Modeling and Analyzing Distributed Heat Pump Domestic Water Heating in Modular Multifamily Buildings

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Abstract

The University of California (UC), Berkeley, Terner Center for Housing Innovation; SmithGroup; and Factory_OS examined the integration of a distributed 120-volt, shared circuit heat pump domestic water heating system in multifamily modular construction. The research team focused on hot water systems because of the high proportion of building energy used for water heating in multifamily apartment buildings in the United States (EIA, 2015); the distributed system focus was chosen for its potential to simplify standardized installation within volumetric modular housing construction practices. The study focused on two primary factors: (1) the energy performance of the distributed heat pump system relative to centralized natural gas and heat pump domestic water heating systems, and (2) the installation cost comparison between a centralized versus distributed heat pump domestic water heating system using modular construction methods. The energy modeling and analysis revealed that centralized heat pump domestic water heating systems in multifamily housing projects could offer 29-percent energy savings compared with traditional, natural gas-fired systems; furthermore, distributed heat pump water heater systems can save an additional 3 percent in energy use compared with centralized equivalents. Built using offsite modular construction techniques, the distributed heat pump hot water system adds an anticipated $1,800 in per-unit installation costs compared with centralized systems without factoring in rebates and incentive programs. In-factory installation also provides potential benefits not captured in this estimate, including faster installation times and higher quality control to minimize onsite rework and maintenance (a common issue with traditional onsite installation), alongside electricity savings throughout a project's life cycle.

Introduction

The sustained rise in housing costs in many metropolitan areas across the United States reflects the severe shortage in housing production relative to the growing demand for more affordable housing options (Kingsella and MacArthur, 2022; Woetzel et al., 2014). Simultaneously meeting the demand for new housing across the country necessitates changes to homebuilding processes that minimize detrimental environmental impacts of new home construction over a building's life cycle, including embodied carbon and energy-efficient operation. Growing legislative momentum at local, state, and federal levels reflects this necessity, including the recent Inflation Reduction Act, which provides more than $50 billion through various programs for sweeping building decarbonization across the United States (Jenkins et al., 2022). This research focuses on two primary design constraints for new housing: environmental impact reduction through energy efficient operations and affordable construction. The more acceptance of technologies, products, and processes that reduce the time, cost, and environmental impact of new housing, the more effectively the United States can address the dual challenges of housing affordability and climate change.

Without cost-saving processes and mechanisms to manage upfront construction costs, previous Terner Center analysis revealed that existing sustainability-focused building codes in California may inadvertently increase the cost of new housing construction by up to 4 percent (Reid, 2020). Without targeted intervention, continued expansion of well-intentioned, environmentally progressive codes pushing for further energy efficiency or full decarbonization (for example, net-zero buildings) may inadvertently increase the already-high costs of new housing construction (Raetz et al., 2020; Reid, 2020). Modular and other offsite construction methods respond to the urgent need to lower the cost and time required for housing development, especially in the multifamily market in dense metropolitan cores, where housing demand and construction costs are high (Bertram et al., 2019; Pullen, 2022). Several recent, overlapping studies from the National Renewable Energy Laboratory (NREL) and funded by the U.S. Department of Energy (DOE) found that modular construction is also uniquely positioned to incorporate resilient and energy-efficient design at reduced costs and with higher quality control, potentially providing more reliable performance over the life cycle of the building (Klammer et al., 2021; Pless et al., 2022; Podder et al., 2020).

This research builds on those and other studies to demonstrate the impact of incorporating distributed heat pump water heater (HPWH) technology into modular construction practices to meet the urgent, intersecting demands of future U.S. housing stock. Both technologies are relatively new or re-emerging in U.S. markets, according to existing studies (Pullen, 2022; Pullen, Hall, and Lessing, 2019) and the research team's interviews with housing industry professionals. Providing real expectations of the energy savings and cost impact of this integration helps developers and architects make informed decisions while balancing construction costs with increasingly ambitious building emissions targets.

The support of the U.S. Department of Housing and Urban Development (HUD) is instrumental for this research because HPWH and modular construction techniques have relatively low (but growing) adoption in the U.S. housing market, according to more than 20 person-hours of interviews conducted by the research team. Although both technologies have higher adoption in other countries, such as Japan, Finland, and Sweden (Bertram et al., 2019; Manley and Widén, 2019), the U.S. context introduces novel risks, opportunities, and challenges (Pullen, Hall, and Lessing, 2019). Thus, government-funded research can assess the viability and potential of coordinated technological interventions such as modular construction and distributed HPWHs to encourage and mitigate the risk of early adopters. That support further improves confidence among industry practitioners and investors—including many of those interviewed—spreading familiarity, adoption, and knowledge sharing, which can ultimately accelerate the production of high-quality housing, built affordably and with minimal environmental footprint.

Research Design

To conduct the analysis, research collaborator SmithGroup provided several prototypical floor plans—for studio, one-bedroom, two-bedroom, and three-bedroom unit layouts—each with local 120-volt shared circuit HPWHs and drain water heat recovery (DWHR) units. The researchers developed the layouts, including plumbing piping and equipment, in the 3D building information modeling software Revit. Detailed energy models evaluated the relative energy performance of natural gas versus HPWH systems and centralized versus distributed HPWH systems. To test the results' sensitivity to climate, the researchers ran energy models using DOE's representative cities for the nine major climate zones in the United States.

Modular housing collaborator Factory_OS provided construction cost estimates for the domestic water heating schemes based on the detailed Revit models and current factory operational information. The distributed system costs were compared against a standard design for a centralized hot water system requiring field installation of the supply and recirculation piping. Future research steps will combine the construction cost information and energy cost data from the whole building energy modeling to provide a combined life-cycle cost assessment. Further analysis will include differences in expected construction duration between onsite and offsite methods and the expected development cost savings.

Technology and Product Review

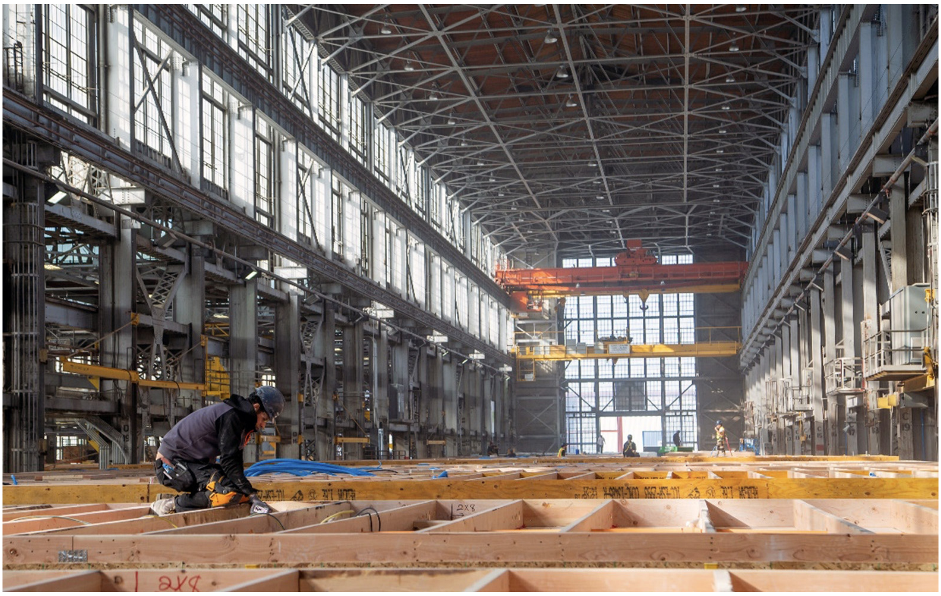
This section introduces the construction method, mechanical systems, and design used in the study.

Modular Construction

Volumetric modular construction is a specific method of offsite and industrialized construction that brings a substantial portion of construction work (as much as 90 percent of total construction value in some cases) into a controlled factory environment. This method often consists of major structural, mechanical, plumbing, and electrical work, incorporated into a full 3D "box" that is then transported to and placed on site. The module can be self-contained to comprise an entire apartment unit (such as a small studio), or several modules can be connected on site to create larger apartment units. See exhibits 1–6 for examples of modular construction processes in Factory_OS's facilities in Vallejo, California, and exhibit 7 for an example of how multiple modules combine to form a two-bedroom unit.

Exhibit 1

Factory_OS Assembly Line



Overview of modules moving through the assembly line. Image courtesy of Autodesk.

Exhibit 2

Factory_OS Assembly Line

Wall assembly on the factory floor using gantry cranes. Image courtesy of Autodesk.

Exhibit 3

Factory_OS Onsite Module Installation

Hallway photo showing site-built connections planned for corridors. Image courtesy of Factory_OS.

Exhibit 4

Interior of Module at Factory_OS

Modules can be shipped with full interiors, including interior finishes and appliances. Image courtesy of Factory_OS.

Exhibit 5

Factory_OS Module Onsite Placement

Setting factory-built modules on site-built concrete podium. Image courtesy of Factory_OS.

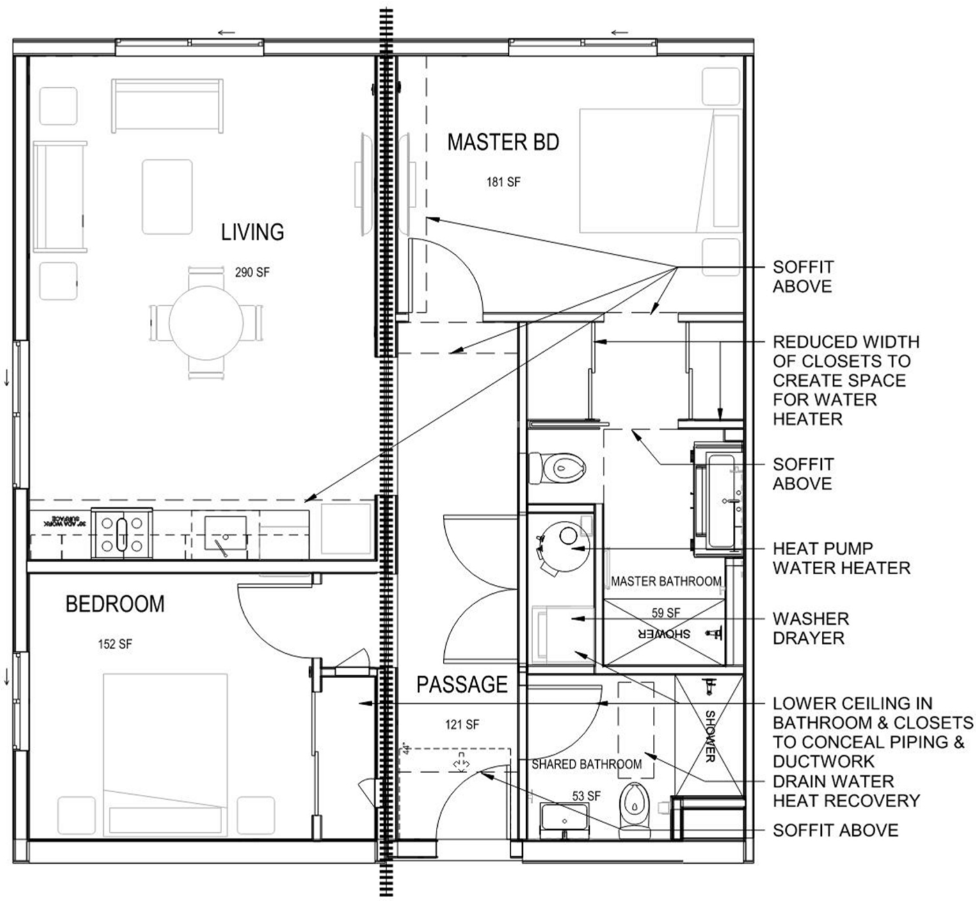
Exhibit 6

Factory_OS Module Onsite Placement

Modular construction in progress on site. Image courtesy of Factory_OS.

Exhibit 7

Two-Bed Apartment Consisting of Two Factory-Built Modules



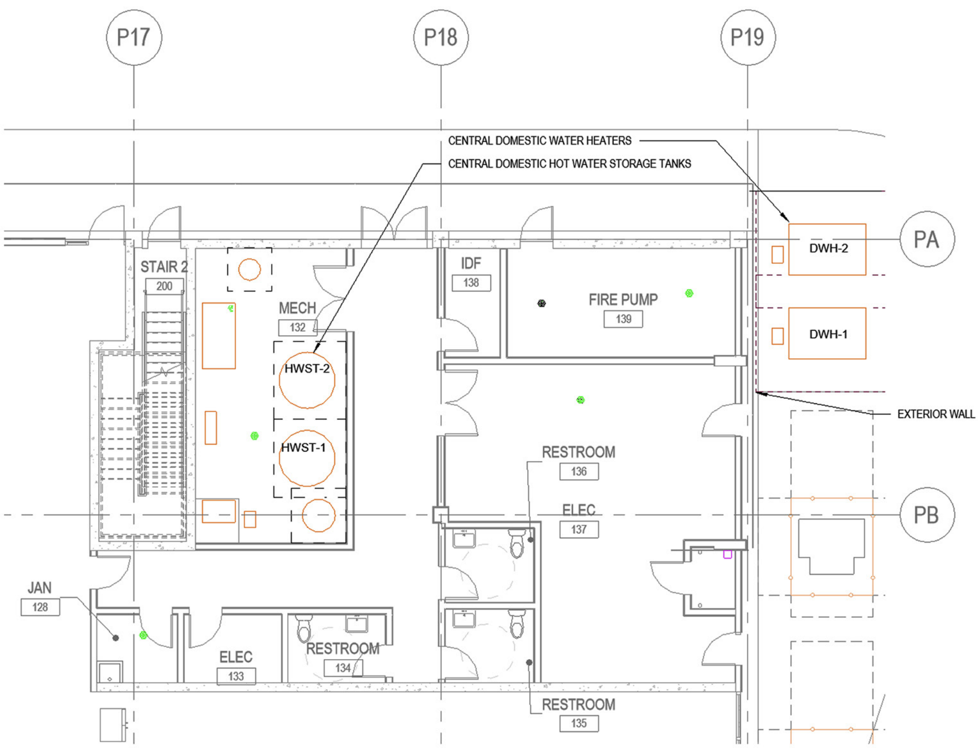
Note: Example of two-bedroom unit using two modules, with module mate line dashed at the center.
Source: Factory_OS

The major motivation for pursuing modular techniques is often the promise of time and cost savings, along with better building quality (Bertram et al., 2019; Pullen, 2022). Time savings largely result from the parallel onsite and offsite work streams; for example, onsite crews can begin excavation and foundation work while in-factory crews assemble apartment units—two work streams that would otherwise need to happen in sequence. Cost savings may occur as a direct result of the time savings and from increases in labor productivity and material efficiency through optimized factory production (Pullen, 2022). Better quality control practices using manufacturing principles and practices may also improve building quality and ultimate project performance (Pless et al., 2022). Finally, factory production can simplify construction processes to be more accessible and ergonomic, lowering the barrier to entry for unskilled workers and increasing diversity in the workforce (Pullen, 2022).

In proven performance toward those potential benefits, a growing body of evidence suggests that offsite construction offers total time savings in the range of 10 to 40 percent and cost savings in the range of 5 to 25 percent compared with traditional onsite construction (Decker, 2021; Pullen, 2022; Smith and Rice, 2015). However, recent research from the Terner Center found that housing industry stakeholders in California only see the *time* savings to be relatively consistent across projects, while cost savings are less predictable and more difficult to measure precisely (Pullen, 2022). Other benefits, including as-built quality and workforce development benefits, show the promising but inconclusive potential that will likely improve as industry familiarity and adoption increase (Pullen, 2022; Smith and Rice, 2015). Nonetheless, interest and investment in offsite and industrialized construction practices continue to grow across the United States, particularly in areas with high housing demand and skilled labor costs (Bertram et al., 2019; Pullen, Hall, and Lessing, 2019).

Exhibit 8

2121 Wood Street First-Level Mechanical Room



DWH = domestic water heater. HWST = hot water storage tank.

Notes: Centralized heat pump water heating system indicated as DWH-1 and DWH-2 (outside building) and HWST-1 and HWST-2 (inside mechanical room). Distribution piping is hidden for clarity. PA, PB, P17, etc. are architectural notation to distinguish building sections.

Source: Factory_OS

Domestic Hot Water Heat Pump Water Heaters

Heat pump systems are commonly used in heating, ventilation, and air-conditioning (HVAC) systems as an all-electric option to heat or cool the air in residential and commercial buildings. However, this technology can also be applied to heating water and is a substitute for fossil fuel-based domestic water heating systems, such as natural gas-fired water heaters or less efficient electric resistance water heaters.

Centralized Domestic Hot Water Heat Pump Water Heaters

In conventional stick-built construction, domestic hot water HPWHs used in large commercial buildings are typically centralized in a mechanical room, which includes a large air-sourced heat pump and storage tank (exhibit 8). In addition, a centralized heat pump design requires a lot of field-installed supply and recirculation piping with associated insulation. The vast amount of domestic hot water piping leads to energy losses as hot water is pumped through the building and transfers heat to its surroundings. A centralized HPWH system used as the reference case for this research project is based on a modular construction project in Oakland, California. The design includes two air-sourced heat pumps that sit outside the building (example in exhibit 9), extract heat from outdoor air, and send it to hot water storage tanks inside the mechanical room. Domestic hot water is then distributed throughout the building from the storage tanks. Although the individual apartment modules are constructed off site, the central water heating system requires field installation and connections to each apartment, which increases construction coordination complexity and field construction time.

Exhibit 9

Typical Example of Central Domestic Hot Water System (Before Insulation of Piping)

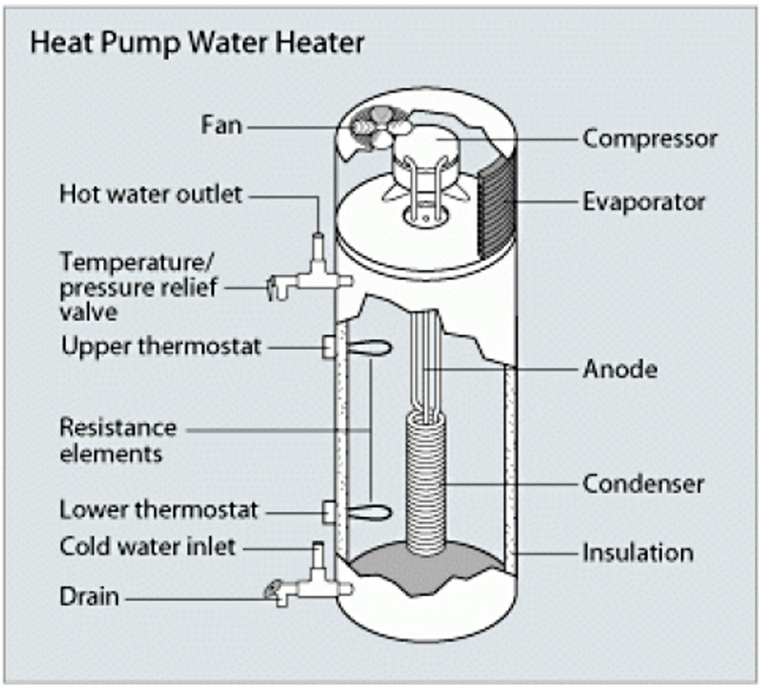
Large installations on roof are most common. Used with permission of Colmac WaterHeat.

Distributed Domestic Hot Water Heat Pump Water Heaters

This system leverages the advantages of prefabricated modular construction by allowing full installation of HPWH and domestic hot water (DHW) piping in the factory, with reduced onsite connections required (for example, for potable water, sanitary waste, and vent connection). Prefabrication requires an all-in-one heat pump (that is, storage tank plus heat pump) rather than the split (tank separate from heat pump) centralized unit used in the reference case. For this study, the all-in-one heat pump (with an example diagram in exhibit 10) is located inside an enlarged closet in the prefabricated apartment modules and extracts heat from inside the occupied space.

Exhibit 10

Representative All-in-One Heat Pump



Note: Compressor, evaporator, condenser, and water storage all provided as single unit.
Source: U.S. DOE

The research team studied off-the-shelf, readily available HPWHs on the market for feasibility. A recent development in the distributed HPWH market is the shared circuit unit, which was used as the basis of design for this research. The shared circuit unit has a smaller electrical load than other products (which frequently offer hybrid operation with a less efficient electrical resistance backup mode) and is designed to plug into a standard 120-volt, single-phase outlet, sharing a 15-amp circuit with other electrical loads. This product targets the retrofit market to simplify natural gas water heater replacement without requiring upgraded electrical service, but the all-in-one installation also aligns well with modular housing methods.

A Note on Distributed HPWH Tank Sizing

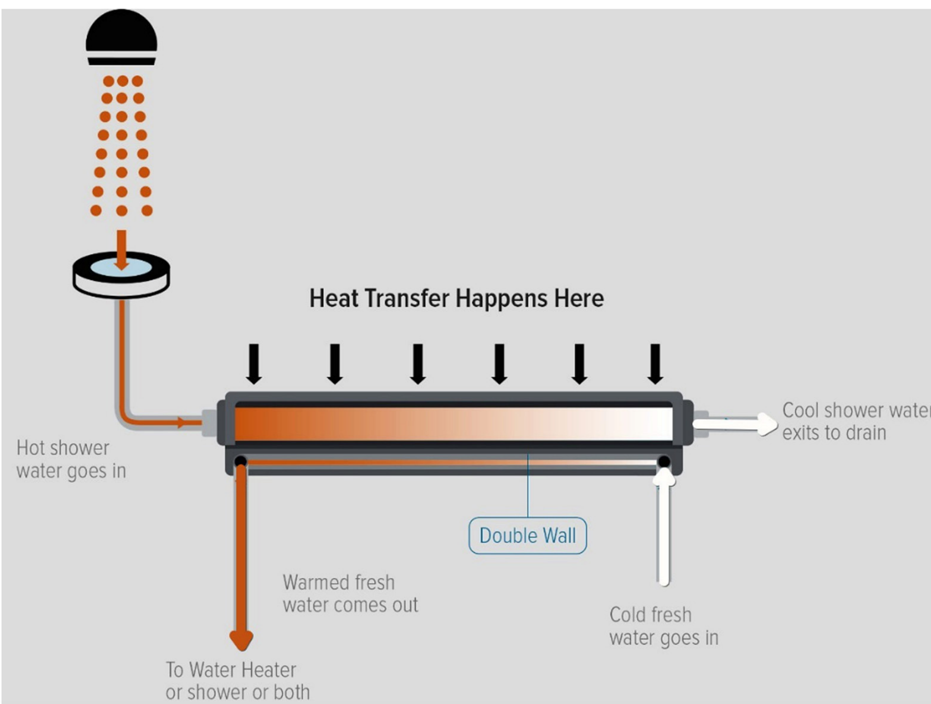
Although the hot water demand profile varies between a studio, one-bedroom, two-bedroom, and three-bedroom apartment, cost advantages to scale exist in real-life projects. Instead of varying the heat pump tank size for each apartment type, the team designed each apartment with the same 50-gallon model. In addition to being sufficient to meet peak hot water demand and recovery rates for all apartment sizes and occupancies on the reference project, using a standard model size for the entire project provides additional cost savings and ease of coordination within the factory. However, tank sizing should be decided on a project-by-project basis.

Drain Water Heat Recovery

DWHR devices exchange heat between warm shower drain water and incoming domestic cold water. As shown in exhibit 11, flow streams do not directly mix: heat is conducted through a metal heat exchanger. The device recovers some of the energy spent heating the shower water after going down the drain to raise the temperature of incoming water without additional electricity use.

Exhibit 11

Horizontal Drain Water Heat Recovery

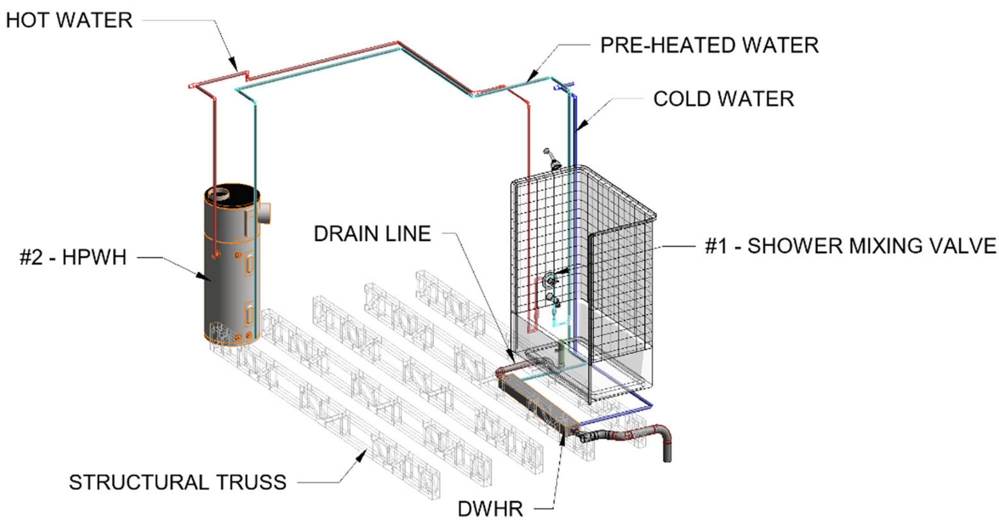


Source: Ecodrain

Minor design adjustments included using a horizontal DWHR (rather than a vertical one), which improves in-factory assembly and reduces distribution heat loss due to proximity to the water heater and shower fixture, but it also slightly increases the risk of clogging (exhibit 12).

Exhibit 12

Diagrams of HPWH and DWHR used in Research Model



DWHR = drain water heat recovery unit. HPWH = heat pump water heater.

Notes: The horizontal drain water heat recovery device pre-heats incoming cold water that is then sent to the shower mixing valve (#1) and heat pump water heater (#2). DWHR coordination from Revit model showing slim profile of heat exchanger allows it to fit between structural framing, with other building elements hidden for clarity.

Overview of Reference Project Used for Analysis

To provide applicable and representative cost and energy use comparison, the research for this project focused on a comparison to a prefabricated 235-unit multifamily building under construction in Oakland, California, for which SmithGroup provided the full engineering design for the mechanical, plumbing, and electrical systems (exhibit 13). This project, 2121 Wood Street, included a centralized HPWH system that directly informed model assumptions and acted as a real-life reference point for energy use and construction cost comparison.

The layouts used as the “base case” for the studio, one-bedroom, and two-bedroom units were designed for the Wood Street project. Each unit type originally included a washer/dryer closet that was enlarged to accommodate the in-unit HPWH for the distributed system. Additional adjustments were made to the layout to accommodate accessibility standards frequently attached to affordable housing funds—a consideration independently recommended by several industry professionals with experience in modular construction and affordable housing projects. In the following sections, the authors use the studio unit to illustrate the changes made for the distributed water heating system (exhibit 14). Similar changes have also been documented for the one- and two-bedroom units in the base case, and a three-bedroom unit was designed with similar intent (although it did not exist in the base case).

Exhibit 13

Reference Project, 2121 Wood Street Architectural Rendering

Source: MBH Architects

Exhibit 14

Architectural Floor Plans of Studio Unit

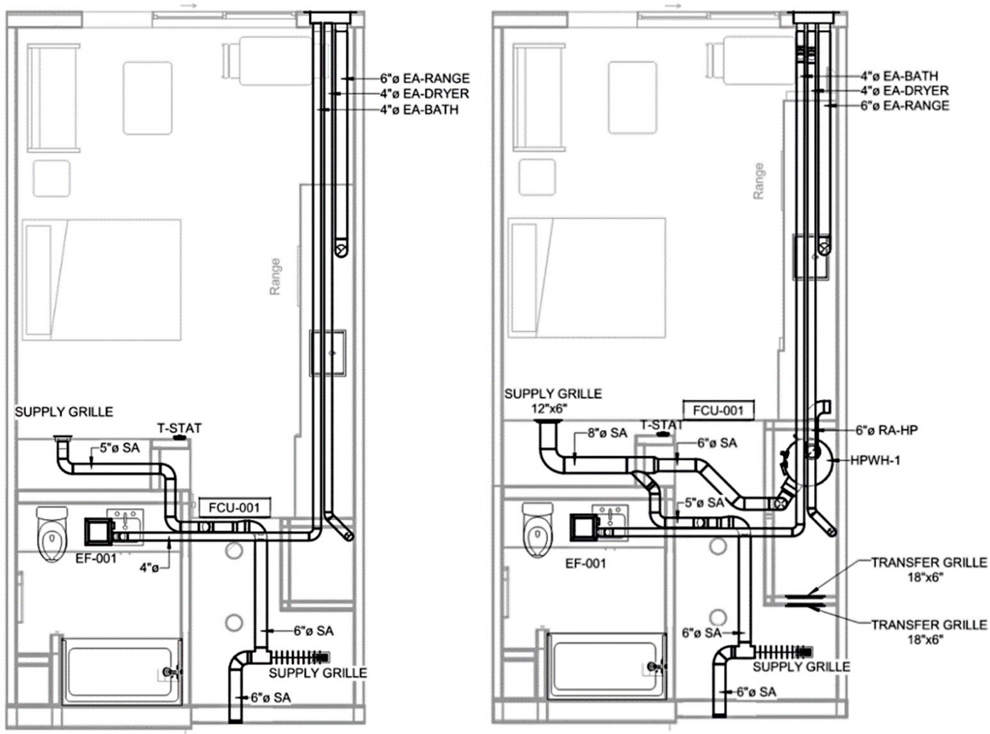
DWHR = drain water heat recovery. HPWH = heat pump water heater.

Note: Architectural floor plans of studio unit comparing base case (left) to revised design with heat pump water heater and drain water heat recovery (right).

The HVAC system was also modified to accommodate the HPWH, which requires two ductwork connections, a source-air inlet, and a discharge air outlet. To minimize the duct runs and to keep the plumbing design compact, the team elected to have the HPWHs use the room air as the source air. The cool air is ducted to mix with neutral temperature air from the central ventilation system to lower the impact of cool discharge air dumped directly from the HPWH into occupied space. Additional design adjustments mitigated the risk of nuisance sound from the HPWH compressor and fan operation. Exhibit 15 highlights the HVAC system layout, and exhibit 16 diagrams the warm air inlet and cool air outlet.

Exhibit 15

HVAC Floor Plans

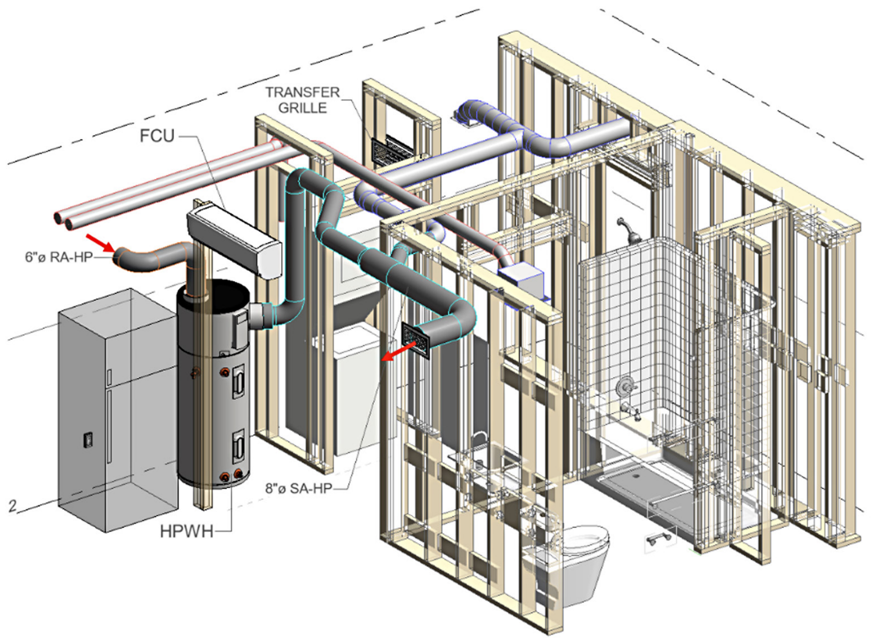


EA = exhaust air. EF = exhaust fan. FCU=fan coil unit. HPWH = heat pump water heater. RA = return air. SA = supply air. T-stat = thermostat.

Notes: HVAC floor plans highlighting changes between reference building, shown on the left, and modified building, shown on the right. Recirculation hoods are not allowed in California, so the kitchen hood ("range" on plan) is exhausted directly outdoors.

Exhibit 16

Warm Air Inlet and Cool Air Outlet



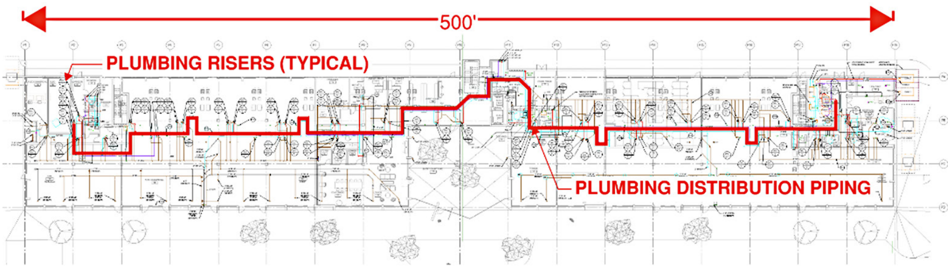
FCU = fan coil unit. HPWH = heat pump water heater. RA-HP = return air to heat pump. SA-HP = supply air from heat pump. Transfer Grille = opening to transfer air into closet.

Note: View showing warm air inlet (arrow in background) and cool air outlet of HPWH (arrow in foreground).

Mechanical piping and plumbing-related modifications were the most extensive changes. Specifically, the entire centralized domestic water heating distribution system was removed. For reference, 2121 Wood Street is a six-story building with approximately 5,000 linear feet of domestic hot water recirculation piping. Exhibits 17 highlights the extensive piping for the central domestic water heating system that can be removed with the distributed system, and exhibit 18 shows the in-unit piping that replaces it.

Exhibit 17

Plumbing Plan

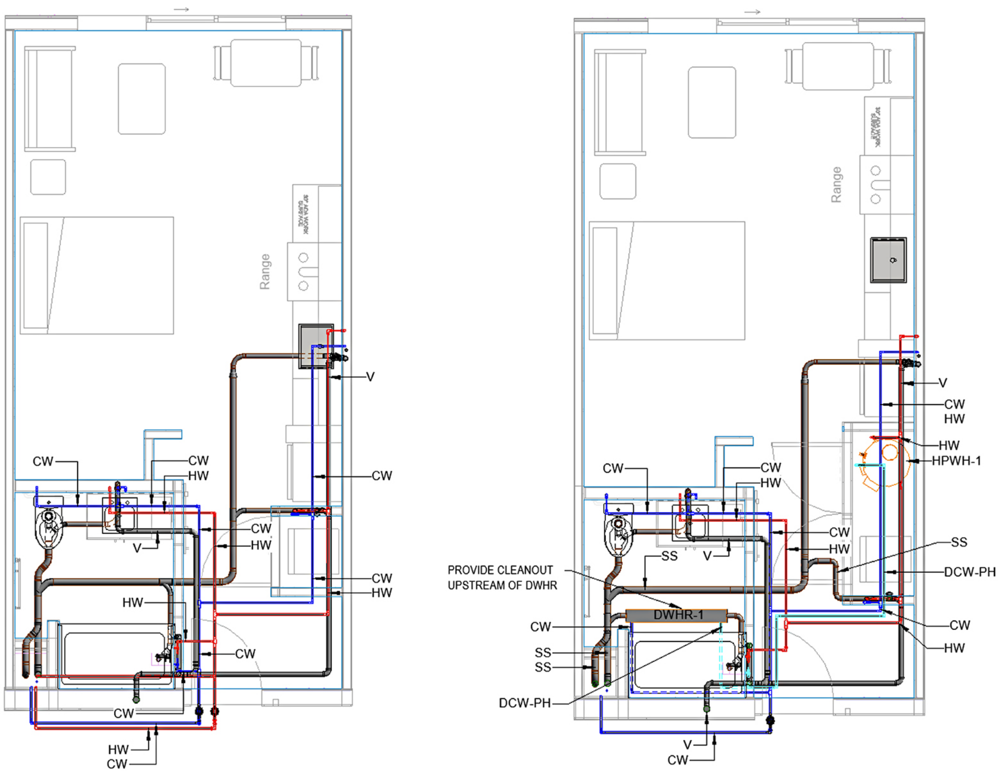


DHW = domestic hot water.

Notes: Ground level plumbing plan highlighting the domestic water heating distribution and recirculation piping that serves vertical risers through each apartment unit. This scope was removed in the modified building with distributed heat pump water heaters.

Exhibit 18

Plumbing and Mechanical Piping Plans



CW = cold water. DCW-PH = pre-heated domestic cold water. DWHR = drain water heat recovery. HW = hot water. V = vent. HPWH = heat pump water heater. SS = sanitary.

Notes: Plumbing and mechanical piping plans show the reference case on the left and the modified plan on the right. The hot water piping in the corridor from the centralized system (bottom of reference case plan) has been removed in the modified plan. Also, the modified plan shows the addition of the pre-heated domestic cold-water piping from the DWHR device.

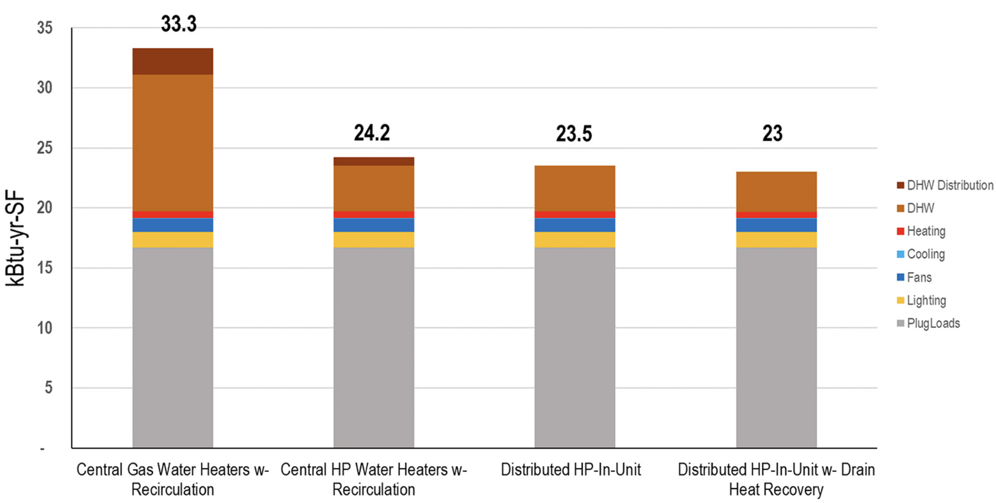
Findings

Energy Analysis Findings

The annual simulation results of the whole building energy model from the reference case 2121 Wood Street building demonstrate that a distributed heat pump domestic water heating system uses less energy annually than a centralized heat pump water heating system in Oakland, California (exhibit 19). Both heat pump water heating options, centralized and distributed, outperform a traditional gas-fired central water heater-based domestic hot water system. The distributed HPWH design, which included free cooling and drain water heat recovery, further reduced energy use. Compared with centralized HPWHs, most of the energy savings for the distributed HPWHs came from removing the hot water distribution recirculation system. Even when insulated to current code requirements, a centralized DHW distribution network results in significant heat loss from the hot water to the interior of the building because the circulating hot water acts as a radiator along the full piping system (on the interior of the building). A centralized HPWH resulted in 29-percent annual energy savings over the gas-fired domestic water heating system. The distributed HPWHs, accounting for impacts to heating and cooling loads (for example, free cooling) during DHW generation, resulted in 3-percent total energy savings compared with a central HPWH. The DWHR system provided an additional 2- to 2.5-percent savings. If all measures were combined, the distributed HPWHs with the free cooling and DWHR produced 31-percent savings—and up to 35-percent savings in cool climates—compared with the centralized gas-fired water heating system. For this analysis, the cool climate was assumed to be Rochester, Minnesota.

Exhibit 19

Baseline Versus Proposed Water Heater Systems



DHW = domestic hot water. HP = heat pump. kBtu-yr-SF = kilo-British thermal units per year per square foot, a measure of energy use normalized for time and building size.

Note: Example energy modeling results from a project located in Oakland, California.

The team expanded the energy modeling analysis to explore if the results found in Oakland, California, would be replicated in other climate zones. The primary impact in different climate zones is whether the "free cooling" produced by cool discharge air from the distributed HPWHs is beneficial or harmful to annual energy use. This relationship is quite complex to model, as it requires an understanding of hourly cooling and heating demands and the behavioral impacts of when an occupant uses domestic hot water. The research team altered DHW fixture draw profiles to represent a realistic day-to-day operation in reference to the research paper from Big Ladder Software (Kruis et al., 2017). Using the above draw profiles, the team was able to perform parametric runs in each climate zone to understand the impacts of the free cooling and the impacts from storage tank heat losses into the space.

The results are somewhat intuitive. In hot, warm, and mild climates, the free cooling provides a benefit to total annual energy use. However, in mixed, cold, and very cold climates, the free cooling is detrimental to overall annual energy use, as the distributed HPWH effectively steals heat from the interior space which must be made up by the space heating system. Exhibit 20 shows the total annual energy impact of the free cooling for a typical one-bedroom unit. The percentage of total energy offset with free cooling is the percentage difference in annual energy with HPWH being inside the unit (free cooling included) versus being located outdoors (free cooling excluded).

Exhibit 20

Impact of Free Cooling from Heat Pump Water Heater on Annual Energy Use

ASHRAE Climate Zone	Climate Condition	Representative City	% Total Energy Offset with Free Cooling
0A	Extremely Hot Humid	Ho Chi Minh City	-0.05%
0B	Extremely Hot Dry	Abu Dhabi	0.12%
1A	Very Hot Humid	Honolulu	0.13%
1B	Very Hot Dry	New Delhi	0.03%
2A	Hot Humid	Tampa	-0.02%
2B	Hot Dry	Tucson	0.06%
3A	Warm Humid	Atlanta	-0.20%
3B	Warm Dry	El Paso	-0.05%
3C	Warm Marine	San Diego	0.04%
4A	Mixed Humid	New York City	-0.44%
4B	Mixed Dry	Albuquerque	-0.37%
4C	Mixed Marine	Seattle	-0.07%
5A	Cool Humid	Buffalo	-1.23%
5B	Cool Dry	Denver	-1.14%
5C	Cool Marine	Port Angeles	-0.11%
6A	Cool Humid	Rochester	-1.88%
6B	Cool Dry	Great Falls	-1.42%
7	Very Cold	International Falls	-2.35%
8	Subarctic/Arctic	Fairbanks	-2.80%

ASHRAE = American Society of Heating, Refrigerating, and Air-Conditioning Engineers.

Note: Positive percentages reflect beneficial free cooling from heat pump water heater, whereas negative percentages indicate that cool air from heat pump water heater increases energy use.

The distributed HPWH outperforms a centralized HPWH system regardless of the climate zone. Even in the extremely cold climate zone 8, locating the heat pump within the unit results in less than a 3-percent penalty on annual energy use. In all climate zones in which distributed HPWHs had detrimental impacts on annual energy use, it was still less in magnitude than the increase in energy associated with a centralized system's recirculation loop.

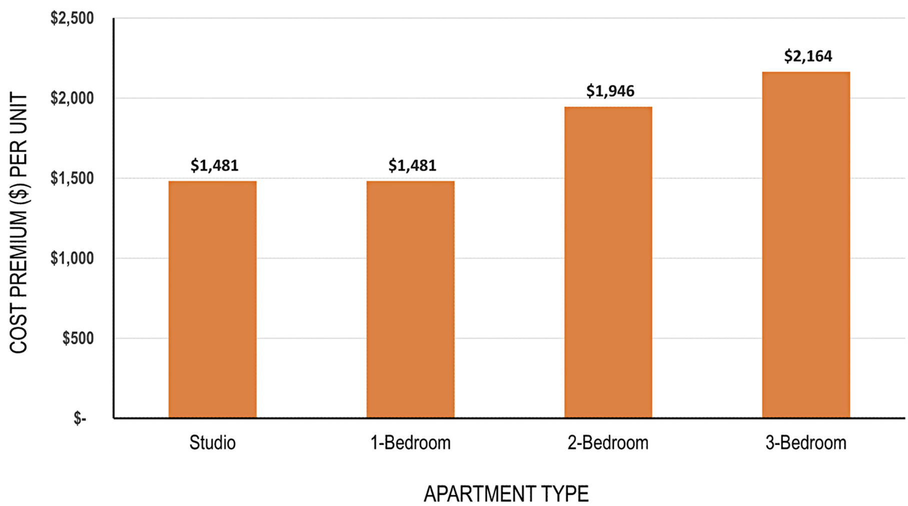
Construction Cost Findings

In modular construction, having an in-unit HPWH will necessarily increase the material and labor cost of the individual prefabricated module compared with a centralized system with only a whole-building HPWH system and no in-unit DWHR (as with the reference project). The cost premium of the distributed system relative to the centralized system reflects an estimate from Factory_OS in the summer of 2022, noted because of product pricing fluctuations due to continued supply chain variability and uncertain impacts of ongoing inflation. The net cost-per-unit premium was calculated by determining each module's cost increase associated with the distributed system relative to the module's base scope with a centralized system, then subtracting the per unit site-built deduction cost. The per unit site built deduction was calculated by dividing the cost of the centralized system's site-built scope by the total number of units in the 2121 Wood Street building. The site-built scope deduction included the plumbing and electrical scope associated with the centralized domestic water heating system, including large central heat pump water heaters, storage tanks, distribution piping, and the recirculation pump. The site-built deduction is based on Oakland, California, labor rates as of 2022 and will vary greatly on the basis of region and year. In the distributed system, domestic cold water piping to the apartments will need to accommodate the additional makeup water flow to the individual HPWHs. However, the flow increase was insufficient to increase the domestic cold water piping size and thus was not considered a cost addition.

The research team compared the electrical system impact of centralized and distributed domestic water heating systems using the reference project for cost differences. The building at 2121 Wood Street has two centralized heat pumps, and each heat pump has a larger compressor and electrical load than an individual distributed HPWH. If applying a shared circuit HPWH distributed system, approximately 235 HPWHs would be distributed across the building's apartment units. The HPWHs would be on a general-purpose receptacle circuit; the kitchen equipment has dedicated circuits. The latter approach offers increased electrical load diversity and resulted in approximately 130 amps less in site electrical load when compared with the centralized system. In the case of 2121 Wood Street, this electrical load reduction was not enough to reduce service size (for example, the size or quantity of required transformers or both); however, having a potential reduction—or at least being electrical load neutral—is a benefit of the distributed approach and could allow for service reductions on projects with a different electrical load profile. Exhibit 21 reflects the final result of the estimated cost comparison across system types.

Exhibit 21

Distributed System Cost Premium After Site Work Deductions



Note: Graph shows cost premium broken out by apartment unit type.

After factoring in the site-built scope deduction, the cost premium of the distributed system varied from approximately $1,500 to $2,200, increasing with the number of bedrooms. For 2121 Wood Street, that would result in approximately $370,000 premium to the project, an approximate 0.5 percent increase in total project cost. These costs do not factor in potential rebate and incentive programs that may be available, given the passage of the Inflation Reduction Act, or through other state and local programs, which could ultimately reduce the cost premium of the distributed system.

Whereas the research team found a material and labor cost premium to the distributed system, prefabricated modules with distributed HPWH systems offer potential time savings to the project by reducing onsite construction scope. However, this factor is difficult to precisely measure due to multiple overlapping onsite trades and subcontractors involved with centralized system installations and, thus, is outside the scope of these estimates.

Factory-built housing may also provide potential quality control improvements that are of particular interest for distributed HPWH systems: the research team's industry interview feedback and the team's experience are that installation problems can frequently undermine the performance (and promised energy savings) of those systems. Modular construction techniques, however, can incorporate an optimal design and installation procedure for HPWHs within each enclosed module, ensuring consistent and reliable installation and inspection practices. Doing so can also integrate in-unit space and water heating capabilities in a standardized set of apartment units offered on multiple projects, which could dramatically reduce the upfront design scope compared with centralized heating systems for multifamily housing projects (which must be designed project to project).

Conclusion

The research findings are promising. Both centralized and distributed HPWH can dramatically reduce domestic water heating and overall building energy use compared with natural gas systems. Although the distributed HPWH system has a per-unit cost premium, modular construction approaches provide benefits to project schedule and installation quality that are not yet captured in this preliminary research. However, integrating distributed HPWH systems into modular building methods is not without unique challenges and opportunities to consider when translating research toward industry adoption:

Building codes: Prescriptive building codes across the United States may not be amenable to innovation in the built environment, including offsite construction processes and HPWH systems. Building codes are often written with onsite construction in mind (Colker et al., 2022), and even minor improvements such as the horizontal DWHR device may require amendments or exceptions to existing local codes. Such adjustments for specific products or technologies can be made, but increased adoption of performance-based codes could more broadly improve the viability and application of innovative, cost-saving, and energy-efficient technologies.

Permitting and inspection processes: Around the country, administratively complicated, unpredictable, and inconsistent permitting and inspection processes can challenge any procedural or technological innovation in construction, including offsite methods. Efforts to streamline and improve the consistency of local permitting procedures allow effective solutions to grow and provide their maximum potential benefit toward affordability and sustainability goals. This statement is especially true for strategies, such as modular construction, that depend on consistent outputs for factory-produced units. Procedural improvements to permitting could include the following:

- Single-agency review, in which developers submit plans through only one local government agency rather than separate submissions and sequential review by planning, fire, building, and public works departments.
- Limits on discretionary review (which can be time-consuming and assess projects based on subjective review standards), such as the adoption of objective review standards in the zoning code.
- Regional or state government interventions that limit local jurisdictions' ability to limit new housing construction, particularly jurisdictions failing to meet housing production needs. Massachusetts 40B, a state law passed in 1969, does exactly this, and Terner Center researchers found several tangible benefits that include lowering the cost of affordable housing construction and making housing delivery more efficient (Reid, Galante, and Weinstein-Carnes, 2016).

Sustainability-focused policies: New and existing tax credits to encourage advanced energy efficiency could cover all or part of the upfront installation cost of distributed domestic hot water heating systems. Early analyses of the Inflation Reduction Act found more than $50 billion dedicated to building electrification and energy efficiency in buildings, primarily through tax credits and rebate programs, for which new multifamily housing construction should be eligible

(Jenkins et al., 2022). Products such as HPWHs (distributed and otherwise) should be eligible for many of these programs, but limited eligibility and administrative constraints may present new challenges. Those challenges may be especially true for aligning incentives with builders and owners of rental properties, many of whom do not see the bulk of the cost savings from upfront investments in energy efficiency. To support the uptake of progressive energy efficiency funding, existing subsidies for affordable housing at multiple levels of government could also add scoring criteria to encourage and reward highly energy- and cost-efficient designs and construction methods. Such scoring systems would tangibly incentivize the adoption of cost-effective, high-quality new construction and send an important signal to researchers and practitioners that could improve and proliferate processes and products to accelerate the trend further.

Learning curves: Professionals across the diverse housing industry—from architects to general contractors to skilled laborers and beyond—will require exposure to and training for any new technology or process in housing construction. These barriers require coordinated engagement across historically fragmented stakeholder networks (including multi-scalar government agencies). Early efforts to accelerate the adoption of technologies such as these include the Advanced Building Construction Collaborative, a DOE-funded initiative to connect and grow viable solutions to many of the challenges facing the built environment industry. The team's broader research initiative will elaborate on potential barriers and opportunities for policy and industry interventions to unlock and encourage the proposed gains from the dual innovations analyzed. The research team will continue to work with industry trade associations, other academic institutions, the press, and government agencies at multiple levels to ensure wide dissemination and amplification of this work. The goal is to remove obstacles to make standard practice out of quality design and construction at affordable costs.

Glossary

centralized water heating system—system for heating water, driven by a large, centralized unit that stores and distributes water, with interconnected piping throughout the entire building. Typically, the water heaters and storage are located on the ground level and can be electric or gas fired.

distributed or decentralized water heating system—system that includes a series of independently operating water storage and heating units in each housing unit in an apartment building, typically located inside a closet.

drain water heat recovery (DWHR)—system that recovers heat from warm shower water going down the drain to preheat cold, incoming water before entering the water heater, saving energy.

electric heat pump—equipment that sources ambient heat from indoor or outdoor air to warm or cool a space, using electricity rather than onsite fossil fuels. Heat pump performance is directly proportional to its coefficient of performance, a metric representing the ratio of useful work output (for example, heating) to input energy required. Typically, heat pumps have coefficients of performance higher than 1, meaning that they produce more energy in heat than they use in electricity.

factory-built or modular housing—housing in which each apartment unit is built to substantive completion in an offsite manufacturing facility, including structural (floors, walls, and ceilings), mechanical, electrical, and plumbing systems. Elements are assembled in the factory to produce the modular "boxes" that are then transported to a project site, with potential savings in project time and cost.

free cooling—the ability of a heat pump water heater to cool the air around it during operation. Free cooling is a result of the heat pump operation that takes warm source air from the room and uses it to generate domestic hot water. The source air then discharges from the heat pump and returns to the room as cool air. This cooling effect is considered free cooling because it is a byproduct of the heat pump water heater's primary goal, which is to generate hot water.

heat pump water heater (HPWH)—equipment option for generating hot water in centralized or distributed systems using electric heat pumps. Typically, these devices source ambient heat from outdoor or indoor air. Heat pump water heaters are not typically considered part of the full-building space heating or cooling system, but they provide free cooling during operation to the individual unit in which they are installed.

shared circuit heat pump water heater—120-volt single-phase distributed heat pump water heater with low current draw that does not require a dedicated electrical circuit. In other words, it can plug into a standard U.S. electrical outlet on a 15 A circuit and share that circuit with other electrical loads in a residential setting.

site-built construction—conventional style of construction, in which raw materials are ordered and shipped separately to be assembled and erected primarily on site.

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