HEAT PUMPS FOR HOT WATER:

INSTALLED COSTS IN NEW HOMES

insight brief

July 2020

AUTHORS:

Michael Gartman
mgartman@rmi.org

Sean Armstrong
Redwood Energy
sean@redwoodenergy.net

KEY INSIGHTS

- **Expected market growth**—Residential heat pump water heaters (HPWHs) are poised for explosive market growth in the coming decade due to technological advancements and political pressure stemming from climate and/or public health initiatives.

- **A knowledge base can counteract market uncertainties**—The HPWH industry suffers from a lack of standardization and available cost data. This insight brief seeks to provide a knowledge base by summarizing data and insights pulled from over 70 different single-family and multifamily developments, leading high-performance homebuilders, and research studies. Additional detail is provided in a technical addendum.

- **Avoided gas distribution can make HPWH the lower-cost option**—Project teams and regulators must consider the cost of gas infrastructure in new residential developments. HPWHs can cost less than gas alternatives in new residential buildings when these infrastructure costs are considered.

- **Distribution bundles can make HPWH the lower-cost option**—Designers can bundle HPWHs with super-efficient hot water distribution components to design a system that costs less to install than a conventionally designed gas system.

- **HPWHs help meet performance standards**—HPWHs are essential efficiency measures for achieving high-performance benchmarks, including California's Title 24 Standard for Code Compliance for multifamily buildings.

- **The future for HPWHs is bright**—Technological progress will yield additional performance gains, contractor training and education can reduce installed costs, and a rapidly changing electric grid will place a premium on the load flexibility services that HPWHs can offer. Also, further renewable penetration will only increase the carbon savings potential of HPWH systems.

INTRODUCTION TO HEAT PUMP WATER HEATERS

Heat pump water heaters (HPWHs) use the same technology that powers your refrigerator to heat your home's hot water, achieving dramatically higher efficiencies than gas or electric resistance options. Despite this advantage, HPWHs are uncommon in existing homes due in large part to higher sticker prices. Over 50% of homes today use water heaters powered by fossil fuels (primarily gas), with the remainder largely using electric resistance heating.[1]

Removing Information Barriers for a Growing Market

The market for HPWHs is growing rapidly, with a 15% compound annual growth rate observed from 2011 to 2019.[2] Further growth is expected in part due to technological progress:

- Heat pumps with an efficiency factor of 3.0–4.0 are now common, representing up to a seven-fold improvement over federal minimum standards for gas water heaters.[i]
- The use of inverter-driven compressors has enabled operation in subfreezing temperatures, opening markets for heat pumps in colder parts of the country.
- Distributors are now introducing HPWHs that operate on 120 Volt, 15 Amp circuits, making HPWHs a viable option for replacing gas heaters in existing homes. HPWHs have previously struggled to penetrate the replacement market, which makes up 82% of all water heater sales.[3]

The heat pump industry also stands to benefit from the growing focus on electrification in cities, states, and countries working toward achieving climate, energy, and/or public health goals. The electric grid is now cleaner than natural gas in much of the United States,[4] and the carbon impact from electrification measures will only improve as the grid gets cleaner. A growing body of research is also revealing the impact natural gas appliances have on both indoor and outdoor air quality.[5] Along with this, a number of governing bodies have already taken action to move away from natural gas. California cities such as San Jose, Berkeley, and Palo Alto no longer permit new gas connections. States including Pennsylvania,[6] Massachusetts,[7] New York,[8] and Virginia are pursuing gas pipeline moratoriums.[9]

Despite this impending growth, HPWH systems remain poorly understood by the North American building industry due in part to a lack of project data and established best practices for these systems. This brief seeks to break that barrier by establishing a knowledge base for residential developers, policymakers, and contractors considering heat pump water heater systems for new residential developments. The data and insights in this report are informed by over 70 past projects, distributor quotes, and cost studies from across the United States. Detailed cost data can be reviewed in the technical addendum provided alongside this report.

---

[i] Statement uses 0.56 UEF, the minimum allowed for a 50-gallon gas water heater under federal appliance and equipment standards (**https://www.energy.gov/eere/buildings/appliance-and-equipment-standards-program**). ENERGY STAR maintains a list of currently available high-performance HPWHs (**https://www.energystar.gov/productfinder/product/certified-water-heaters/**).

HPWH System Options

Part of the challenge with understanding and contextualizing the cost for heat pump water heaters is the sheer number of different options possible. This report covers three system types:

- **Central Systems:** Whole-building water heaters that use a recirculation system shared by all residences in a multifamily building.
- **Individual Systems:** A single 50–80 gallon tank per residence, commonly found in single-family homes as well as many low-rise (one to three story) multifamily buildings.
- **Multi-Central Systems:** A hybrid option where each two to eight residences in a multifamily building share their own central plant, which can use one or more of the same 80-gallon tanks commonly found in individual systems.

Centralized domestic hot water (DHW) systems are commonly specified in multifamily buildings because they save space, reduce design coordination, and are centrally maintained. Central system designs also take advantage of inconsistent demand across tenants to reduce total per-person capacity compared to individual systems, reducing installed costs and providing a benefit for constrained electric grids. However, because most of these central systems rely on long runs of piping to supply and recirculate hot water to and from users, they can be less than half as efficient as individual systems that deliver hot water directly, increasing operating costs.[10]

Individual systems provide one water heater per home, most commonly 50–80 gallon tanks. This system design is common within both single-family and multifamily homes. Tanked heat pump water heaters are factory-built, making them easier to install, design, and maintain. These systems also significantly reduce piping heat losses in comparison to central systems, but generally come at a higher per-residence installation cost.

Multi-central systems utilize the same tanked water heaters used in the individual domestic hot water systems but instead supply clusters of two to eight units per hot water plant, typically distributing water through a manifold. These systems achieve greater operating efficiency than central systems by avoiding recirculation loop heat losses, while resulting in significantly lower installed costs than individual systems due to economies of scale. Multi-central HPWH systems are uncommon today, but they can save more energy and carbon per dollar spent than any other option. This makes them a particularly effective solution for achieving zero-energy standards or other performance benchmarks.

Each system requires additional design considerations:

- Central system sizing is highly dependent on the efficiency of the distribution system that brings hot water from the central plant to occupants (as detailed in this report).
- HPWHs require designers to balance storage capacity, compressor size, and temperature maintenance strategies, with different combinations yielding different cost and performance benefits.
- System placement and ventilation strategies can affect both performance and value. Peak efficiency is obtained by siting systems indoors and ventilating during winter months only, but designers may select a simpler ventilation strategy or choose to site systems outdoors or in unconditioned spaces to maximize rentable square footage.
- Designers must consider the cost and performance benefit of incorporating electric-resistance backup heating (known as a hybrid system), which can reduce installed costs and help guarantee performance at the expense of overall efficiency.
- Costs increase for systems with inverter-driven compressors (which improve efficiency and may be necessary for systems sited outdoors), “smart” controls (which allow greater bill savings for buildings with time-of-use rates or demand charges), and other supplementary features.

All these design variants have a place in different buildings, climates, utility territories, and installer markets, making it challenging to define representative system costs. The wide range of costs shown in this report are also specifically for new construction projects, and do not incorporate the myriad factors that can further influence the cost of a retrofit project.

HPWHS CAN RENDER GAS INFRASTRUCTURE UNNECESSARY

Many system installers assume that heat pump water heaters are simply more expensive than gas systems because similar components (e.g., 50-gallon heat pump tanks vs. 50-gallon gas tanks) often come at a higher cost. However, this calculation typically does not account for the hidden cost of the gas infrastructure necessary to supply gas alternatives. When even a portion of that infrastructure is included, heat pumps become cost-competitive and are sometimes the lowest-cost option available:

EXHIBIT 1

Installed Cost per System Type (Gas Infrastructure Costs Included

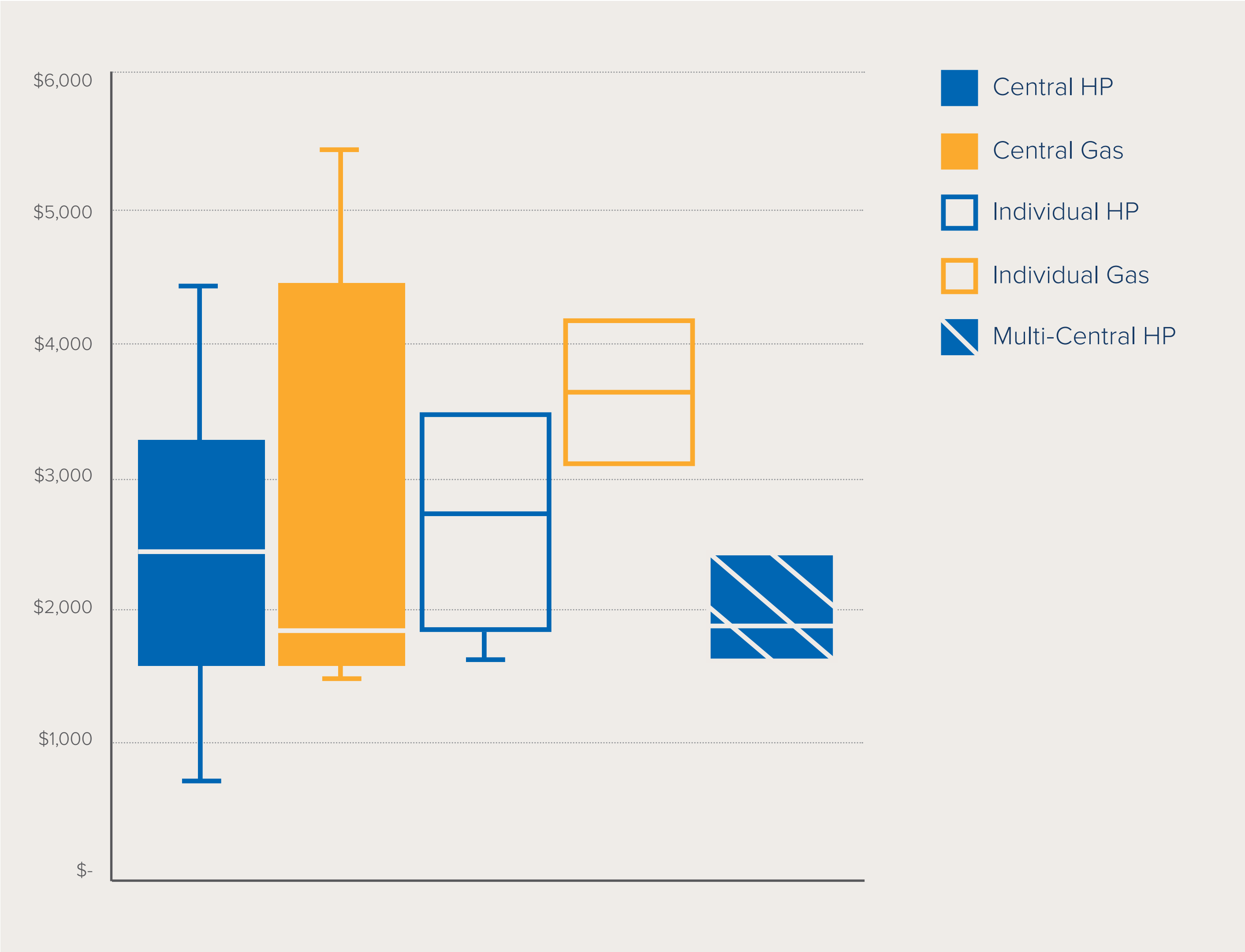


EXHIBIT 2

Installed Cost per System Type (Gas Infrastructure Costs 50% Included)

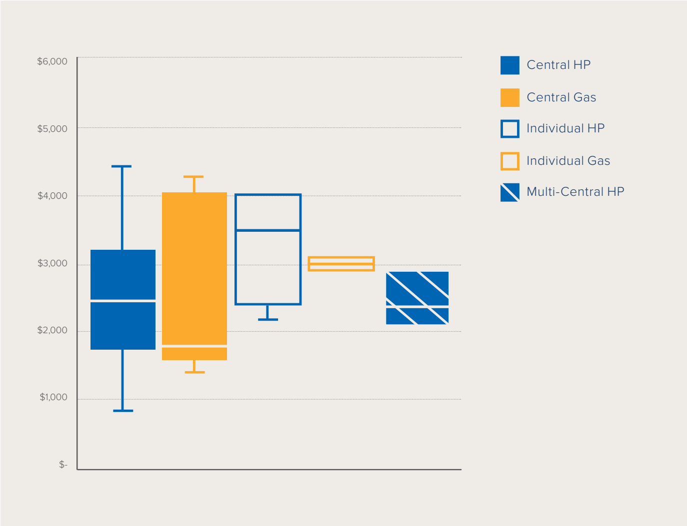
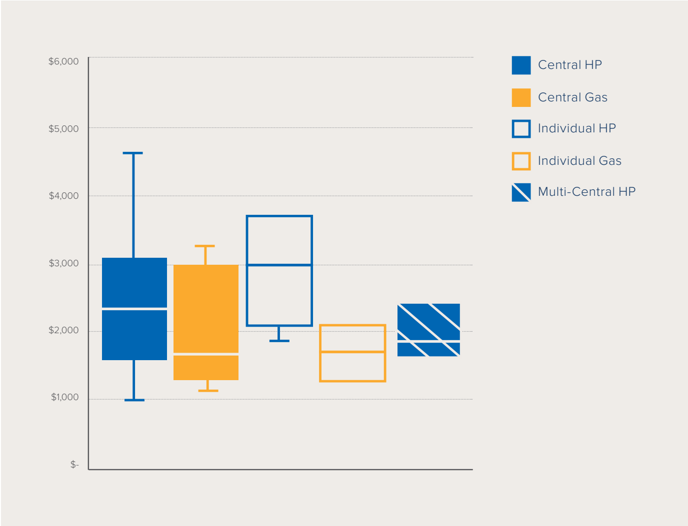


EXHIBIT 3

Installed Cost per System Type (Gas Infrastructure Costs NOT Included)



These cost ranges do not include any rebates or incentives, which can further elevate HPWHs as a cost-optimized option. While some utilities do still offer incentives for gas water heaters, authorities across the country are focusing incentives on HPWHs as part of their efforts to achieve long-term carbon goals and minimize future investments in gas infrastructure.[ii] The most aggressive programs are offered in California:

- BayREN: up to $1,500
- Sacramento Municipal Utility District: Up to $3,000
- Silicon Valley Clean Energy: up to $3,500

Prescriptive rebates are significantly less common for central systems, but performance-based rebates may be available. Developers and contractors must perform their own market research to understand how available rebates impact DHW design considerations. Policymakers should consider these numbers to guide appropriate incentive design.

Unlike gas units, HPWHs in new developments typically do not incur any added cost for electrical infrastructure because modern apartments built with 100–125 Amp, 240V panels are usually able to add 15 Amp, 240V heat pump water heaters, while apartments with 200 Amp, 240V panels are easily able to accommodate 30 Amp, 240V heat pump products.

[ii] No identified rebate offered more than $400 for a gas water heater. This amount is offered by BayREN in California and UGI Utilities in Pennsylvania.

Defining Gas Infrastructure Costs

The added cost of natural gas supply on any given project can vary widely based on site conditions, utility practices, local labor costs, and municipal regulations. The representative costs for gas infrastructure used in this are primarily based off PG&E quotes (normalized to reflect national-average costs) and corroborated against other available project data and reports.[11]

EXHIBIT 4

Gas Infrastructure Components and Representative Costs

COMPONENT	NORMALIZED COST
Main Extension	$15/ft. for single-family $10/ft. for multifamily
Service Extension	$1,700 per building with trenching $1,200 per building without trenching
Meter	$270 for single-family $270 per meter plus $270 per meter manifold outlet for multifamily
In-Home Infrastructure	$730 for single-family $550 per unit for multifamily
Plan Review	$0-$1,000 per building, varies widely by location

New developments that will use gas require a connection to the gas main, a gas meter, lateral service piping between the gas main and meter, and a distribution system within the building. Buildings being constructed in an undeveloped area can also require an extension of the gas main, at a substantial cost increase. Gas utilities often pay part of the cost for these gas main extensions, or even the lateral service piping, based on a profitability assessment—but standard practice varies widely between utilities.

Costs increase significantly where a main extension is needed—but these costs vary widely from site to site. The Fermin Court project profiled for this report represents a worst-case example: this Los Angeles urban infill project required trenching under a busy street to supply natural gas, at an estimated cost exceeding $2,000 per housing unit.

Designers looking to understand the true cost of a natural gas DHW system must also de-rate the estimated cost of natural gas supply to account for the other equipment using it: space heating systems, cooking equipment, and/or clothes dryers. Natural gas end-use breakdowns will vary widely based on local climate and which of these systems are in place—but on average, DHW makes up more than 50% of a 5+ unit multifamily building's gas use.[12] If a DHW system is the only natural gas user specified, 100% of the natural gas supply infrastructure costs should be considered.

The gas infrastructure costs cited in this report only incorporate the costs typically observed by residential developers and do not include additional costs for supply infrastructure and maintenance that are typically recouped through utility bills. Policymakers should consider the full societal cost of the gas infrastructure necessary to provide gas water heating in determining how aggressively to support heat pump alternatives.

SUPER-EFFICIENT SYSTEMS REDUCE COSTS

This brief does not incorporate the ongoing energy and maintenance costs of various heat pump and gas system options, which can vary significantly based on system efficiency, local utility rates, and climate (heat pump water heaters can result in lower operating costs than gas systems in a range of conditions).[13] However, the efficiency of the overall system design can dramatically impact the installed cost because this efficiency defines the system's required capacity. Savvy engineers can design super-efficient HPWH systems that use smaller components to provide the same essential services, resulting in a lower installed cost than a traditionally designed gas alternative.

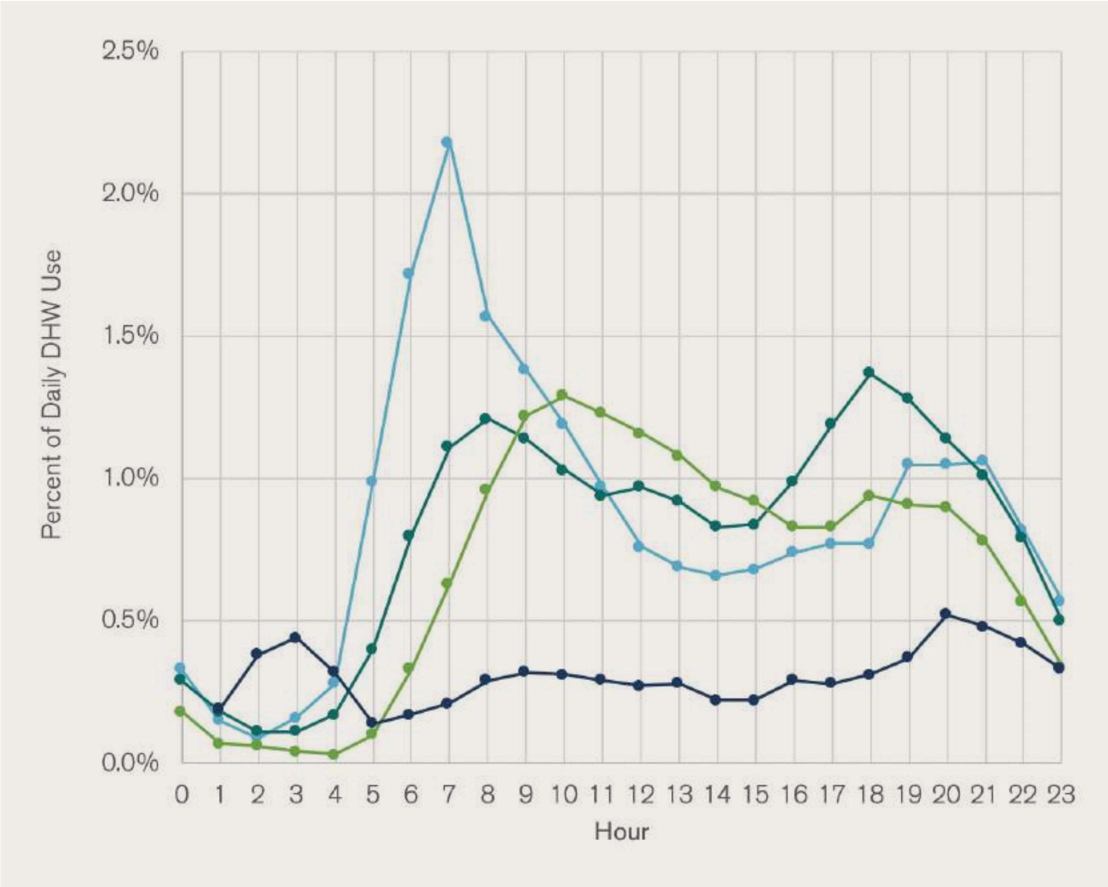
Bundling HPWHs with Super-Efficient Distribution

Bundling an HPWH plant with a super-efficient distribution network can reduce required system capacity by over 50%, resulting in a hot water system that is cheaper than gas systems designed with conventional components.

Standard low-flow fixtures can reduce the required plant capacity of any DHW system by 25%.[iii] Minimizing shower flow rates are a particularly valuable strategy for minimizing peak load, based on national water usage trends:

EXHIBIT 5

National Average Water Load Profiles Per Hot Water End Use[14]



[iii] International Association of Plumbing and Mechanical Officials (IAPMO) calculator utilized to determine 99th percentile demand flow rates assuming one bathroom faucet (baseline 1.5 gallon per minute [gpm], low-flow 1.0 gpm), one shower (baseline 2.0 gpm, low-flow 1.5 gpm), one dishwasher (baseline 1.3 gpm, low-flow 1.0 gpm), and one kitchen faucet (baseline 2.2 gpm, low-flow 1.5 gpm).

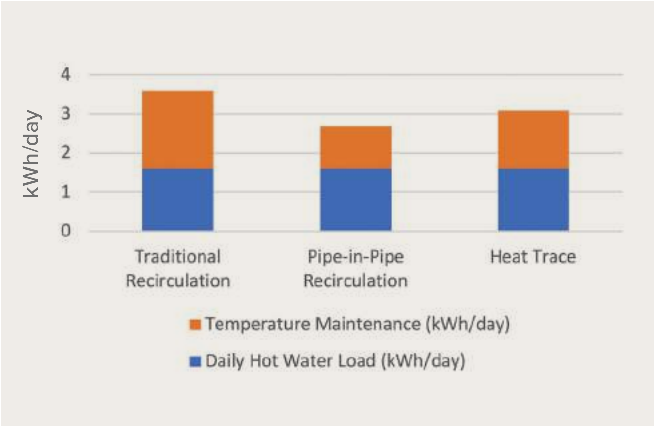
Replacing the traditional 3/4” pipe used for in-unit distribution with smaller 1/2” or 3/8” pipes can further reduce heat loss for all system types and can cut wait times by up to 75%—but these skinny pipes can have a shorter lifetime in areas with hard water, where water softening is necessary. Using flexible PEX tubing rather than copper pipe with 90-degree angles can counteract the friction losses introduced by this smaller piping.

Central systems can further benefit from replacing the long piping runs inherent in traditional looped recirculation systems, which result in both a substantial energy penalty and long wait times for hot water, with more efficient design options such as pipe-in-pipe recirculation systems that cut energy use by as much as 25%.[15]

Using super-efficient distribution components to minimize and flatten DHW loads is particularly important for HPWH systems, where efficiencies are reduced with part-load operation (gas systems yield a negligible performance penalty). More education and training are necessary to empower designers and contractors to ensure that systems are right sized for optimal performance and cost.

EXHIBIT 6

Modeled Energy Use for Three Recirculation System Options



Case Study 1: Solara

- Location: Rotterdam, NY
- Building: 24-unit multifamily
- Normalized Installed Cost: $1,110 per residence

This 24-residence all-electric Passive House apartment complex in upstate New York represents the pinnacle in cutting-edge HPWH performance. The system uses 3 tons of water heating capacity for 24 housing units thanks to a super-efficient distribution system using 3/8" piping and low-flow fixtures to reduce hot water use by 25%. This in turn decreases the heat pump size and cost. The specified Chiltrix heat pumps use an inverter, allowing the compressor to run at the right speed during cold weather in upstate New York. It works even covered in snow. Best of all, it was cost-effective: the $1,110-per-residence price tag was less than half the median cost quoted for central HPWH systems.

Achieving Peak Efficiency with Multi-Central Systems

Multi-central systems minimize efficiency losses associated with distribution systems by serving clusters of homes to reduce the length of required piping runs. At the same time, they are able to take advantage of the efficiencies of scale afforded to central systems. Multi-central system load calculations can reduce per-residence capacity because of the fact you and your neighbors probably won't take showers at the same exact time (known as "usage diversity"). Multi-central systems designed and sized by professional mechanical engineers have paired two to three apartments per 80-gallon tank (set to 140°F with thermal mixing valves), cutting system costs dramatically while still meeting peak loads.

Hot water demand for a multi-central system can also be met by multiple tanked units piped in series to increase redundancy, or by larger products using the more sophisticated technology most commonly used in central systems. Among these products is Sanden's SanCO2, the only HPWH product available in the US market that uses CO_2 as a refrigerant—achieving a dramatically lower global warming potential (GWP) than more common products.

Multi-central system designs are uncommon today and require a forward-thinking design team to implement—but the concept of sharing water with your neighbors has long been used in central systems. These systems are a breakthrough innovation for DHW systems and can result in dramatic energy and carbon savings at a cost competitive with central gas systems.

Creative project designers can place multi-central HPWH plants in a variety of locations to further optimize square footage, cost, and performance. Heat losses are typically minimized by using a manifold for distribution, but recirculation systems can also be utilized effectively.

Case Study 2: Bank Flats

- Location: Philadelphia, PA
- Building: 28-unit multifamily with retail
- Normalized Installed Cost: $2,000 per residence

Onion Flats, a multifamily developer in Philadelphia specializing in the Passive House certified and all-electric design, constructed Bank Flats to zero-carbon performance at only $157/square foot. The firm has utilized multi-central HPWH systems as a cost-optimal measure for achieving Passive House certification, which allows its projects to be prioritized for Pennsylvania Low Income Housing Tax Credit (LIHTC) grant funding.

Bank Flats used a comprehensive cost optimization process to land at a novel water heating layout: 28 units share eight 80-gallon HPWHs with an efficient “pipe in a pipe” recirculation system and 3/8” in-unit plumbing. Each stack of three to four apartments is fed by a plant with two hybrid HPWH tanks plumbed in series and located in the basement. Basement air is conditioned to allow the hybrid water heaters’ single-speed compressors to operate at peak efficiency. This insight brief’s technical addendum includes schematic drawings for Bank Flats.

Case Study 3: Coliseum Place

- Location: Oakland, CA
- Building: 59-unit multifamily
- Normalized Installed Cost: N/A (full cost not provided)

Coliseum Place, a six-floor affordable housing complex developed by Resources for Community Development, uses a similar design as Bank Flats. It has an efficient distribution system with a manifold distributing water to 3/8” piping delivered to each low-flow fixture separately. This design allows 80-gallon HPWHs to serve 2.3 residences each (some residences are served by two separate plants). Each water heater closet is sited and vented to an elevator corridor to simplify installation and optimize HVAC performance.

Cost estimators for Coliseum Place found that the multi-central systems saved $2,950 per apartment over the cost of a central gas system when incorporating 100% of gas infrastructure costs (an electric HVAC system had been specified).

This insight brief’s technical addendum includes schematic drawings for Coliseum Place.

HPWHS ARE IDEAL FOR PERFORMANCE BENCHMARKS

Because HPWHs can use 80% less site energy than a comparable gas system,[iv] they are typically a cost-optimal measure for achieving high-performance benchmarks even when they represent a cost increase over gas alternatives. This was confirmed for single-family homes in RMI's 2018 report ***Economics of Zero Energy Homes: Single Family Insights***, where energy models identified HPWHs as a cost-optimal measure in all six cities modeled.

This performance benefit is especially true of multi-central HPWH systems, which can yield 90% site energy savings over a central gas system option at a comparable cost.[v] These savings are virtually required for achieving zero energy performance in mid-rise multifamily buildings, where a lack of space for rooftop solar systems puts energy efficiency at a premium. The Bank Flats and Coliseum Place case studies profiled in this brief provide two examples of utilizing this design strategy in mid-rise multifamily buildings.

[iv] Compare federal minimum 0.56 UEF for 50-gallon gas furnaces to a 4.0 COP HPWH. Note that realized savings are typically lower than rated for HPWHs because heat pump performance degrades at part-load operation and in colder conditions.

[v] Using the 80% savings assumption detailed previously and an additional 50% savings based on potential losses in a central distribution system as shown in Exhibit 6.

Case Study 4: Mithun Development

- Location: San Francisco
- Building: 105-unit multifamily
- Normalized Installed Cost: $3,540 per residence

Mithun, a leading West Coast architecture firm, found that all six of its 2019 Bay Area multifamily developments could be most cost-effectively constructed with central HPWHs. In one example, the HPWH estimate ran 62% lower than the gas estimate when incorporating 100% of gas infrastructure costs (an electric HVAC system had been specified).

This outcome was largely a result of California's Standard for Code Compliance, which requires that gas systems be offset with a solar thermal array serving 20%–35% of the building's load based on building type and climate (owners often specify larger systems to optimize performance). HPWH systems are not subject to this solar thermal offset requirement.

EXHIBIT 7
DHW Cost Quotes in Mithun Conceptual Estimate

A CHANGING LANDSCAPE

Heat pumps can already be cost-competitive today in a range of scenarios and market conditions should only become more favorable. NREL's 2017 Electrification Futures study projects a roughly 30% reduction in per-unit costs between 2020 and 2040,[16] although distributors surveyed cautioned that more modest savings should be expected. Savings in new construction should largely be driven by a larger and better trained HPWH installer workforce. While material costs are largely expected to remain constant, the same NREL study also projects a 10%–20% gain in rated efficiency factor, suggesting that some future homes will be able to use smaller, less-expensive products to do the same work.

A changing utility grid should provide an additional benefit to the HPWH market. Studies suggest that gas rates in California could exceed $15/therm by 2050, with prices over $4/therm expected even with optimized gas system transition planning.[17] While electricity rates may also increase, they are expected to do so at a slower rate.

HPWHs offer an additional operational savings opportunity when they use "smart" controls, which can optimize operating hours against time-of-use electricity tariffs. These controls provide load flexibility to the grid by prioritizing operation at off-peak times, allowing consumers to reduce their electric bills. RMI's 2017 analysis for ***The Economics of Electrifying Buildings*** found that Oakland-area systems under PG&E's default time-of-use rate could save 3% on their bills with these smart controls—but that homeowners under a more aggressive opt-in rate could save over 20%. Time-of-use electric tariffs are becoming more common nationwide as utilities work to meet the load flexibility requirements and challenges of a highly renewable grid.

Renewable grid penetration provides another benefit for HPWHs: they will cause fewer emissions, making them a better investment for carbon savings goals, as renewables penetrate electricity grids over time. RMI's analysis shows that electrification is already beneficial for reducing emissions from utilities in all but two of the contiguous US states.[18] Future HPWH generations will also be developed with CO_2 and other low-GWP refrigerants, further improving the measure's overall environmental impact.

The expected growth in demand for HPWH systems provides homebuilders, installers, and policymakers with an opportunity to innovate or risk being left behind. Homebuilders and installers should start working with HPWH systems early both to build important new expertise and to differentiate themselves in the market. And policymakers should consider both the importance of HPWH systems in meeting their climate goals and the opportunity that this explosive market growth provides for local job development, an essential pillar of equitable electrification.

APPENDIX: COST DETAILS

The data collected from dozens of projects, reports, and industry leaders surveyed for this brief can be accessed at **rmi.org/insight/heat-pump-hot-water-cost**

The numbers referenced in this report have been normalized to ensure a consistent context across the various data points considered in this study. Three adjustments were made in this analysis to achieve normalized cost numbers:

- **Fully loaded costs:** Many of the cost quotes provided for this report did not incorporate sales tax and/or contractor margins for overhead and profit. These costs were added where necessary. Where standard contractor margins were not apparent from other project information, a 15% margin was added to approximate typical practice.

- **Natural gas infrastructure:** Many of the natural gas system quotes provided for this report made no mention of natural gas supply infrastructure because many contractors consider these costs separately from the cost of their building's natural gas end uses. To ensure a consistent comparison of true costs across natural gas and heat pump system options, rule-of-thumb costs for natural gas supply infrastructure have been added where they were not already present.

- **Local labor cost adjustment:** Many of the cost data points utilized in this report come from California's Bay Area, a hotbed for heat pump installations and a place where construction labor rates can be nearly triple those of low-cost areas in the United States.[19] Normalized costs have been adjusted to account for these regional cost variations using RS Means' 2020 City Cost Indices for mechanical assemblies, providing a national average cost.

Developers and policymakers alike will typically be best served by considering these normalized costs and then adjusting for their project's local conditions (i.e., their assumed contractor margin and labor rates). The raw data collected from report sources can also be accessed in the technical addendum and may be particularly useful for designers in the Bay Area (where many of our quotes originated from).

ENDNOTES

[1] 2015 Residential Energy Consumption Survey, US Energy Information Administration, May 2018.

[2] ENERGY STAR® Unit Shipment and Market Penetration Report Calendar Year 2019 Summary

[3] Glanville, Paul, Gas Heat Pump Water Heaters in CA: Field and Laboratory Results, Mar. 13, 2019.

[4] "What is U.S. Electricity Generation by Energy Source?" US Energy Information Administration, Oct. 25, 2019 update, **https://www.eia.gov/tools/faqs/faq.php?id=427&t=3**

[5] Seals, Brady et al., Gas Stoves: Health and Air Quality Impacts and Solutions, Rocky Mountain Institute, 2020. **https://rmi.org/insight/gas-stoves-pollution-health/**

[6] Hazardous Liquid Pipelines Permitting Moratorium Act, SB 443, (2019).

[7] Pescaro, Matt, "Massachusetts Issues Moratorium on Columbia Gas after Lawrence Gas Leak," *NBC Boston News*, Oct. 23, 2019, **https://www.nbcboston.com/news/local/Massachusetts-Issues-Moratorium-to-Restrict-Work-by-Columbia-Gas-After-Lawrence-Gas-Leak-562113851.html**.

[8] DiSavino, Scott, "National Grid Says No New NYC Gas Customers Without Williams Pipeline," Reuters, May 17, 2019, **https://www.reuters.com/article/us-national-grid-williams-new-york-pipel/national-grid-says-no-new-nyc-natgas-customers-without-williams-pipeline-idUSKCN1SN2GW**.

[9] Fossil Fuel Projects Moratorium; Clean Energy Mandates, HB 1635, Passed by the House 51-48 on Jan 21, 2019. **https://lis.virginia.gov/cgi-bin/legp604.exe?191+sum+HB1635**.

[10] Oram, Sean, "Hot Water Temperature Maintenance Pilot Study," Ecotope, presented at the ACEEE Hot Water Forum Feb 2017; and Zhang, Yanda, *Multifamily Central Domestic Hot Water Distribution Systems*, Prepared for the California Energy Commission by Heschong Mahone Group, June 2013.

[11] Janice Berman to California Energy Commission, December 5, 2019.

[12] 2015 Residential Energy Consumption Survey, US Energy Information Administration.

[13] Shapiro, Carl et al., *Field Performance of Heat Pump Water Heaters in the Northeast*, Pacific Northwest National Laboratory, February 2016, **https://www.nrel.gov/docs/fy16osti/64904.pdf**.

[14] DeOreo, Mayer et al., Residential End Uses of Water 2015, June 2016, Water Research Foundation.

[15] Oram, Sean, "Hot Water Temperature Maintenance Pilot Study," Ecotope, Presented at the ACEEE Hot Water Forum, Feb 2017.

[16] Jadun, Paige, et al., *Electrification Futures Study: End-Use Electric Technology Cost and Performance Projections through 2050*, National Renewable Energy Laboratory, NREL/TP-6A20-70485, 2017, **https://www.nrel.gov/docs/fy18osti/70485.pdf**.

[17] California's Gas System in Transition, Gridworks, 2019; and Aas et al., Natural Gas Distribution in California's Low Carbon Future, Prepared for California Energy Commission, October 2019.

[18] Internal analysis to be published in 2020.

[19] International Construction Market Survey of 2019, Turner & Townsend, **http://www.turnerandtownsend.com/en/perspectives/international-construction-market-survey-2019/international-construction-market-survey-app/**.