2024 PROJECT PEER REVIEW
U.S. DEPARTMENT OF ENERGY
BUILDING TECHNOLOGIES OFFICE

BTO Peer Review:

Cost Compression of Heat Pump Water Heaters (HPWHs) for Multifamily Housing in Cold Climates

Joseph Rendall, ORNL

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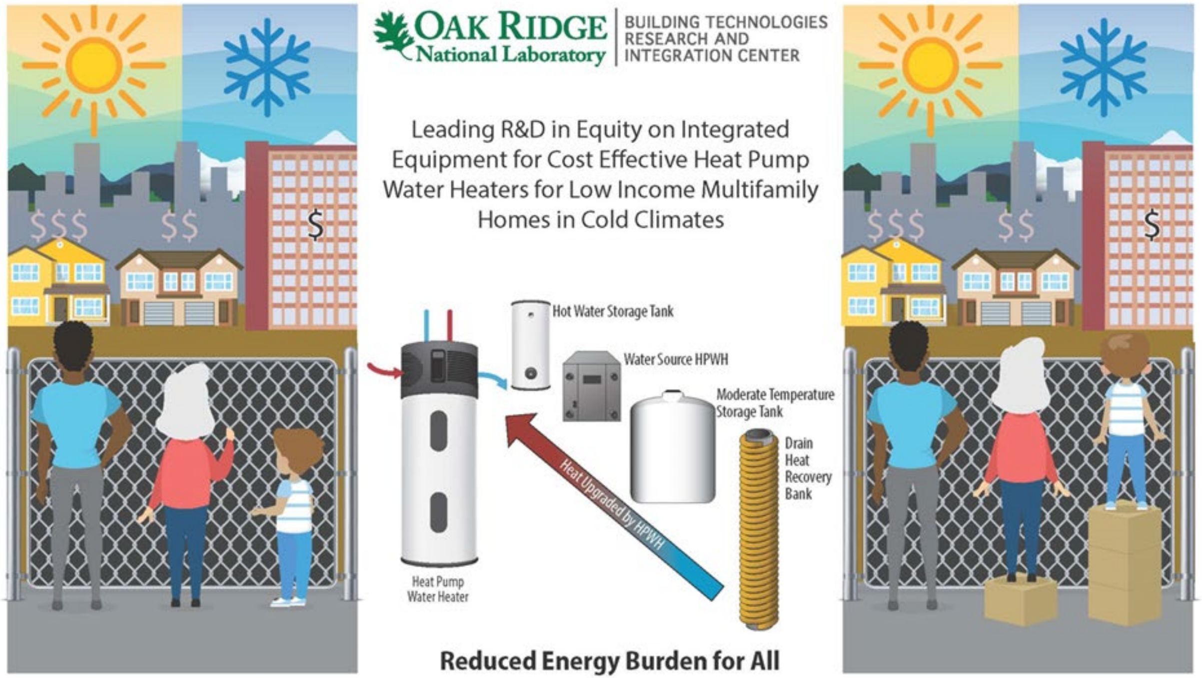

Equality
(Unitary HPWH for all)

Equity
(Climate specific HPWH technology)

Oak Ridge National Laboratory
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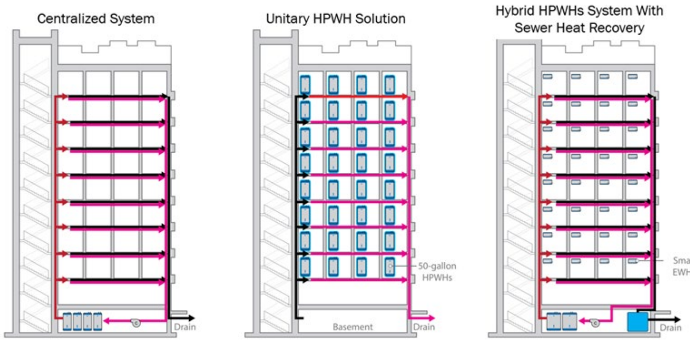
BTO-03.03.02.60
FY22 ET Lab Call (L095-1553)

Project Summary

OBJECTIVE, OUTCOME, AND IMPACT

A drain-source heat pump water heater technology will be developed to significantly (up to 40%) reduce the energy burden associated with water heating for residents of multifamily buildings. The modeling, lab-scale experimental and pilot installation will verify this high-performing technology and increase the market adoption of heat pump water heaters.



TEAM AND PARTNERS

Oak Ridge National Laboratory

Argonne National Laboratory

AO Smith — Innovation has a name

Gary Klein and Associates, Inc. "Where water and energy connect"

STATS

Performance Period: FY22–FY25

DOE Budget: $2,400k Cost Share: $600k (*expected*)

Milestone 1 (Y23): Cost-effective system design for low-income multifamily units modeled.

Milestone 2 (Y24): Experimentally validate design for low-income multifamily units.

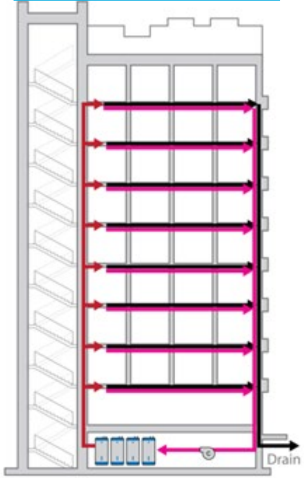
Milestone 3 (Y25): Demonstrate design in pilot study.

Problem Heat Pump Water Heater (HPWH) is Expensive for Some

- T1: Air-source HPWH (AS-HPWH) year-round performance.
- T2: Current sewer heat recovery systems are expensive.
- T3: The operational costs HPWH technologies higher than natural gas when COP < 3-4.
- B1:The initial cost of HPWHs was a major barrier to adoption.
- B2: Unitary HPWHs replacing central natural gas system increase electric bill for tenants.

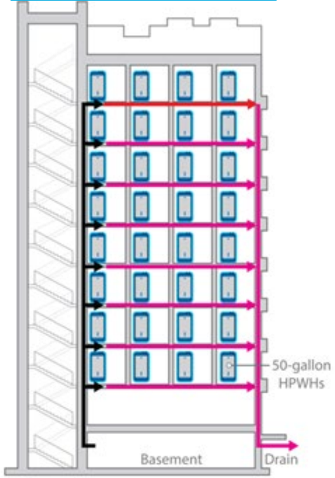
Problems

Centralized Natural Gas or AS-HPWH



High CO_2
High Cost

Unitary HPWH or Electric Resistance



High CO_2
High Cost

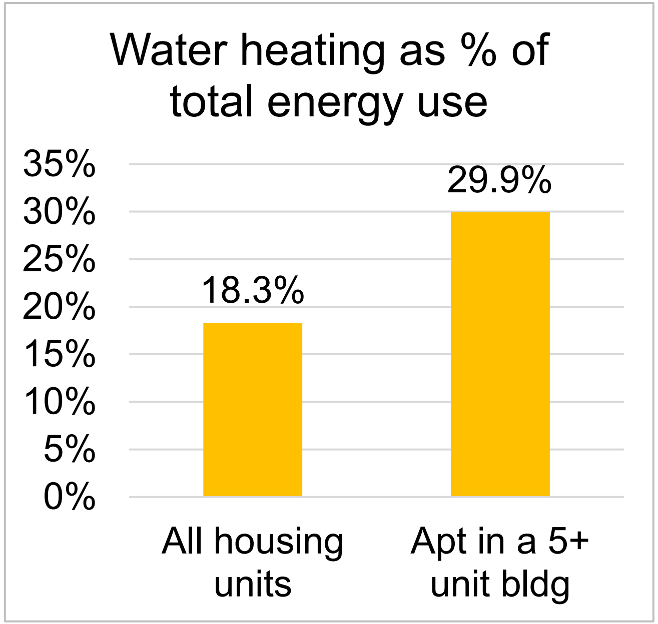
Centralized Drain-Source HPWH

Solution

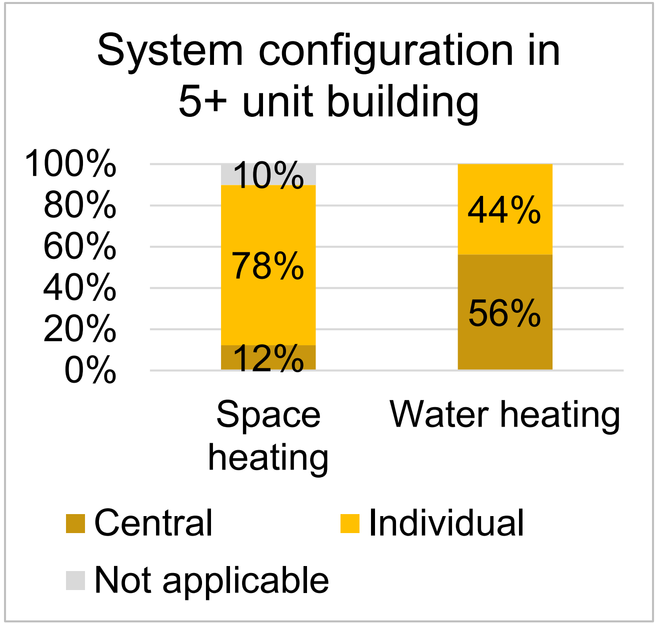
Alignment and Impact Reducing the Total Costs of Water Heating by 30%, Increasing HPWH Efficiency by 50%, and Reducing Carbon by 60% compared to electric resistance or natural gas

- The equitable solution for water heating in multifamily buildings in cold climates is the technology with the **lowest energy burden**—the DS-HPWH.
- The lowest-cost system had **life cycle costs 30% below the baseline of unitary HPWHs** when unitary systems had the maximum incentives applied.
- There is a **positive feedback mechanism** of recovering more heat as more hot water is used, and the configuration allows for **thermal load shifting increase by 300%** compared to typical centralized AS-HPWHs.
- The new source of captured heat significantly increases **25% to 400% efficiency**.
- The high-performing system allows for **reduced life-cycle carbon by 75%** when including grid impact.

Approach Water heating is higher energy use in multifamily buildings than all other house types



Water heating is a larger portion of total energy use in 5+ unit building



Both central and individual water heating systems are prevalent in 5+ unit building

Source: 2020 Residential Energy Consumption Survey Data, US Energy Information Administration

J. Rendall, et. al., "Heat Pump Water Heating for Multifamily Buildings in Cold Climates to Reduce the Energy Burden for Residents with Low to Moderate Incomes" ASHRAE (Winter 2024).

Energy justice

Approach A High Concentration of Energy Burden Is Found in 5+ Unit Multifamily Buildings

Mini Malhotra

- 18% of housing units in the United States are in 5+ unit multifamily buildings.
- 60% of 5+ unit buildings are occupied by low- and moderate-income households.
- Low-income households are vulnerable to energy cost burdens.

Subgroups	Sample size	Median energy burden	Median annual income	Median annual energy expenditures	High burden percentage (>6%)	Severe burden percentage (>6%)
All households	53,539	3.1%	$58,000	$1,800	25%	13%
Single family	37,423	3.1%	$70,020	$2,160	24%	12%
Multifamily (5+ units)	9,936	2.4%	$35,450	$960	22%	12%
Low-income multifamily (5+ units, ≤ 200% FPL)	4,563	5.6%	$14,300	$960	47%	26%

Source: Drehobl et al. 2020. How High Are Household Energy Burdens? An Assessment of National and Metropolitan Energy Burden across the United States. ACEEE Report.

M. Malhotra et. al., Cost Reduction of Heat Pump Water Heating in Cold Climates for Low to Moderate Income Families. 8th International High Performance Buildings Conference at Purdue. West Lafayette, IN (July 2024).

Energy justice

Approach Systematic Approach Allowing for Down-selection through Modeling to Prototype Installation at Field Site

FY23–FY24

Component and system modeling

1. Conceptualized system design alternatives
2. Modeled energy performance
3. Compared life-cycle cost
4. Modeled CO_2 life cycle

FY24–FY25

Scaled experimental validation of models

1. Build test bed for DS-HPWH
2. Simulate user demand
3. Determine energy performance
4. Validate models

FY25–FY26

Prototype field pilot

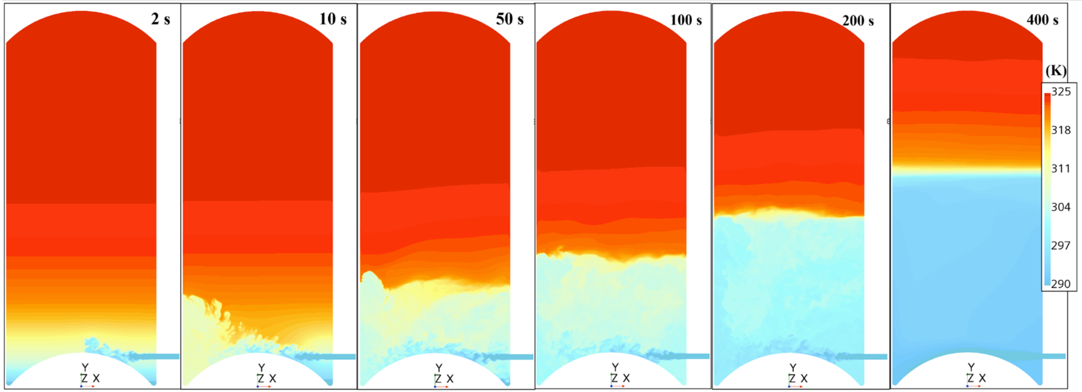
1. Premonitor energy use at field site
2. Commission DS-HPWH
3. Determine energy performance
4. Validate models

R&D Milestone 1 Component Modeling – High-Fidelity Computational Fluid Dynamics (CFD) Modeling

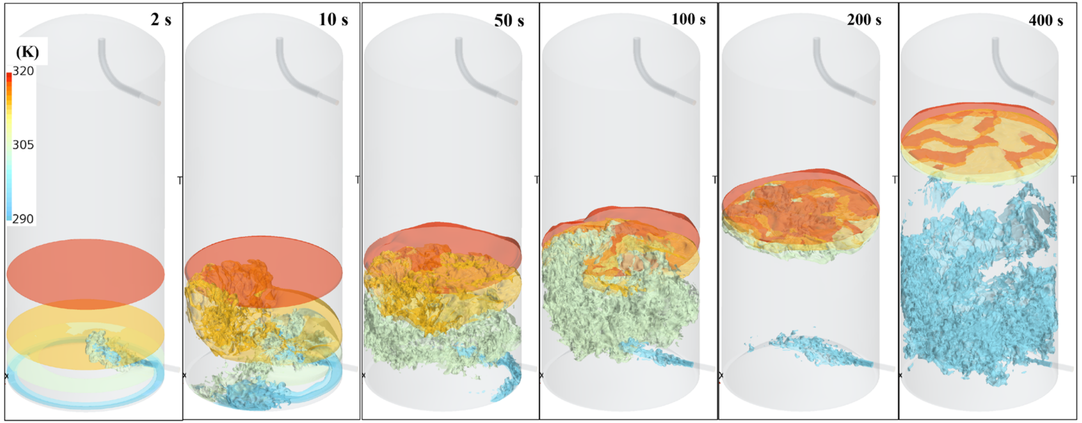
Thien Nguyen

- High-fidelity numerical simulations of HPWH featuring Unsteady Reynolds-Averaged Navier-Stokes and Large Eddy Simulations were successfully developed.
- Outcomes from this work will provide a better understanding of the thermal fluid flow mixing for HPWH.
- CFD results used to improve the physics-based thermodynamic model used for system design and evaluation of HPWH technology.
- Future work includes reduced order models to decrease computational requirements.

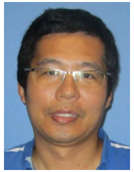
Transient temperature contours



Transient isosurfaces of temperature

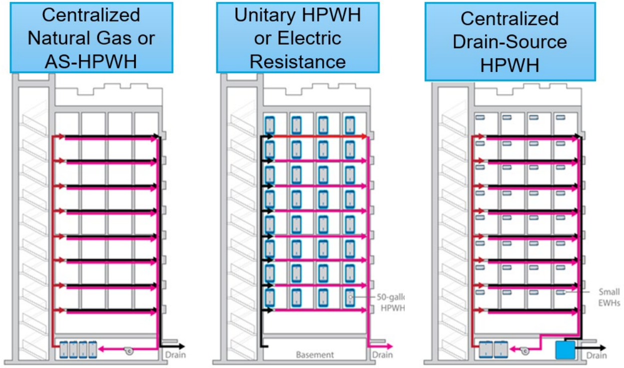


R&D Milestone 2 Model System Performance

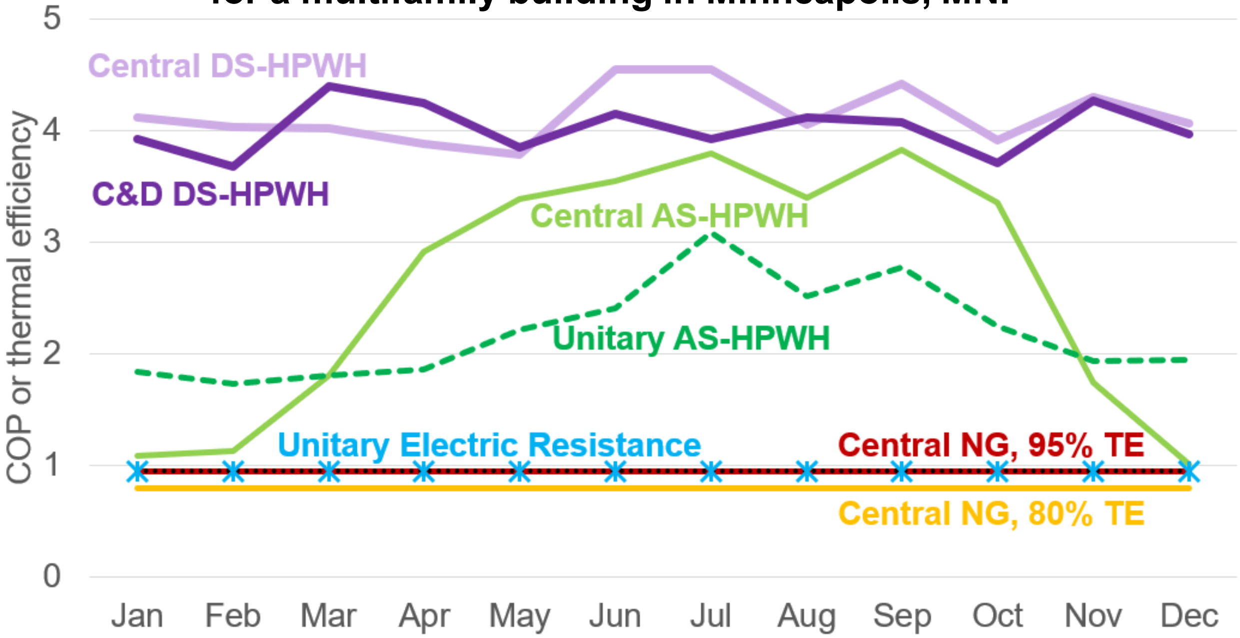



Yanfei Li   Jian Sun

- Developed eight centralized system models of HPWH and four unitary water heaters

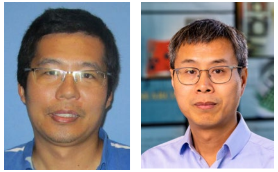


Performance analysis for water heating systems for a multifamily building in Minneapolis, MN.

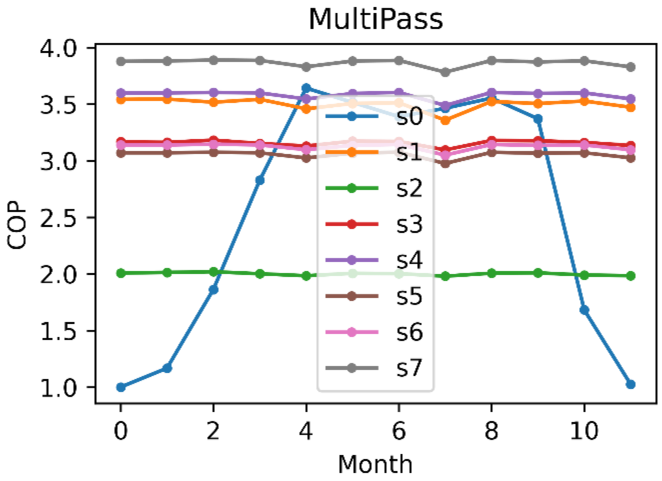


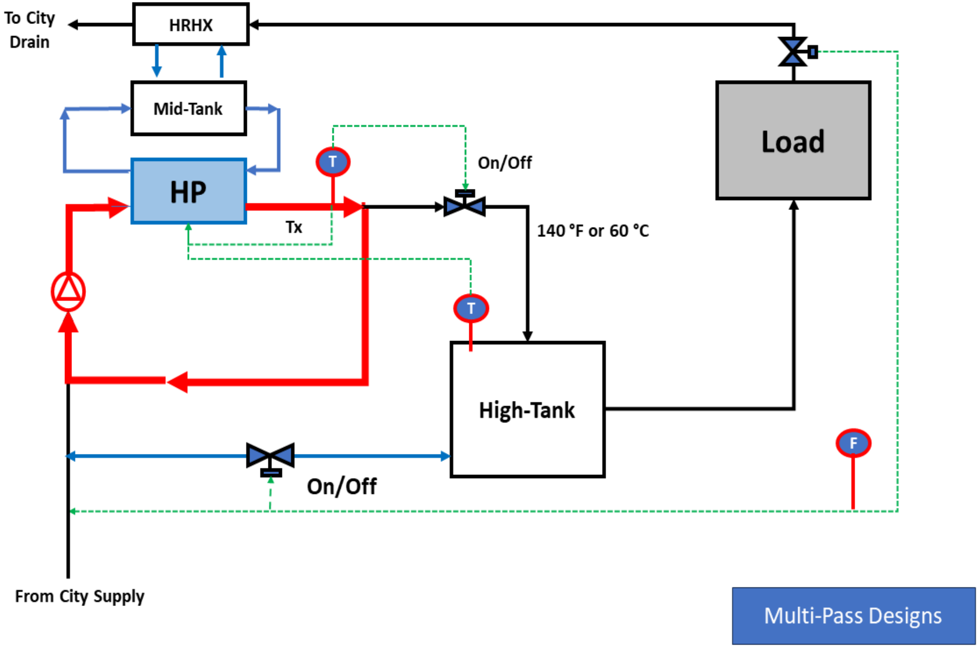
A Modeling Study of Heat Pump Water Heater Systems for a Multi-family Building (Submitted 2024) (**Y. Li**)

R&D Milestone 3 Models Inform Controls



- Implemented multipass controls and single-pass controls for seven water systems.

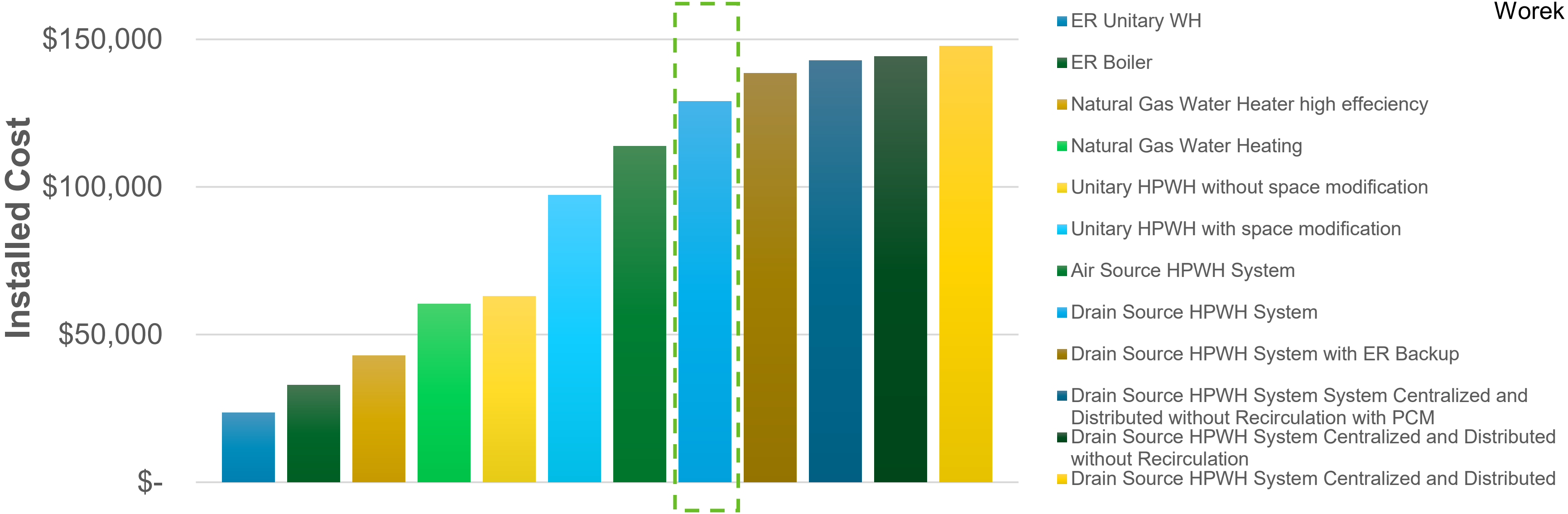




Proper controls are critical to estimating system performance in real world.

R&D Milestone 4 All Costs for Systems Identified

William Worek



Installed costs of 12 water heating systems were determined from RSMeans 2023

- Unitary electric resistance water heating (ER-WH) lowest
- DS-HPWH with centralized and distributed configuration most expensive

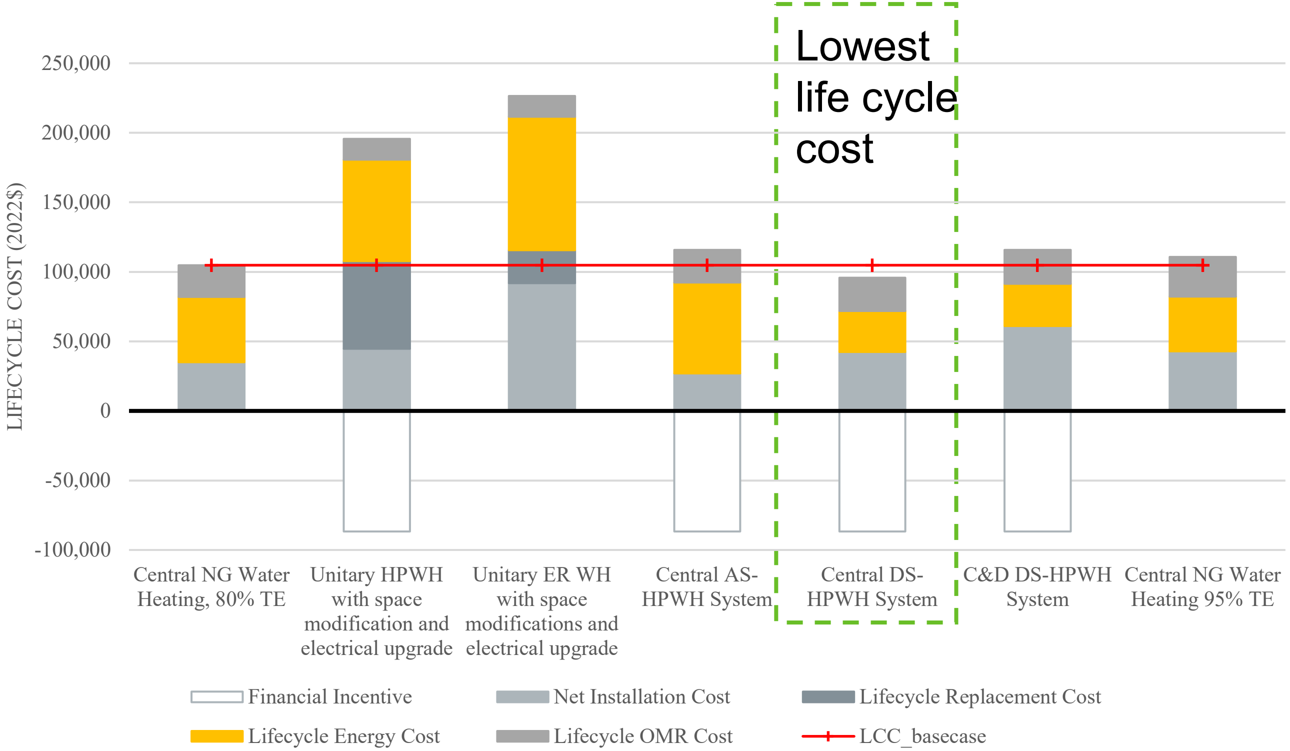
R&D Milestone 5 Selection of Drain-Source HPWH Multifamily Configuration Based on All Costs

Mini Malhotra

Easwaran Krishnan

Life-cycle costs:

- Installed cost
- Energy cost
- Operation, maintenance, and repair cost
- Replacement cost
- Financial incentives



M. Malhotra et. al., Cost Reduction of Heat Pump Water Heating in Cold Climates for Low to Moderate Income Families. 8th International High Performance Buildings Conference at Purdue. West Lafayette, IN (July 2024).

R&D Milestone 6 Verify Drain Heat Recovery Performance in Lab

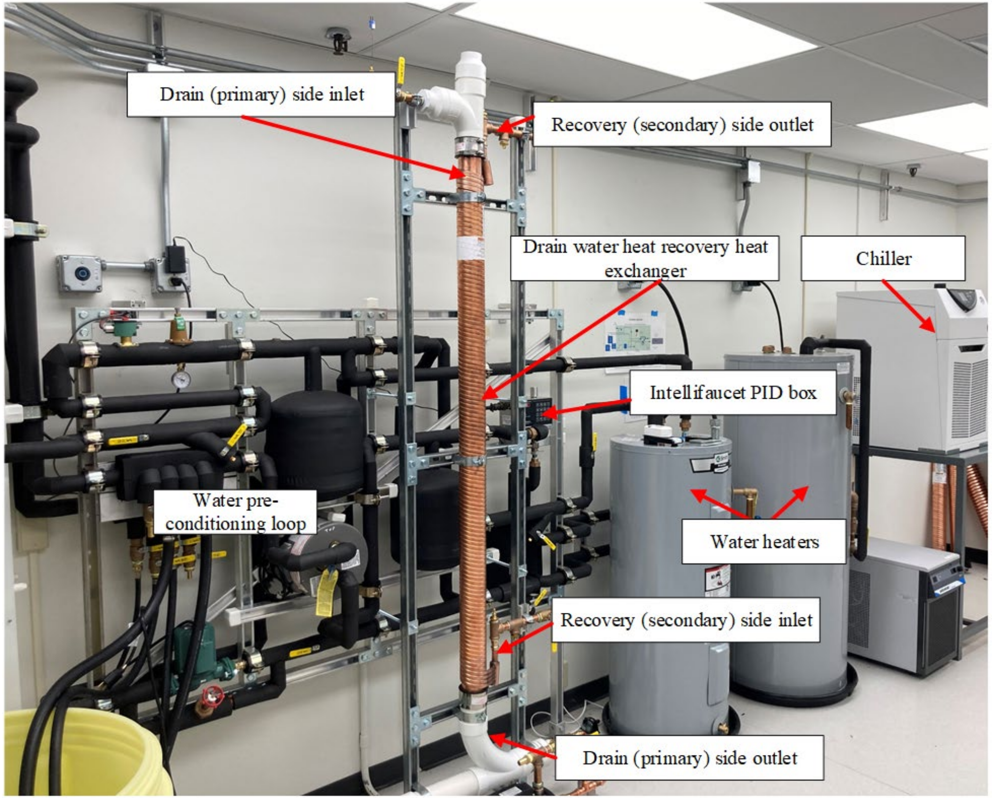
Easwaran Krishnan

Muneesh Murugan

- Built heat exchanger (HX) test facility
- Tested flows 0.5 to 3 GPM for multiple heat exchangers and configurations
- Evaluated distributors for increased performance.
- Developed UA correlations for the system model.

Effectiveness 45%–85%
0.7–3 kW transferred from 0.5 to 3 GPM

E. Krishnan et. al., Performance Evaluation of Drain Water Heat Recovery Exchangers for Heat Pump Water Heaters, *Proceedings of the Herrick Conferences,* West Lafayette, IN (July 2024).



R&D Life Cycle Analysis (ANL)


Michele Morales
Hao Cai

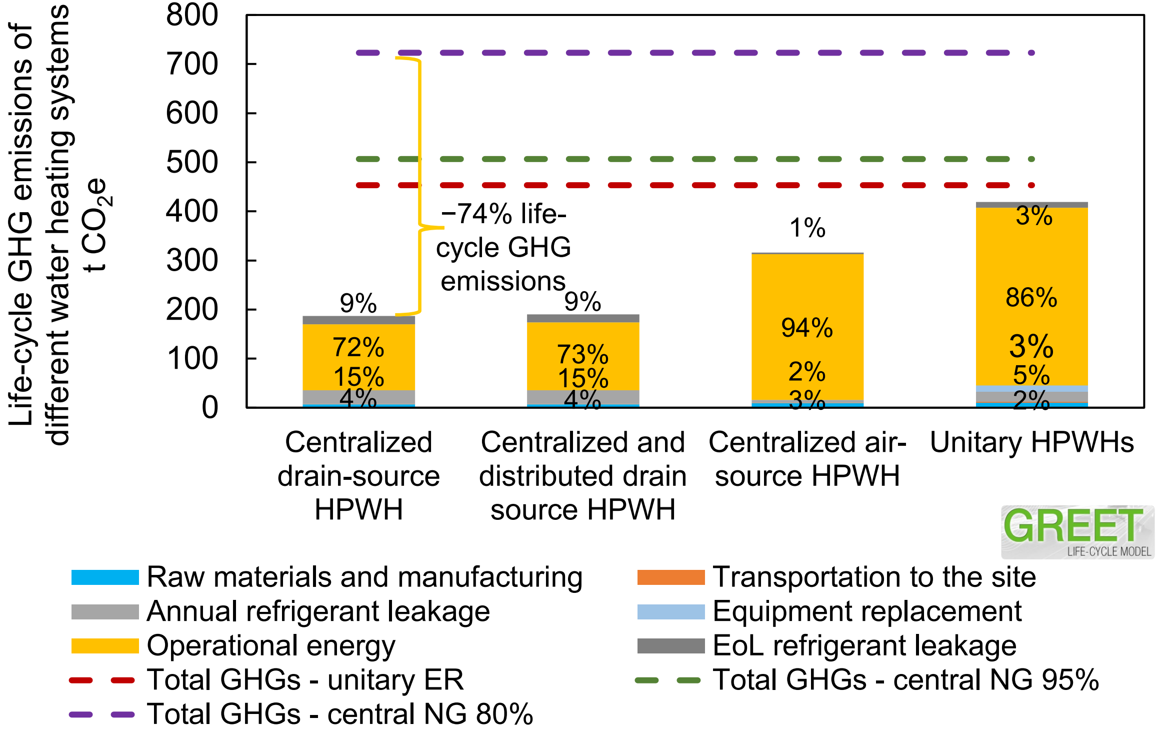
- Operational vs. embodied greenhouse gas (GHG) emissions for unitary electric resistance, air source HPWH, drain source HPWH and centralized natural gas water heater.
- Life cycle analysis (LCA) model:
  - Life cycle embodied GHG emissions were modeled using R&D GREET 2023 and its GREET Building module.
  - Operational energy associated emissions consider future grid decarbonization, as projected by the U.S. EIA [a]
    - The Midcontinent ISO (MISO)[b] regional electricity mix is used, which is expected to reduce GHG emissions by 70% from 2024 to 2051, driven by expansion of renewable energy.
  - Unitary systems were assumed to be fully replaced in year 15.
  - All HPWH assume a refrigerant annual leakage and end-of-life (EoL) leakage at rates of 2.5% and 20%, respectively.

[a] Wang, et al. (2023). Summary of Expansions and Updates in R&D GREET® 2023. United States. https://doi.org/10.2172/2278803.
[b] Midcontinent Independent System Operator (2024). api.misoenergy.org/MISORTWD/lmpcontourmap.html
[C] International Institute of Refrigeration (2015). Guideline for Life Cycle Climate Performance, BSR/ASHRAE/ICC Standard 240P. First Full Publ. Public Review Draft

R&D Life-cycle GHG Emissions of Water Heating Systems, Minneapolis (MN)

Michele Morales

Hao Cai



- All HPWH systems offer lower GHG emissions compared to incumbent technologies;
- Upfront GHG emissions of HPWH vary between 4% to 6% (incl. replacement), equivalent to about two years of central D&S HPWH operational emissions and one year of air source HPWH operational emissions;
- Life-cycle embodied GHG emissions from refrigerant leakage could represent 24% in central D&S HPWH, 3% in air source HPWH, and 8% in unitary HPWH.

R&D Energy Burden Analysis

Zhenglai Shen

- Reduce energy cost and burden of vulnerable groups[1]
- Support sustainability and climate goals
- Encourage equitable energy access
- DS-HPWH reduces energy burden 14% to 42%, relatively

LEAD data[1]

Multifamily household data

EB = Energy Cost / Income

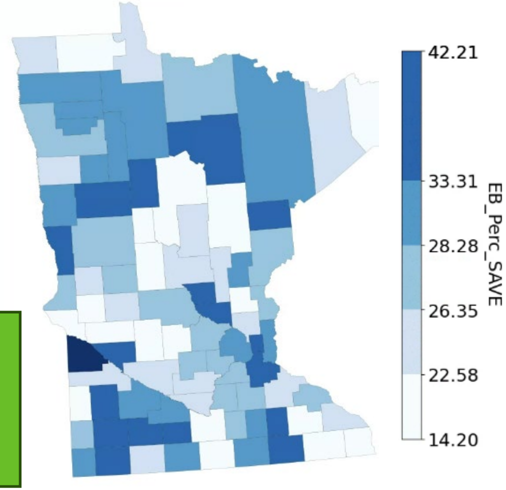
Calculate county-level EB (EB_AVG)

Cost saving = DSHPWH – Baseline

Calculate relative EB savings

Visualize in map

Initial results for Minnesota



Energy burden savings in relative percentage

[1]Shen et al. (2023), *Energy Research and Social Science,* 97, 102949.

Future Work Major Milestones

- Experimental verification of system design in lab (12/31/24)
- First prototype commissioned for 20-unit multifamily complex in cold climate (6/30/25)
- Performance evaluations (6/30/25 to 6/30/26)
- Deployment (Residential Building Integration and Commercial Building Integration) (FY26 going forward)

Presentations

- Hot Water Forum ACEEE 2023 and 2024 (**J. Rendall**)
- ASHRAE Winter Conference 2024 (**J. Rendall**)
- (2) High Performance Building Conference 2024 (**M. Malhotra, E. Krishnan**)

Published work

- **J. Rendall** et. al., "Heat Pump Water Heating for Multifamily Buildings in Cold Climates to Reduce the Energy Burden for Residents with Low to Moderate Incomes" ASHRAE (Winter 2024).
- **E. Krishnan** et. al., Performance Evaluation of Drain Water Heat Recovery Exchangers for Heat Pump Water Heaters, *Proceedings of the Herrick Conferences,* West Lafayette, IN (July 2024).
- **M. Malhotra** et. al., Cost Reduction of Heat Pump Water Heating in Cold Climates for Low to Moderate Income Families. 8th International High Performance Buildings Conference at Purdue. West Lafayette, IN (July 2024).

Thank you

Oak Ridge National Laboratory

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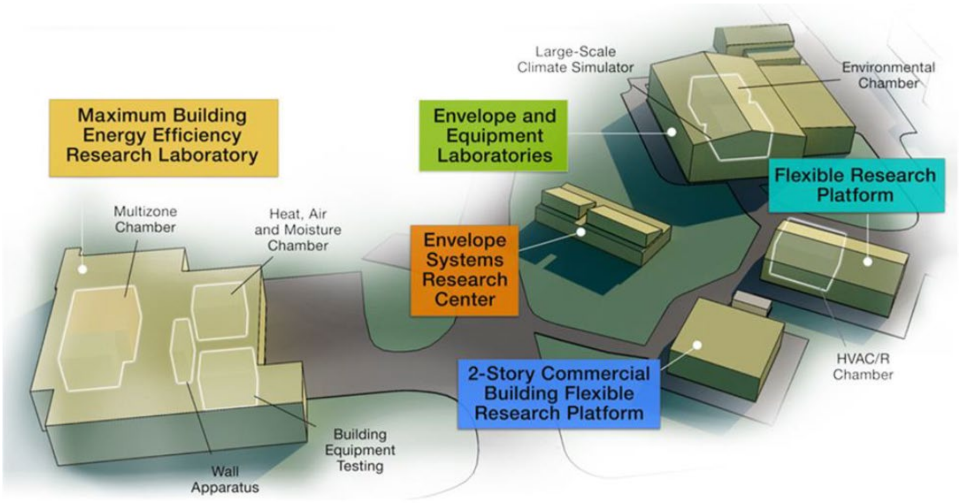


The **Building Technologies Research and Integration Center (BTRIC)** at ORNL has supported DOE BTO since 1993. BTRIC is comprised of more than 60,000 square feet of lab facilities conducting RD&D to develop affordable, efficient, and resilient buildings while reducing their greenhouse gas emissions 65% by 2035 and 90% by 2050.

Scientific and Economic Results
139 publications in FY24
140+ industry partners
60+ university partners
16 R&D 100 awards
64 active CRADAs

BTRIC is a DOE-Designated National User Facility

Reference Slides

Project Execution

	FY2023				FY2024				FY2025			
Planned budget	800K				800K				800K			
Spent budget	400K				1,200K				800K			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Past Work												
Milestone 1: Component models												
Milestone 2: System models												
Milestone 3: Controls interact with other models												
Milestone 4: Costs identified for all systems												
Milestone 5: Selection of system (go/no-go)												
Milestone 6: Performance evaluations of heat recovery												
Current/Future Work												
Milestone 7: Lab scale evaluation of system												
Milestone 8: Prototype installed in field (go/no-go)												
Milestone 9: Prototype performance monitored 1 year												

Critical component backordered until 10/31 for milestone 7

Team

Oak Ridge National Laboratory

Principal Investigators


Kashif Nawaz


Joe Rendall

System cost analysis, LCA, Equity champions


Mini Malhotra


Zhenglai Shen

System design and experimentation


Easwaran Krishnan

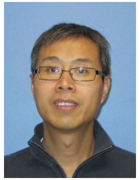

Brian Kolar

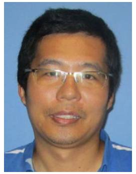

Muneesh Murugan


Jamieson Brechtl


Aaron Thornton

Modeling and controls


Jian Sun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"Where water and energy connect"

2024 MSIIP


Dance Prescott

2023 SULI


Finnian Casey

U.S. Department of Energy | Office of Science


Steve Memory


Tim Rooney


Jiamin Yin

AO Smith
Innovation has a name

HPWH design