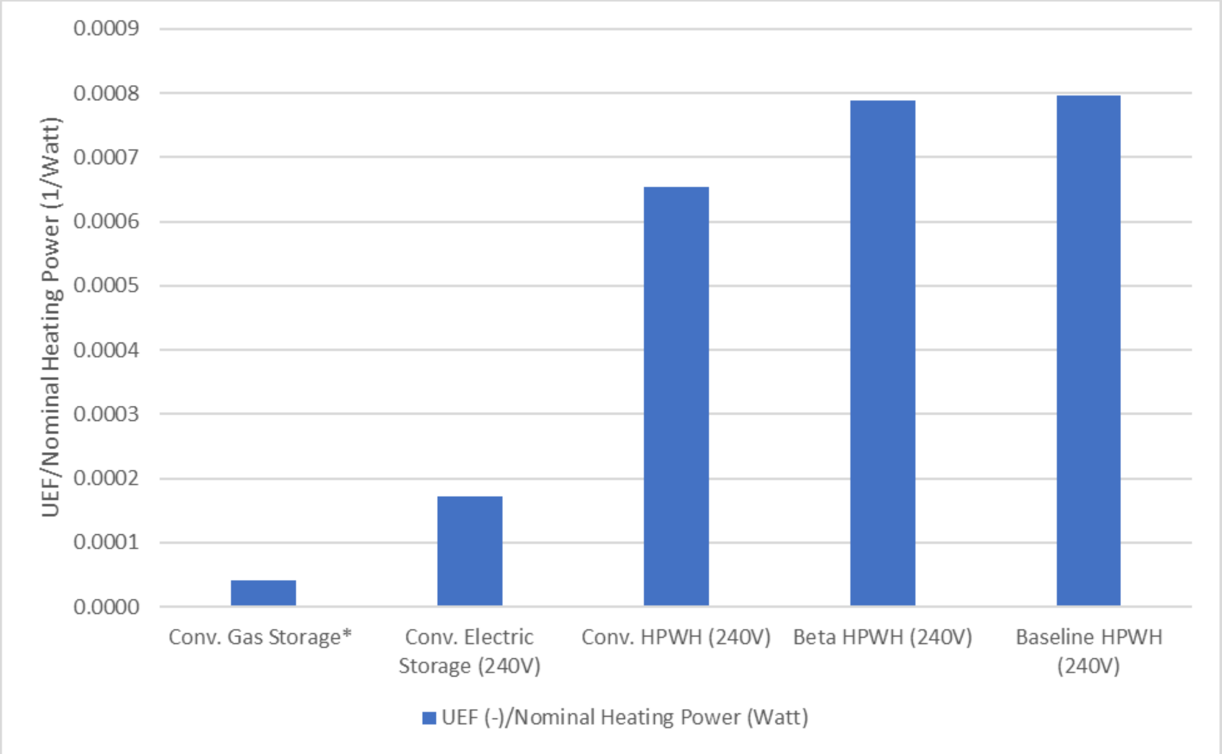


Progress: Experimental Prototype Beta

- Few capsules
- Distributed internal fins
- Lower heat losses (passed UEF)
- No improvement to FHR

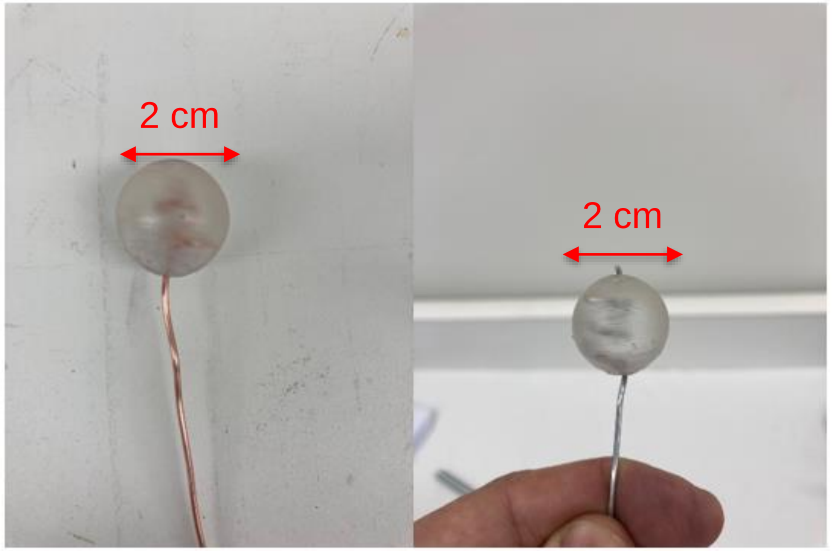


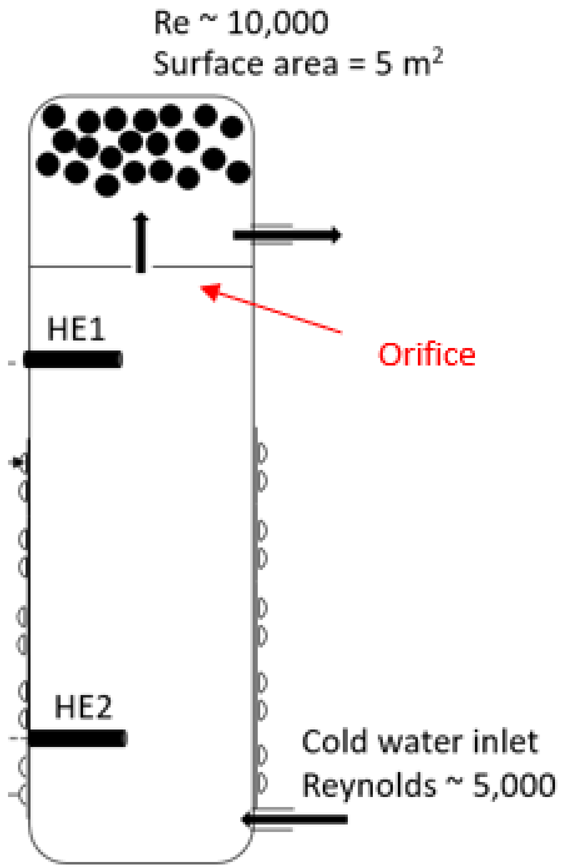




Progress: Epsilon Design Updates

- Design has large surface area and high Reynolds number
- 3D printed flexible allow for density tuning of the capsules
- Discussing with manufacturers for mass production of the capsules



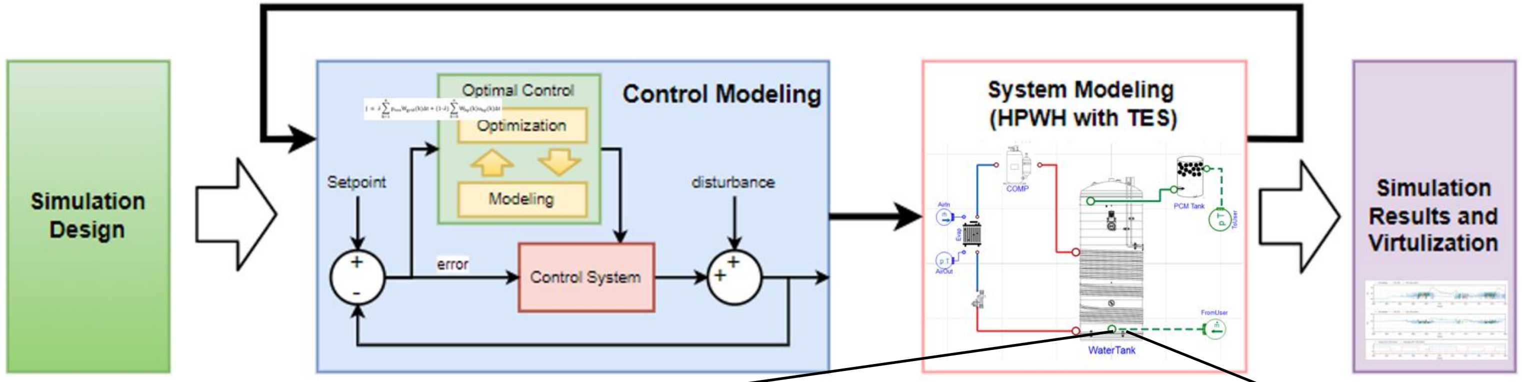


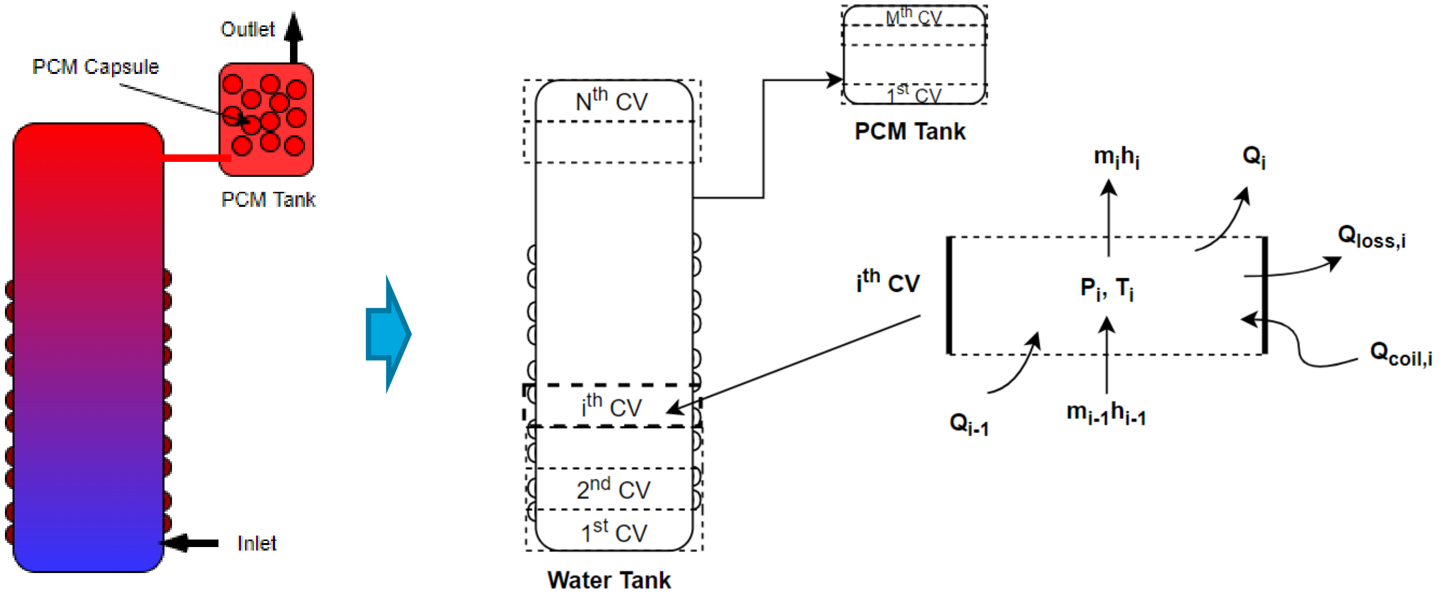
Hot water heater technology	Nominal storage (gallons)	FHR Rating	UEF Rating	Reynolds Number	Surface Area (m^2)
Baselined HPWH (208 V)	50	60.1			
Baselined HPWH* (208 V)	50	61	3.90		
Baselined HPWH (240 V)	50	69.2	3.63		
Prototype Alpha HPWH* (208 V)	56	79	2.78	10,000	5
Prototype Beta HPWH (240 V)	50	69.0	3.86	250	3.2
(*Estimated*) Epsilon HPWH (240 V)	**50**	***75***	***3.5***	**10,000**	**5**

Development of Model-Based Co-simulation Platform

Inputs for System Model

- Water draw schedule
  - ✓ Flow
  - ✓ Temperature
- Ambient conditions
- Parameters
  - ✓ Rated performance of HP
  - ✓ Tank geometry





Water Tank Model

$$0 = m_{i-1} - m_i$$

$$m_i C_{p,i} \frac{dT_i}{dt} = (m_{i-1}h_{i-1} - m_i h_i) + Q_{coil,i} - Q_{loss,i} + s_i(Q_{i-1} - Q_i)$$

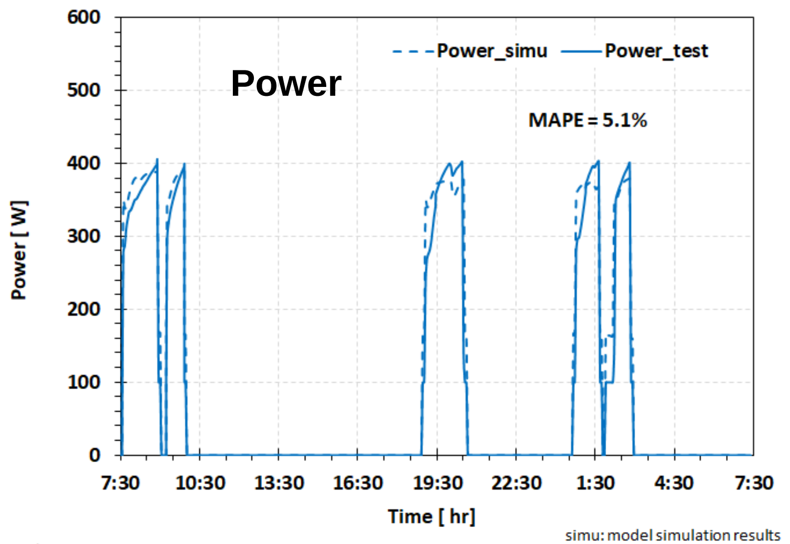
$$0 = (p_i - p_{i+1}) + dp_{f,i} - \rho g z_i$$

PCM Tank Model

$$m_i C_{p,i} \frac{dT_i}{dt} = (m_{i-1}h_{i-1} - m_i h_i) + Q_{pcm,i} - Q_{loss,i} + (Q_{i-1} - Q_i)$$

$$m_{pcm,i} C_{pcm,i} \frac{dT_{pcm,i}}{dt} = Q_{pcm,i} = \frac{\lambda_i A_i}{\Delta z}(T_{pcm,i} - T_i)$$

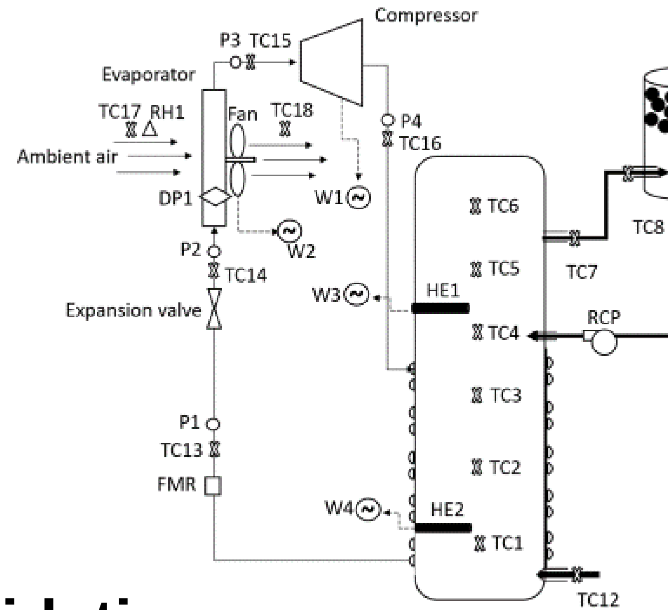
Simulation Results

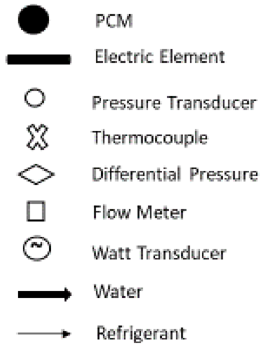


Power: heat pump power consumption

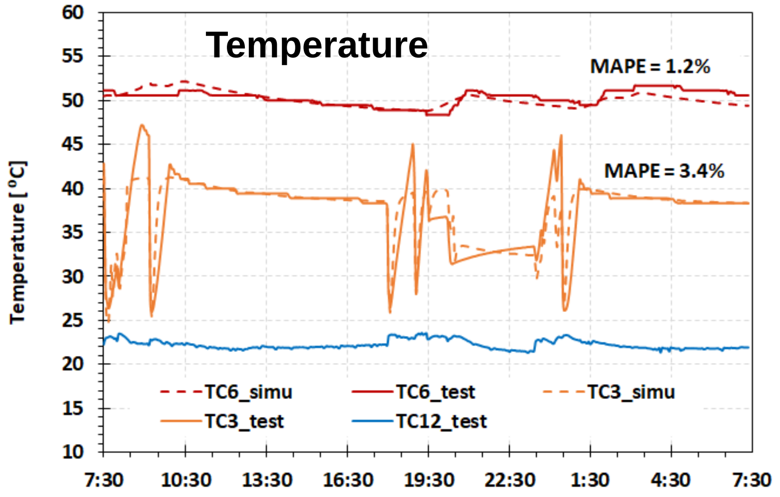
simu: model simulation results
test: lab test results

Model Validation



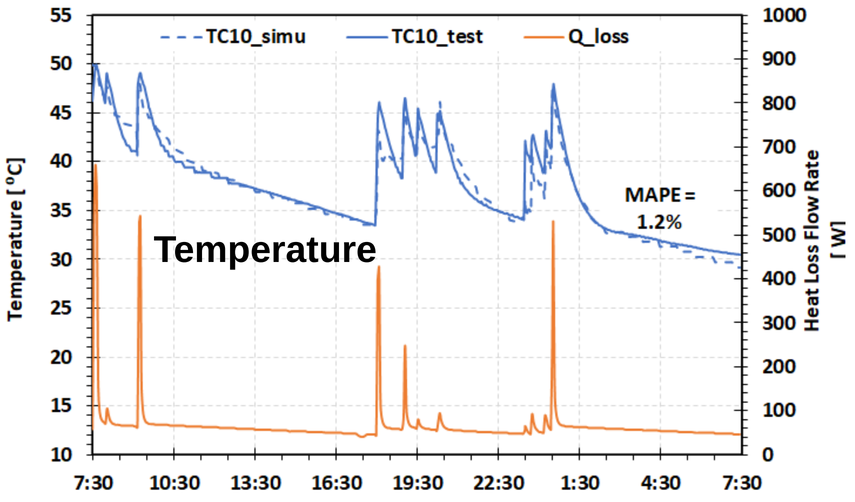


DP1	Evaporator Air
FMR	Mass Flow Meter Refrigerant
FMW	Volumetric Flow Meter Water
P1	Inlet Expansion Valve
P2	Inlet Evaporator
P3	Inlet Compressor
P4	Inlet Condenser
RCP	Recirculation Pump
RH1	Evaporator Inlet
TC1	Lowest HPWH Tank
TC2	Low-Mid HPWH Tank
TC3	Mid-Low HPWH Tank
TC4	Mid-High HPWH Tank
TC5	High-Mid HPWH Tank
TC6	Highest HPWH Tank
TC7	Outlet HPWH Tank
TC8	Inlet PCM Tank
TC9	Middle PCM Tank
TC10	Outlet PCM Tank
TC11	Recirculation PCM Tank
TC12	Inlet Cold Water
TC13	Inlet Expansion Valve
TC14	Inlet Evaporator
TC15	Inlet Compressor
TC16	Inlet Condenser
TC17	Inlet Evaporator Air
TC18	Outlet Evaporator Air
W1	Compressor
W2	Fan
W3	Higher heating element
W4	Lower heating element



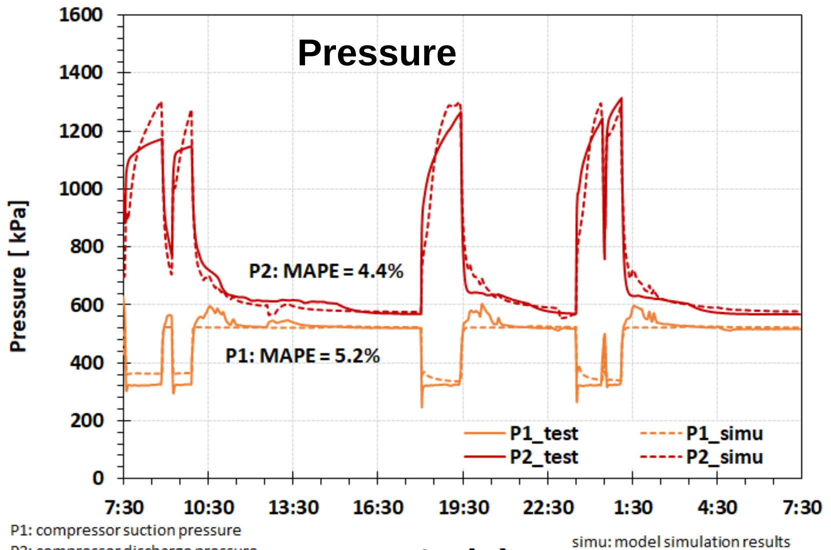
TC6: highest HPWH tank water temperature
TC3: mid-low HPWH tank water tempertaure
TC12: tempertaure at inlet cold water tempertaure
(the location of TC6, TC3, and TC12 refer to Figure 6)

simu: model simulation results
test: lab test results



TC10: Outlet PCM tank water temperature
Q_loss: Heat loss of PCM thermal energy storage tank
(the location of TC10 refers to Figure 6)

simu: model simulation results
test: lab test results

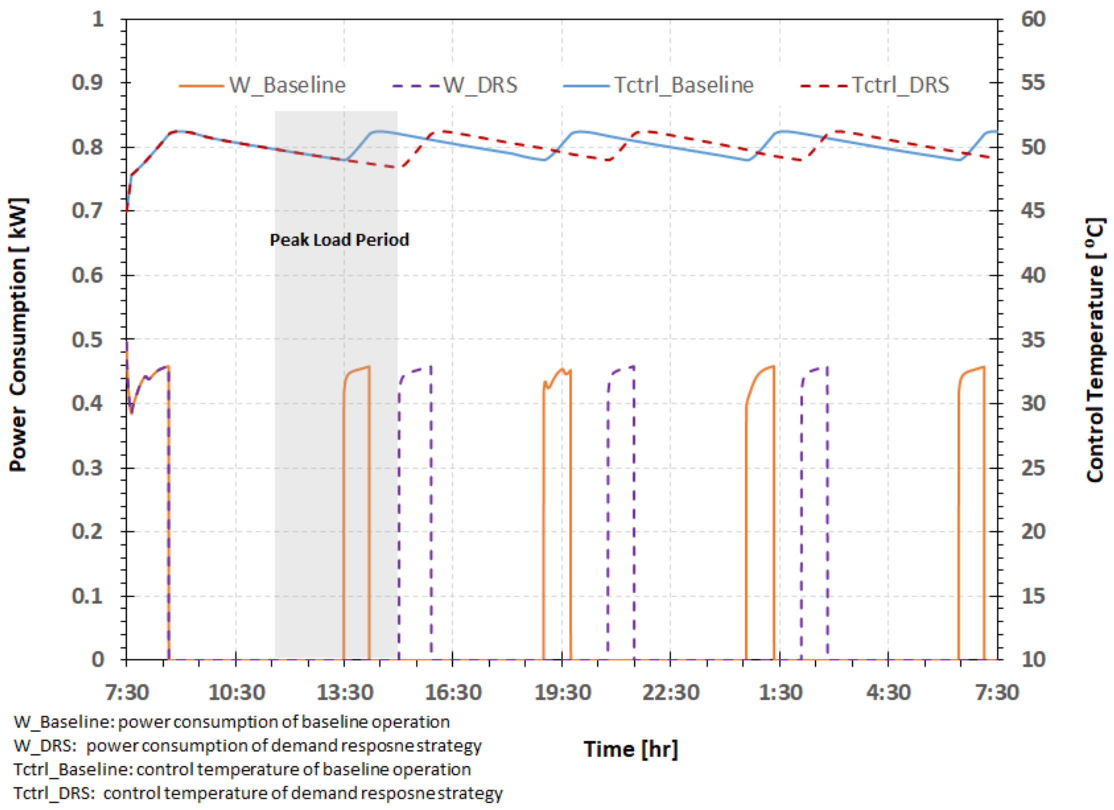


P1: compressor suction pressure
P2: compressor discharge pressure
(the location of P1 and P2 refer to Figure 6)

simu: model simulation results
test: lab test results

Simulation Results – demand response control

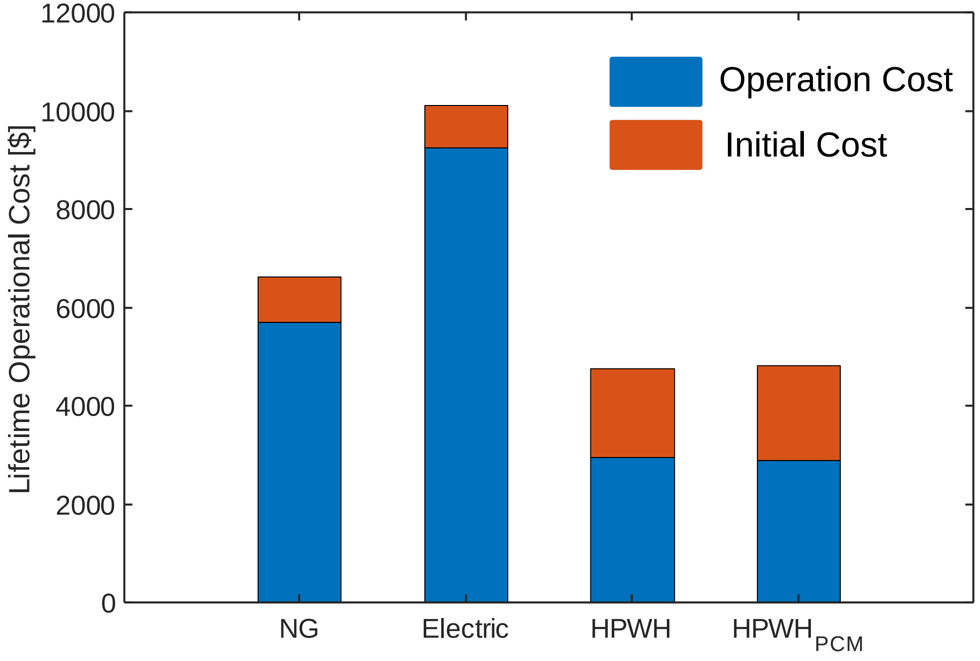
- **Peak period (3.5 hours)**
  - 11:30 and 15:00
- **Dead band increased 5°C**
  - Lowest temperature 48°C (118 °F)
- **2.5% less energy consumed***
- **Draw profile from UEF medium usage**



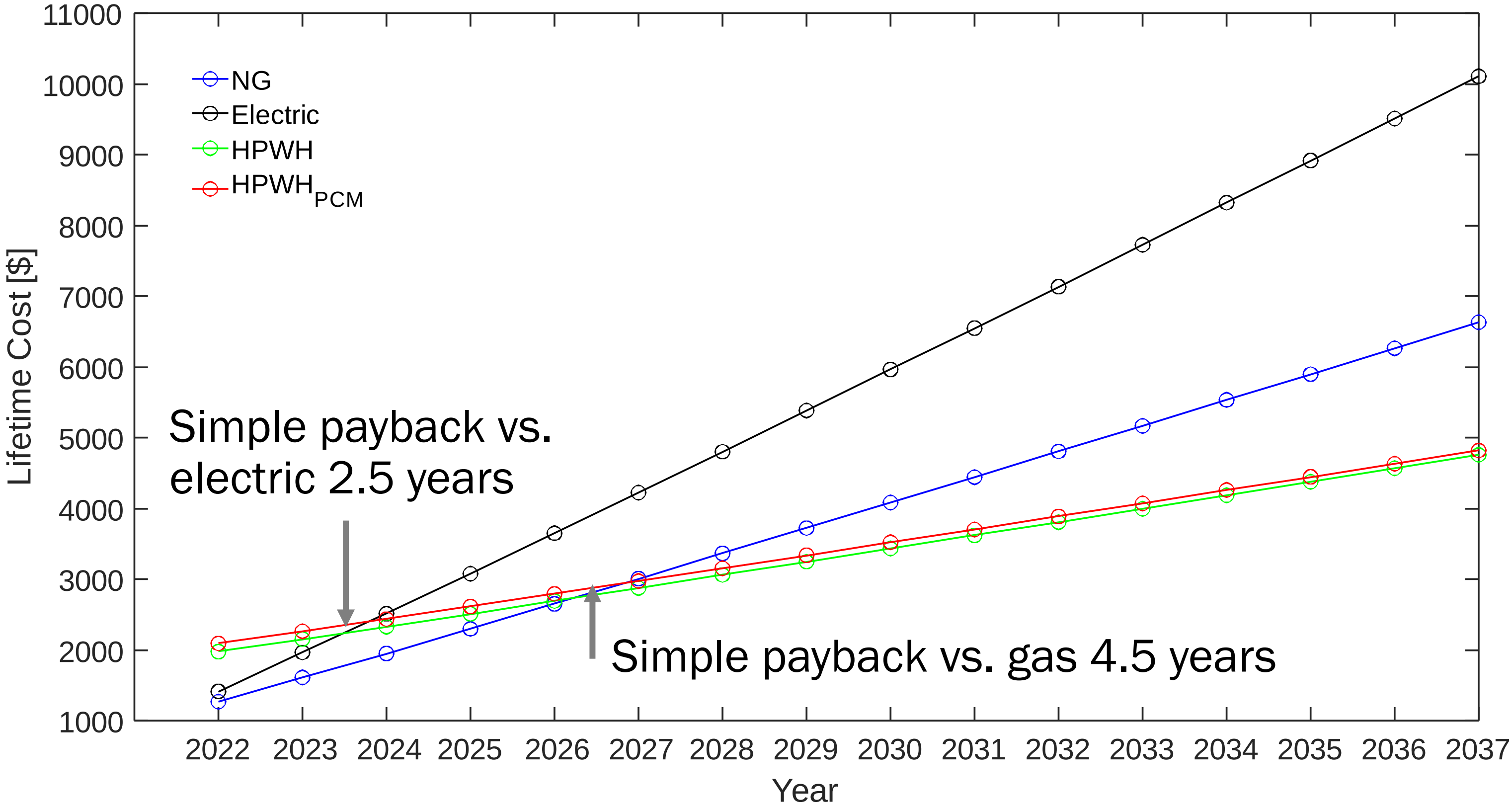
* Energy required shifted into the next day

Cost Analysis

Lifetime Cost (for 16 years): Initial Cost (equipment + installation) + Operation Cost



Division Census: **New England**



- All water heaters are 50-gallon capacity
- Retail costs of water heaters are from A.O. Smith
- $HPWH_{PCM}$ results are obtained through experiments (UEF and FHR)

- Monthly Hot Water Draw (gal/day) and Energy Consumption (Btu/month) are obtained by 'EERE(Energy Efficiency and Renewable Energy Office) 2017'
- Future energy costs are referenced by 'Annual Energy Outlook' (EIA 2022)

(Ref: https://www.eia.gov/outlooks/aeo/)

Future Work

Experimental Study

- Encapsulation mass manufacturing
- Testing spheres for density control
- Epsilon performance testing

Modeling and Control

- Optimization of the sphere geometry and fin number
- Control optimization

Publications and Intellectual Property

- **Conference proceedings or presentations**
  - Sun, J., Nawaz, K., Rendall, J., Brechtl, J., and Elatar, A., "Model-based Co-Simulation of Heat Pump Water Heater with Embedded Phase Change Materials Thermal Energy Storage," *Herrick Conferences*, 2022.
  - Rendall, J., Asher, W., Brechtl, J., Li, K., Yang C., Sun, J., and Nawaz K., "Experimental Results of Density Controlled Phase Change Material Capsules for Increased First Hour Rating for Heat Pump Water Heaters," *Herrick Conferences*, 2022.
- **Journal publications (*submitted*)**
  - Sun, J., Nawaz, K., Rendall, J., Brechtl, J., and Elatar, A., "Heat pump water heater enhanced with phase change materials thermal energy storage: modeling study" submitted to *ICHMT, 2023*
  - Rendall, J., Elatar, A., and Nawaz, K., "A comprehensive review: phase change materials for system integration and optimization in domestic heat pump water heaters," submitted to *Renewable and Sustainable Energy Reviews*, 2022.
  - Rendall, J., Brechtl, J., Nawaz K., Elatar, A., Sun, J., An, K., Liu, X., and Asher, W., "Experimental Results of Density Controlled Phase Change Material Capsules for Increased First Hour Rating for Heat Pump Water Heaters" In Review – *ICHMT,* 2023
- **Patent applications**
  - Rendall, J., Nawaz, K., Asher, W., Elatar, A., Sun, J., Brechtl, J., Liu, X., An, K., Zhang, M., "Density controlled phase-changing materials (PCM) spheres for increased heating power and optimal delivery temperature in hot water tanks" *patent application* US 20230082570A1, 2023.

Thank you

Oak Ridge National Lab

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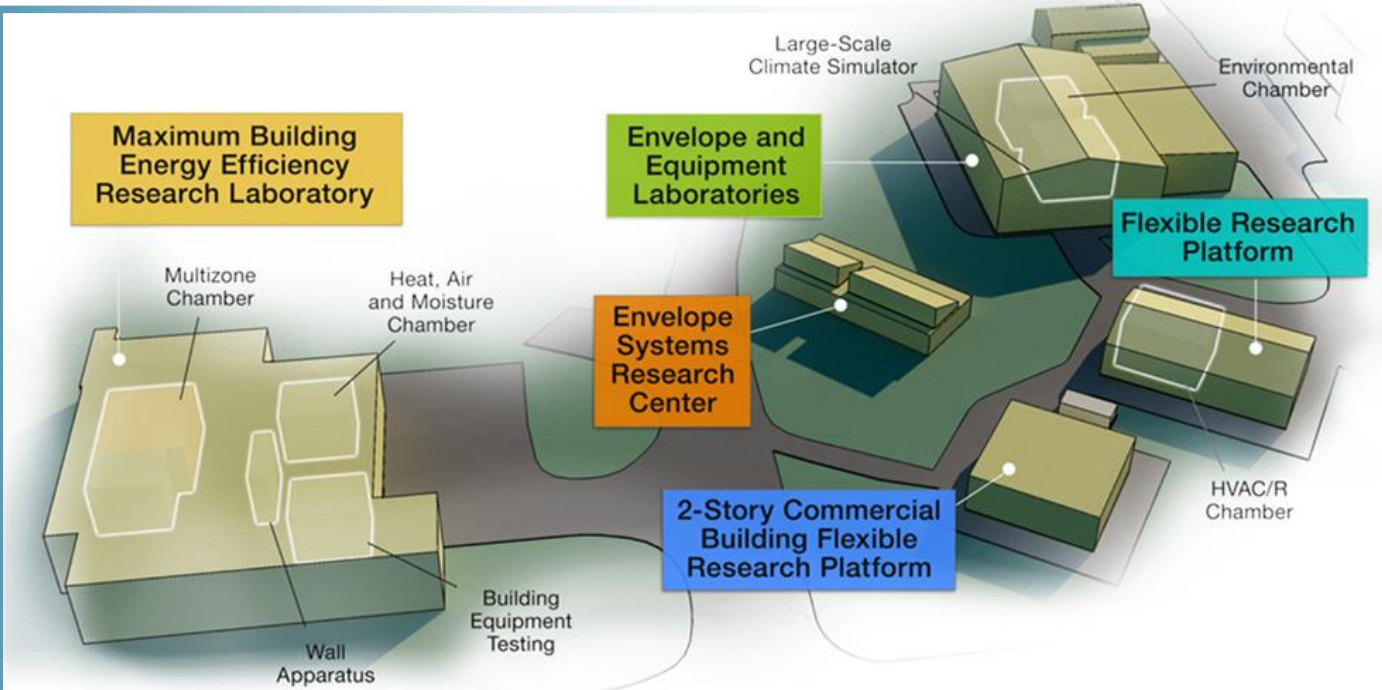
WBS 03.02.02.36, FY 21 AOP Water Heating R&D



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Scientific and Economic Results

236 publications in FY22
125 industry partners
54 university partners
13 R&D 100 awards
52 active CRADAs

BTRIC is a DOE-Designated National User Facility

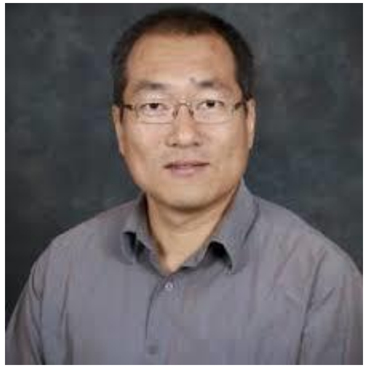
REFERENCE SLIDES

Project Execution

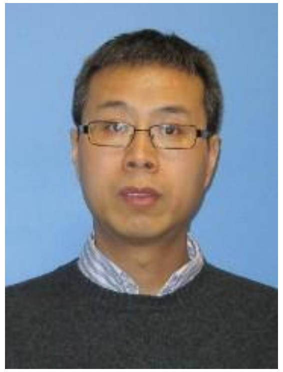
	FY2021				FY2022				FY2023			
Planned budget	300K				300K				300K			
Spent budget	300K				150K				100K			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Q1 Milestone: Literature Review												
Q2 Milestone: Downselection of TES Materials												
Q3 Milestone: Alpha Prototype Construction												
Q4 Milestone: FHR Testing Showing 20% Savings (G/NG)												
Q2 Milestone: CFD Analaysis of Alpha Design												
Q3 Milestone: Beta Prototype Construction												
Q4 Milestone: FHR Testing Showing 5% Increase (G/NG)												
Current/Future Work												
Q1 Milestone: Market Analysis												
Q2 Milestone: CFD Capsule Optimization												
Q3 Milestone: Epsilon Testing: Increase UEF & FHR												
Q4 Milestone: Epsilon Field Testing: Shift 4 hr Load												

Team


Kashif Nawaz


Bo Shen


Joe Rendall


Jian Sun


Steve Memory


Jiamin Yin


Ahmed Elatar