Cost Reduction of Heat Pump Water Heating in Cold Climates for Low to Moderate Income Families

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ABSTRACT

Heat pump water heaters (HPWHs) are much more efficient than natural gas burner or electric resistance water heaters but have poor performance at low ambient air temperatures. In multifamily residences, unitary air-source (AS) HPWHs installed in small mechanical closets draw usable heat from indoor space, resulting in higher space heating loads in winter, especially in cold climates where water heating loads are typically higher than in warm climates. In multifamily buildings served by centralized HPWH systems, AS-HPWHs require make-up air from the outdoors, significantly impacting their capacity and energy performance in colder months. Therefore, incentivizing AS-HPWHs that draw heat from indoor space or require substantial amounts of outdoor air may not alleviate the energy burden for low-income households in cold climates. To address these challenges, a novel system has been proposed that integrates centralized water-source (WS) HPWH with drain water heat recovery (DWHR) to utilize warm temperature drain water as the heat source, and small tanks distributed to each apartment to reduce heat loss in the centralized hot-water recirculation loop. The modeled performance of this hybrid Centralized & Distributed (C&D) drain-source (DS) HPWH system in cold climate yielded a yearly coefficient of performance (COP) exceeding 4.0.

This paper provides a concise summary of modeling and presents a technoeconomic analysis, comparing the life cycle costs of proposed DS-HPWH system in centralized and C&D configurations with central AS-HPWH and traditional water heating solutions including unitary electric resistance, unitary HPWH and central natural gas water heating system. Besides the installation and maintenance costs, the analysis accounts for the financial incentives available to low-income households offered through IRA (Inflation Reduction Act). The results demonstrate that the proposed DS-HPWH technology is cost competitive compared to all other analyzed water heating technologies.

1. INTRODUCTION

According to the 2021 American Housing Survey data (US Census, 2022), 18% of housing units in the U.S. are located in multifamily buildings with five or more units. Approximately 60% of multifamily housing units are occupied by low- and moderate-income (LMI) households (earning 80% or less of area median income) (DOE, 2024a). Low-income households are particularly vulnerable to energy cost burdens, with about 26% classified as severely energy burdened, spending more than 10% of their income on energy costs (ACEEE, 2020). With water heating accounting for about 30% of total energy consumption in multifamily housing (EIA, 2023a), which is 10-13% higher than all housing types, improving energy-efficiency for water heating in the multifamily sector is important for reducing the energy burden of low-income families. Additionally, in multifamily buildings, both central and individual water heating systems are prevalent (56% and 44%, respectively). This highlights the potential to develop energy-efficient water heating solutions in both centralized and distributed configurations.

Nationally, electricity is the most common fuel used for water heating in multifamily buildings. However, in cold climates, natural gas systems are slightly more prevalent. The increasing momentum of electrification will promote the adoption of heat pump water heaters (HPWHs), along with other heat pump technologies across all climates. The IRA (Inflation Reduction Act of 2022) offers substantial financial incentives for installing heat pump technologies and promoting electrification, with higher incentives provided for low-income families (BPA, 2024). However, HPWHs suffer significant performance challenges in cold climates, particularly in multifamily buildings. In distributed configuration, unitary air-source (AS) HPWHs installed in small mechanical closets draw usable heat from the indoor space, resulting in higher space heating loads in winter; this compounds with the higher water heating loads of winter due to lower mains water temperatures. In centralized configuration, AS-HPWHs require air from the outdoors that significantly impact their capacity and energy performance. Therefore, incentivizing AS-HPWHs that draw heat from indoor space or require substantial amounts of outdoor air may not alleviate the energy burden for low-income households in cold climates. A heat source at higher temperatures could significantly improve the coefficient of performance (COP) of HPWHs in cold climates, and drain water heat recovery (DWHR) presents as a viable solution.

In this work, a novel system has been proposed to overcome the performance related challenges in multifamily buildings in cold climates. The proposed hybrid Centralized & Distributed (C&D) water heating improves the centralized systems by including a water-source (WS) HPWH typically used for geothermal applications. The system includes the "regenerative braking of water heating" DWHR with a water-source HPWH as the source of heat on the evaporator side of the HPWH. The DWHR harvests heat from the drain when its temperature is warm enough (i.e., above 40 °F) and stores it in a large moderate-temperature storage tank. The stored heat is then available for lifting to domestic hot water temperatures by the WS-HPWH. Since the source temperature for the WS-HPWH is significantly higher than the AS-HPWH, high performance and capacity is realized - this water heating system is coined as a drain source (DS) HPWH. Finally, small tanks are distributed to each apartment to reduce the heat loss in the centralized hot-water recirculation loop.

2. SYSTEM PERFORMANCE MODELING

To conduct modeling and analysis, a 30-unit multifamily building in Minneapolis, Minnesota (in ASHRAE climate zone 6A; Cold–Humid) was considered. The modeling involved two tasks: modeling of water demand and drain water characteristics (results presented at ORNL/ORISE Summer Intern Symposium, Summer 2023), and the performance of HPWH system and components (Li *et al.*, 2024, article under preparation).

2.1 Modeling water demand, water draw pattern and drain water characteristics

Water use in multifamily buildings can be considered as the combined total of multiple individual water consumption patterns typical in single-family homes. To account for the variations in household size and composition, daytime occupancy, and water-using behavior, randomized schedules of year-long hot and cold water events were generated for each unit and aggregated for the building (Figure 1). Hot water end uses included clothes washing and dishwashing (at 130 °F or 54.4 °C), and kitchen and bathroom sinks, showers, and baths (at 110 °F or 43.3 °C mixed-water temperature), as shown in Table 1. Hot-water event schedules were generated using the DHW Event Schedule Generator (Hendron *et al.*, 2010), which accounts for realistic probability distributions of start time, duration variability, flow rate variability, clustering, fixture assignment, vacation periods, and the variation in mains water temperature due to climate and seasonality. Considering that cold water usage is also beneficial to the DS-HPWH as the city water temperature is often warmer than the outdoor temperature during the winter, cold water end uses including toilet flushing, cold-water draws in sinks, showers, and bath faucets, and cold rinses in clothes washers at city water temperature were also estimated using survey-based estimates (DeOreo *et al.*, 2016; listed in Table 1) and translated into randomized event schedules using MATLAB. These schedules were used to determine the overall water demand and drain water characteristics for the entire building. Drain water temperatures were assumed to be trended towards the indoor temperature of 72 °F (22.2 °C) under the condition of no flow and from the toilets – as the toilet water warms to indoor in-between flushes. Water for irrigation was not considered in the estimates as it does not go down the main drain. With these assumptions, the average hot water and cold water use were 45.9 gal/day (173.8 L/day) and 88.6 gal/day (335.4 L/day) per unit, respectively.

For modeling drain water flow rate and temperature, the temperature change during water use and the mixing of hot- and cold-water discharge from all dwelling units within the building were accounted for. Water loss due to evaporation, splashing, mist, and leaks, and the elapsed time between water draw and drain events were ignored. The temperature of drain water was approximated after accounting for indoor sensible heat gain estimates for each hot water end use (based on Wilson *et al.*, 2014) and assuming that water discharge from toilets and after cold water use in sinks, showers, and bath faucets achieves indoor temperature before draining. To estimate the energy available for heat recovery from the drain water, drain water temperature was multiplied by the volumetric flow rate of water, temperature-dependent density, and specific heat to determine the potential energy stored for drain temperature above 40 °F (4.4 °C). Heat loss from the drain water to the building or heat gained was ignored in this initial estimate. The peak hot water demand of 57 kW and an average recoverable energy for HPWH to be ~7 kW for drain water temperature above 40 °F (4.4 °C) for Chicago. The analysis in this paper is for Minneapolis MN and the values are slightly higher for demand (see Table 1). The proposed DS-HPWH system would be highly feasible and perform significantly better than AS-HPWH configurations even when considering some performance loss in experimentation not represented in the model.

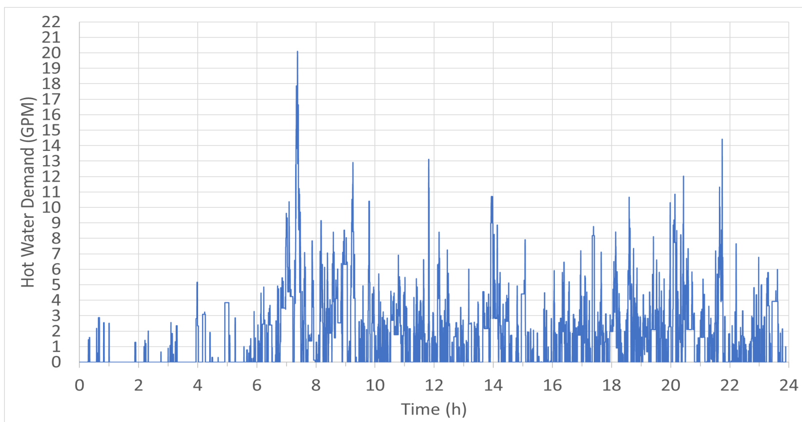

Figure 1: Daily hot water draw for the building

Table 1. Average daily water-use characteristics (Hendron *et al.*, 2010; Wilson *et al.*, 2014; DeOreo *et al.*, 2016)

Water use	Use temp. (°F)	Hot water use fraction	Water use (gal/day)			Internal heat gain (Btu/day)		Drain temp. (°F)	Recoverable energy (Btu/day)
			Total	Hot water	Cold water	Sensible	Latent		
Hot-water use									
Clothes washer, hot-water wash	130	1.00	**1.5**	1.5	—	0	0	130	1,089
Clothes washer, warm (90 °F–110 °F)	100	0.62	**1.5**	1.0	0.6	0	0	100	768
Clothes washer, cold (60 °F–80 °F)	70	0.24	**1.7**	0.4	1.3	0	0	70	426
Dishwasher (125 °F wash, >140 °F rinse)	130	1.00	**4.5**	4.5	—	0	0	130	3,385
Shower	110	0.75	**28.0**	20.9	7.1	1,482	1,408	98	14,870
Bath	110	0.75	**7.0**	5.2	1.8	371	0	104	3,721
Sink	110	0.75	**25.0**	18.7	6.3	619	281	106	13,964
Cold-water use									
Toilet	72	—	**70.0**	—	70.0			72	20,433
Sink cold-water draw (~5% of total)	51	—	**10.4**	—	10.4			51	3,030
Clothes washer, cold rinse (~5% of total)	51	—	**10.4**	—	10.4			51	952
Domestic hot water total			**69.2**	**52.1**	**107.8**	**Total recoverable energy**			**70,518**
Total water use			**160.0**	**Total recoverable energy (for 30 units)**					**2,115,540**

Water use	Use temp. (°C)	Hot water use fraction	Water use (L/day)			Internal heat gain (Wh/day)		Drain temp. (°C)	Recoverable energy (Wh/day)
			Total	Hot water	Cold water	Sensible	Latent		
Hot-water use									
Clothes washer, hot-water wash	54.4	1.00	**5.7**	5.7	—	0	0	54.4	319
Clothes washer, warm (32.2 °C–43.3 °C)	37.8	0.62	**5.7**	3.8	2.3	0	0	37.8	225
Clothes washer, cold (15.6 °C–26.7 °C)	21.1	0.24	**6.4**	1.5	4.9	0	0	21.1	125
Dishwasher (51.7 °C wash, >60 °C rinse)	54.4	1.00	**17.0**	17.0	—	0	0	54.4	992
Shower	43.3	0.75	**106.0**	79.1	26.9	434	413	36.7	4,358
Bath	43.3	0.75	**26.5**	19.7	6.8	109	0	40.0	1,091
Sink	43.3	0.75	**94.6**	70.8	23.8	181	82	41.1	4,093
Cold-water use									0
Toilet	22.2	—	265.0	—	265.0			22.2	5,989
Sink cold-water draw (~5% of total)	10.6	—	39.4	—	39.4			10.6	888
Clothes washer, cold rinse (~5% of total)	10.6	—	39.4	—	39.4			10.6	279
Domestic hot water total			**262.0**	**197.2**	408.1	**Total recoverable energy**			20,668
Total water use			**605.7**	**Total recoverable energy (for 30 units)**					620,029

For a distributed water heating system, the unit-level water use assumptions required unitary water heaters with 15,350 Btu/h (4499 W) heating capacity and 50-gal (189.3 L) storage capacity. For a 30-unit complex, the heating capacity was 460 kBtu/h (135 kW) with 2,500-gal (9464 L) storage. For a central water heating system of the same size, the ASHRAE sizing (ASHRAE, 2023) resulted in a 400 kBtu/h (117 kW) heating capacity and 750-gal (2839 L) storage – a 3.3 times reduction in storage with 15% decrease in capacity due to the intermittent use of hot water. Unit-level 50-gal (189.3 L) water heater typically runs 2 hours a day which suggest the recoverable energy of 2,116 kBtu/day (620 kWh/day) is sufficient as it can provide the central HPWH with 400 kBtu/h (117 kW) for 5.29 hours – assuming a 50% effective heat recovery rate and COP of 2.

2.2 Modeling system performance

The proposed DS-HPWH system was modeled in centralized and C&D configurations. Various attributes and components that were modeled included: the water demand profile, heat pump, high temperature water tank (HTWT), medium temperature water tank (MTWT), heat recovery heat exchanger (HRHX), and auxiliary components. The heat pump unit heats up the water and pumps to HTWT to be delivered to the building, from where discharge water flows into the city drainage. A recirculation loop reintroduces hot water back into the HTWT to provide instant hot water availability at the start of water use as well as heating source to the MTWT for maintaining stable water temperature for use by heat pump evaporator. The HRHX is used to recover energy from discharge water. The city water loop provides water to both the HTWT and the system makeup. The modeled performance of centralized and hybrid C&D DS-HPWH system yielded a yearly coefficient of performance (COP) exceeding 4.0 in cold climate of Minneapolis MN, as shown in Figure 2. This performance far exceeds that of traditional water heating technologies commonly considered for multifamily buildings.

For technoeconomic analysis of the proposed DS-HPWH system compared with various other alternatives for replacing a central natural gas water heating system with 67% thermal efficiency, following replacement options were considered:

1. Centralized natural gas (NG) system with 80% thermal efficiency (i.e., the minimum standard),
2. Unitary HPWHs with space modification that required electrical upgrades,
3. Unitary electric resistance (ER) water heaters with space modification that required electrical upgrades,
4. Centralized air-source (AS) HPWH system,
5. Centralized drain-source (DS) HPWH system,
6. Centralized and distributed (C&D) drain source (DS) HPWH system,
7. Centralized natural gas (NG) water heating system with 95% thermal efficiency.

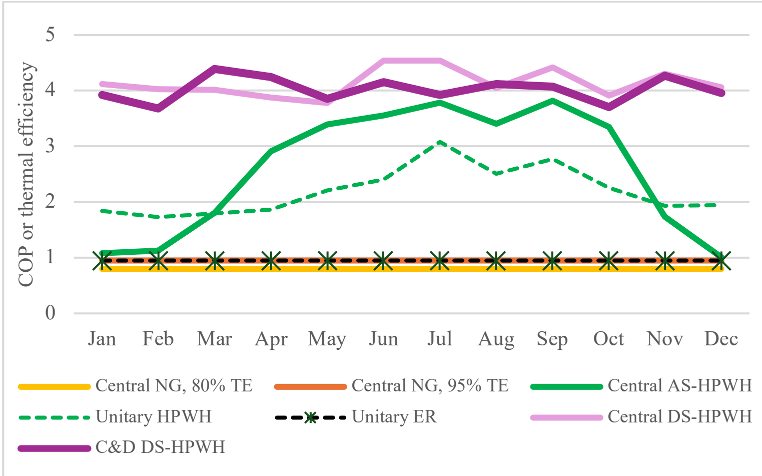

Figure 2: Modeled energy performance of DS-HPWH compared with traditional water heating technologies for Minneapolis, MN

3. LIFETIME ENERGY COST FOR VARIOUS WATER HEATING TECHNOLOGIES AND FUEL SOURCES

A preliminary analysis was conducted to compare the energy costs of water heating across various technologies, fuel sources, and efficiency levels. The aim was to identify the minimum COP required for HPWHs to yield operational cost savings over other technologies, potentially leading to a payback.

3.1 Analysis

The analysis compared the following water heating technologies and fuel sources:

- Natural gas water heaters: with 67%, 80% and 95% thermal efficiency,
- Electric resistance water heaters: with 95% efficiency,
- Propane-based water heaters: with 70% thermal efficiency,
- Fuel oil-based water heaters: with 85% thermal efficiency,
- Heat pump water heaters: with COPs ranging from 2 to 5.

The analysis utilized energy price projections from the 2023 Annual Energy Outlook (AEO) reference case for the United States and its nine census divisions (EIA 2023b). These projections were based on the National Energy Modeling System (NEMS), operating under the assumption that:

- The projections reflect the prevailing laws and regulations as of November 2022, including the Inflation Reduction Act (IRA) enacted by the US Congress in 2022 (US Congress, 2022).
- Delivered fuel prices encompassed all necessary activities involved in producing, importing, and transporting fuels to end users.
- No consideration was given to local utility prices, demand charges, or connection charges.
- There were no considerations for potential increases in natural gas prices resulting from fuel switching, as outlined by Nadel (2023).

3.2 Results

The energy costs were projected over a span of 27 years. Figure 3 illustrates these energy costs for HPWHs and other water heating technologies in dollars per kWh energy consumed based on the projected energy price for the United States divided by the system efficiency. The energy cost varies with the system performance – COP in case of heat pumps and thermal efficiency for other systems. For the US national average case, the energy cost for HPWHs with COP of 2 and NG based systems with 67% thermal efficiency would be lower than propane, fuel oil and electric resistance water heating systems with 70%, 85% and 95% thermal efficiency, respectively.

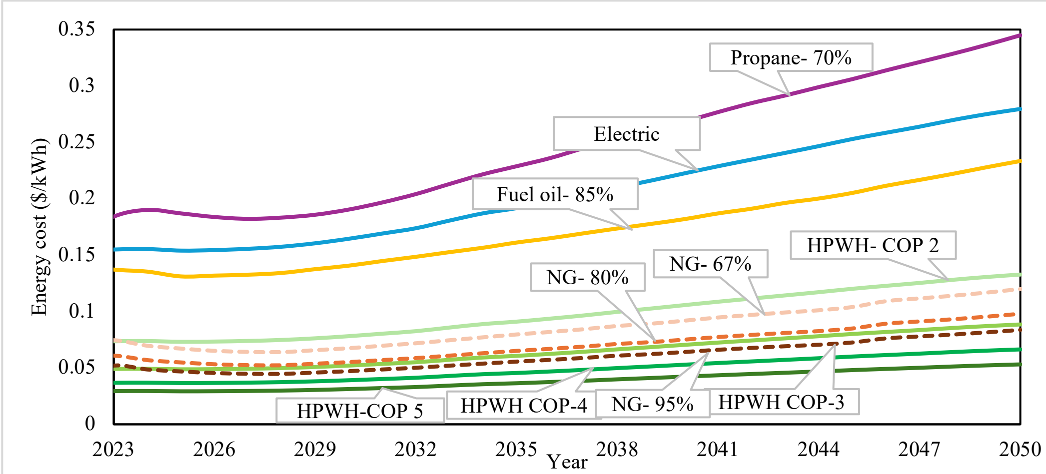

Figure 3: Energy costs (national averages) of heating water by energy source (2023 to 2050)

Following the same methodology, analyses were carried out using regional price projections for the nine census divisions, allowing for identifying the minimum COPs required for HPWHs to yield operational cost savings over natural gas-based technologies. The results are summarized in Figure 4.

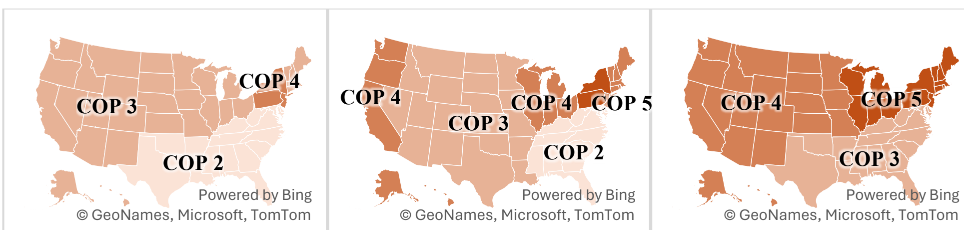

Figure 4: Minimum HPWH COPs to achieve operational costs lower than 67%, 80% and 95% thermal efficiency natural gas water heaters

The projections of operational (fuel) costs indicate that a minimum HPWH COP of 3 is required for three census divisions (South Atlantic, East South Central, and West South Central) in order to achieve energy cost savings over natural gas water heaters with a 95% thermal efficiency, whereas HPWHs with COPs of 4 would be required in the Pacific, Mountains and West North Central regions. COPs of 5 would be necessary for HPWHs to be beneficial in New England, the Middle Atlantic, and East North Central regions.

4. LIFECYCLE COST ANALYSIS

In view of minimum COPs identified in section 3, the modeled COPs for DS-HPWH in section 2 shows COPs high enough to suggest potential payback in most cold climate regions. Thus, lifecycle cost analysis was conducted accounting for the product installation, maintenance, replacement, and user costs incurred throughout the life of proposed DS-HPWH configurations compared with traditional water-heating technologies. The paybacks were then determined.

4.1 System-specific Details

Installed cost: The installation cost data included material, labor, equipment costs, overhead, and profit if applicable, from RSMeans (2023). Additionally, certain equipment cost data was directly obtained from manufacturers. The installed cost of the analyzed systems is shown in Table 2. The list of components for costing included:

1. Water heaters of different types (AS-HPWH, DS-HPWH, ER, NG) and sizes,
2. Water storage tanks of various sizes and configurations,
3. Heat exchangers with varying capacities,
4. Expansion tanks in different sizes,
5. Pumps of various capacities,

6. Fans for equipment room ventilation,
7. Copper piping ranging from ½” (15 mm) to 4” (100 mm), all assumed to be installed with insulation,
8. Copper fittings, including elbows, tees, couplings, etc., pressed to reduce installation labor costs, also in sizes from ½” (15 mm) to 4” (100 mm),
9. Other components such as waste heat recovery heat exchangers.

Financial incentives: Multiple financial incentive options including the IRA modeled and measured performance-based tiered rebates (HOMES), electrification rebates (HEAR), and tax credits (25C) (BPA, 2024) were compared for the analyzed systems.[1]

- HOMES required at least 20% modeled or 15% measured performance improvement from the whole-building perspective.
- HEAR included rebates up to $1,750 for HPWHs, up to $4,000 for electric panel upgrade, and up to $2,500 for electric wiring, with 100% of costs covered for low-income households and 50% for moderate-income households.
- IRA tax credit[2] included 30% of installation cost for HPWH and panel upgrade, with a $2000 per household cap for HPWH and $600 per household cap for panel upgrade.

For all eligible systems analyzed[3], HEAR rebates offered the highest incentive amount.

Operation and maintenance (O&M) costs:
The O&M costs and frequency for the analyzed systems throughout the service life of the system were determined considering industry practices for system components, as shown in Table 2. The replacement of components, such as anode rod and pump, were considered as O&M costs.

Table 2: Cost estimates

Item	Central NG, 80% TE	Unitary HPWH	Unitary ER	Central AS-HPWH	Central DS-HPWH	C&D DS-HPWH	Central NG, 95% TE
Installed Costs							
System installed cost[1,2]	$35,137	$131,400	$91,937	$113,771	$129,048	$147,708	$42,870
Financial incentives[3]	-	$86,700	-	$86,700	$86,700	$86,700	-
Operation and maintenance Costs[4]							
Heat exchanger cleaning ($250 @6 months)	x			x	x	x	x
Refrigerant charge check ($300 annually)				x	x	x	
Condensate neutralization ($200 annually)							x
Duct cleaning ($23.2 annually)				x			
Burner tuneup ($300 annually)	x						x
Anode rod replacement (100 per tank @ 5 years)	x	x	x	x	x	x	x
Pump replacement ($1500 @15 years)				x	x	x	

[1]Includes electrification costs
[2]The capital cost is net installed cost (i.e., including the cost of electrification minus financial incentives). Replacement cost (if service life less than the study period) is equal to the equipment installed cost, excluding the cost of electrification and financial incentives.
[3]Includes $1750 times 30 for HPWH system and $1140 times 30 for electrification.
[4]Burner replacement and refrigerant recharge are not included.

[1] Stacking of financial incentives was not optimized as potential paths are different depending on the scope of retrofits for low-income and moderate-income households (Rinaldi and Wiltshire-Gordon, 2023).
[2] Rinaldi and Wiltshire-Gordon (2023) noted that IRA tax credit is less effective option for many low-income homeowners, because many lack the tax liability needed to claim a credit.
[3] DOE (2023) specifies that central HPWH may not qualify as an eligible appliance for rebate until ENERGY STAR establishes system-based criteria for them. However, it notes that DOE will issue further guidance on this matter. Considering that the modeled COP of the proposed DS-HPWH system is above 4.0, exceeding that of unitary HPWH which is eligible for rebate, to ensure a fair comparison of lifecycle costs for all replacement options, HEAR rebates were accounted for central HPWH systems.

Service life: For centralized water heating systems, a service life of 28 years was used (Wadsworth, 2024). For distributed system a service life of 15 years was used (DOE, 2024b). These are leaning towards the longer expected life based on the references. For C&D systems, a service life of 28 years was used which included replacement of unitary water heater at year 15.

4.2 LCC Inputs, Assumptions, and Limitations

Energy price and projections: The LCC analysis was performed using the 2022 annual average commercial electricity and natural gas prices for MN and energy price projections through 2050 for Census Division 4 (i.e., West North Central) obtained from the US Energy Information Administration (EIA 2023b). As a note, EIA fuel price projections do not account for the increase in electricity price due to higher electricity demand or potential increase in natural gas bill (i.e., higher fixed cost component) as an impact of increasing electrification over the years (Nadel 2023).

Discount rate: The analysis was based on real discount rate of 3% based on 2022 dollars, eliminating the need for assumptions regarding inflation rates. This approach mitigates potential uncertainties associated with varying inflation rates across different cost categories, such as energy, labor, and materials.

Study period: A 28-year study period was considered to align with the service life of central water heating system, which involved one replacement cycle for unitary systems.

Assumptions and limitations:

- Input data such as initial costs, operational costs, maintenance costs, and service lives are accurate.
- Operating conditions are relatively stable over the study period/service life.
- All alternatives are comparable in terms of performance, quality, and service life.
- Intangible benefits (e.g., to occupants and utilities) and nonmonetary factors, which could affect decision-making, cannot be accounted for.
- Changes in economic conditions, energy prices, technology advancements, and other factors may affect the accuracy of the analysis.

4.3 Results

Life cycle costs for analyzed water-heating technologies are shown in Figure 5. The life cycle cost of the proposed DS-HPWH is centralized configuration is the lowest among all alternatives analyzed. Figure 6 shows the cumulative cashflow for the analyzed systems, where the discounted payback is the year when the cumulative cash flow lines intersect. At 3% real discount rate, the discounted payback for the proposed DS-HPWH in centralized configuration has a 11-year payback vs. centralized natural gas water heaters when incentivized at the level of unitary air source heat pump water heaters for the reference case in Minneapolis, MN.

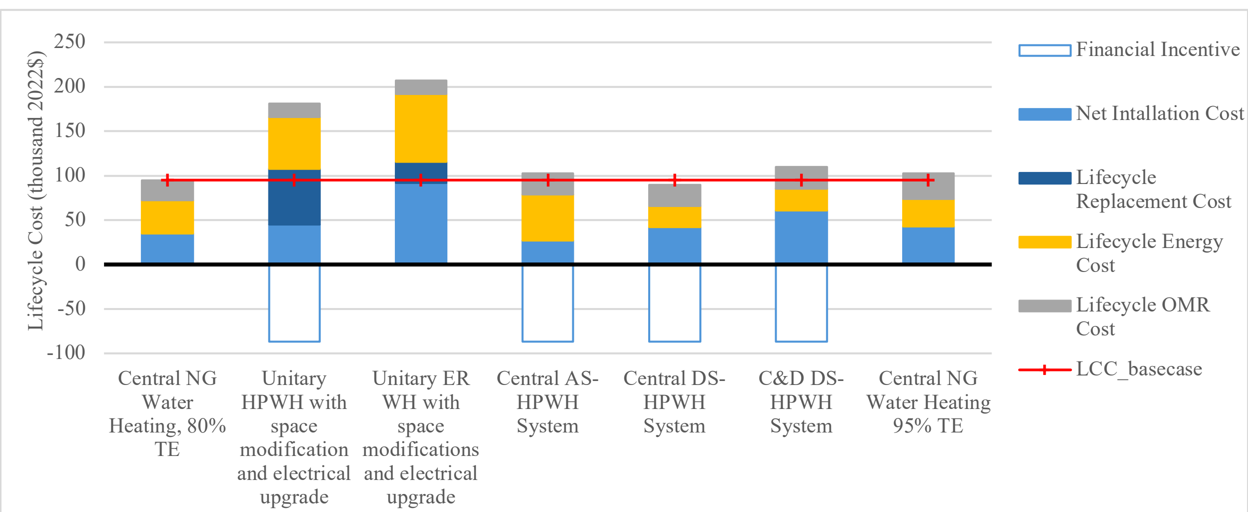

Figure 5: Lifecycle costs for seven water-heating configurations

Further analysis showed a 10-year and 12-year discounted payback at 2% and 5% real discount rate, respectively. The water-source HPWH system is fictitiously incentivized at the level of unitary HPWHs with electrification. ER stands for electric resistance, and OMR stands for operation, maintenance, and repair.

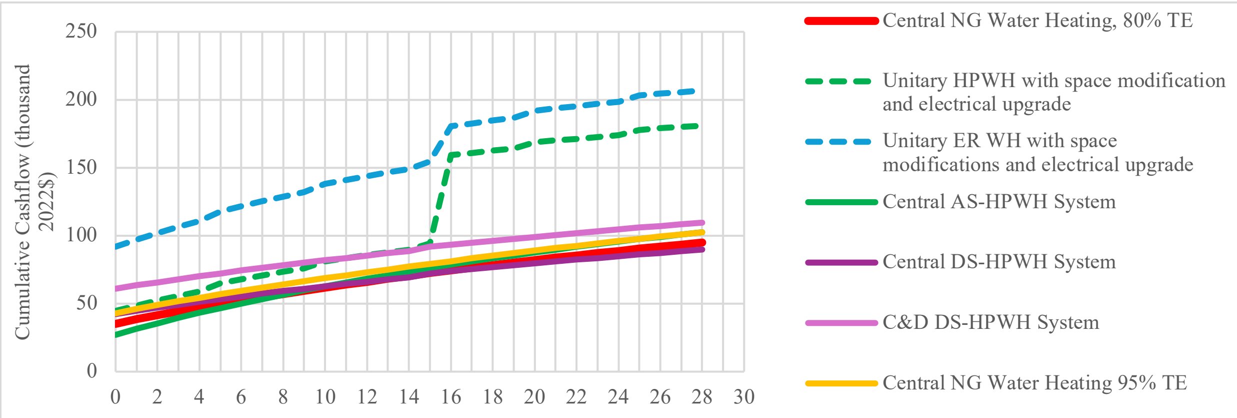

Figure 6: Cumulative cash flows for the seven systems compared in Figure 5

5. DISCUSSION

The LCC analysis compared various water heating solutions, including the proposed DS-HPWH system in centralized and C&D configurations, for multifamily buildings with low- to moderate-income families for cold climates. While the incentives for electrification with space modification for unitary HPWHs are quite high, but the operational cost savings are not sufficient for a payback to exist compared with the NG water heating system.

However, the DS-HPWH system with the same level of incentives as for unitary HPWHs with electrification shows a 11-year discounted payback compared with NG (indicated in Figure 6 as the year when cumulative cashflows intersect) because the performance of the DS-HPWH system in cold climates is much better than the performance of the AS-HPWH systems in the unitary or centralized configuration. The centralized DS-HPWH system has the lowest life cycle energy costs, whereas unitary electric resistance WH has the highest. Additionally, the unitary systems have a replacement cost at year 15 that results in much higher life cycle costs. The centralized systems have higher component replacement costs, but these are not enough to result in a significant difference in Figure 5.

Local utility incentive programs and the cost of connecting to natural gas have not been analyzed in detail for this work. The discounted payback for these water heating systems will vary by utility provide due to additional incentives, the local price of electricity compared to natural gas, and the bill structure of the electricity compared to the natural gas.

The energy price projections used for the LCC analysis are based on how U.S. and world energy markets would operate through 2050 under current laws and regulations as of November 2022 under evolutionary technological growth assumptions. EIA also models side cases including the high and low zero-carbon technology cost cases to examine the sensitivities around capital costs for electricity-generating technologies that produce zero emissions, which include renewables, nuclear, and diurnal storage technologies. The capital costs and operating and maintenance costs may decline over time from learning by doing as commercialization expands and construction and manufacturing experience accelerates. EIA's Low Zero-Carbon Technology Cost case assumes faster, exogenously determined technology cost declines through 2050, resulting in about a 40% cost reduction by 2050 compared with the Reference case (EIA 2023b). These cases will be explored in detail in future LCC work.

6. CONCLUSIONS

The water-heating demand in Minneapolis, Minnesota, was modeled and inputted into the heat pump (HP) system model to determine the energy requirements and coefficient of performance (COP) for multiple water heating systems.-The model COPs were then used as inputs into the Life Cycle Cost (LCC) analysis to determine the energy-based operational costs. The product, installation, and profit costs of various types of water-heating equipment were determined by RSMeans were used as inputs for the net installation cost in the LCC analysis. Finally, incentive programs were identified for the various water heater types. Incentives for the technology with the lowest life cycle energy cost (DS HPWHs) were explored by applying the current incentives for unitary HPWHs with electrification. In conclusion, centralized DS HPWH's appear economical when incentivized at the level of unitary HPWHs and compared to centralized gas water heating. In all modeled cases the DS-HPWH will have higher performance than AS-HPWHs throughout the entire year in cold climates.

This new technology brought together as a system of parts of existing equipment is highly novel and should be widely applicable in new construction and in some retrofit scenarios. Future work of the project is simulated experimental studies of a 2-unit complex and a field site demonstration in a low-to-moderate income family multifamily building in a cold climate.

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