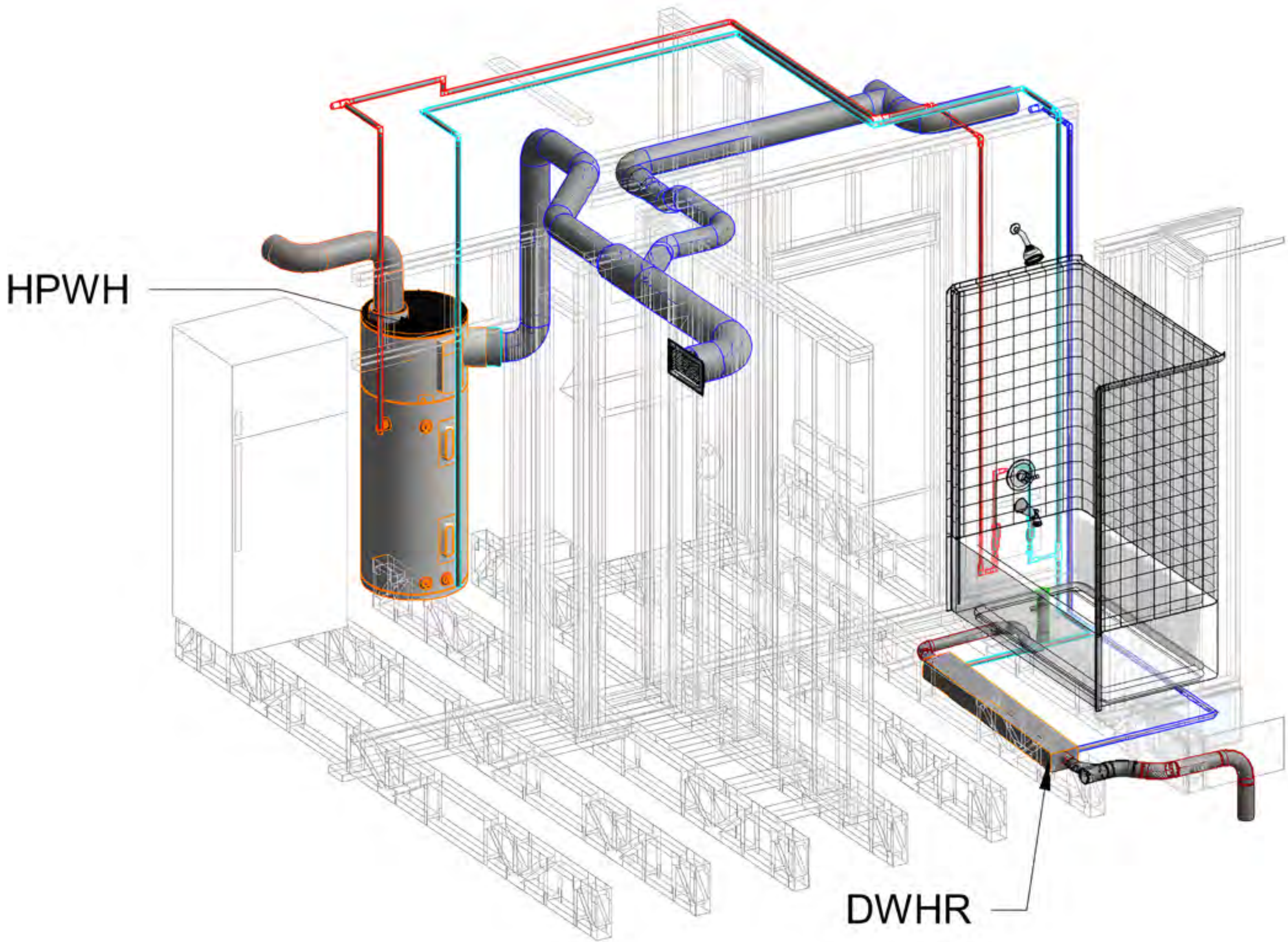
Analyzing Cost and Energy Use Impact of Integrated Hot Water Systems in Modular Construction



U.S. Department of Housing and Urban Development | Office of Policy Development and Research

DISCLAIMER

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Analyzing Cost and Energy Use Impact of Integrated Hot Water Systems in Modular Construction

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Foreword

The Biden-Harris administration is committed to cutting total greenhouse gas emissions by at least 50% by 2030. Achieving such a drastic reduction in housing requires both high energy efficiency and a transition from the use of fossil fuels. In housing, the electrification of heating systems is an important step in the transition to net zero energy and building decarbonization.

This report, *Analyzing Cost and Energy Use Impact of Integrated Hot Water Systems in Modular Construction*, examines the potential of distributed versus centralized electric heat pump water heater systems in volumetric modular multifamily housing application. According to the U.S. Energy Information Administration, water heating accounts for a large proportion of building energy use in multifamily apartment buildings in the United States, making it a potential significant source for energy savings resulting from a transition to electrification.

The energy modeling and analysis described in the report found that centralized or distributed heat pump domestic water heating systems in multifamily housing projects can offer 29 percent energy savings compared to traditional, natural gas-fired systems. Distributed heat pump water heater systems can save an additional 3 percent in energy use compared to a centralized electric heat pump.

In addition to the energy saving and greenhouse gas reducing potential of heat pump water heater, the in-factory installation of the heat pump water heaters offers other potential benefits including faster, simplified, and quality-controlled installation that can be standardized across projects, reducing installation issues (which can compromise performance) and design time and complexity compared to centralized systems.

The evidence in this report helps building owners and developers justify the additional costs of heat pump water heaters. The distributed, modular construction approach examined in this report is potentially scalable to small multifamily and multi-unit (2–5 unit) single-family structures that constitute a substantial share of the U.S. rental stock. As the nation faces housing and climate crises, we hope that developers and building owners will consider utilizing modular construction methods and distributed heat pumps. These sustainable technologies can help alleviate the crises and offer advantages such as faster build times, reduced waste, improved quality control, energy savings, and lower carbon emissions.

Solomon Greene
Principal Deputy Assistant Secretary for Policy Development and Research
U.S. Department of Housing and Urban Development

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EXECUTIVE SUMMARY

UC Berkeley's Terner Center for Housing Innovation, SmithGroup, and Factory_OS examined the potential of integrating a distributed 120-volt, shared circuit heat pump domestic water heating system in multifamily modular construction. Water heating comprises a high proportion of building energy use in multifamily apartment buildings in the U.S. (EIA, 2015), and a distributed system with individual heat pump water heaters in each unit aligns well with volumetric modular housing construction practices. The study focused on two primary factors: 1) the energy performance of a distributed electric heat pump water heater system relative to centralized systems using either natural gas or electric heat pumps, and 2) the life cycle cost comparison between these systems based onsite and in-factory, modular installation cost estimates for an actual reference project. The energy modeling and analysis found that centralized or distributed heat pump domestic water heating systems in multifamily housing projects can offer 29 percent energy savings compared to traditional, natural gas-fired systems; furthermore, *distributed* heat pump water heater systems can save an additional 3 percent in energy use compared to a centralized electric heat pump. With an offsite modular construction approach, the distributed system adds an anticipated $500 to $2,200 in per unit installation costs compared to centralized systems (without factoring in rebates and incentive programs), and the centralized electric heat pump system offers the lowest life cycle cost. However, in-factory installation offers additional potential benefits including faster, simplified, and quality-controlled installation that can be standardized across projects, reducing installation issues (which can compromise performance) and design time and complexity compared to centralized systems. HUD and other government agencies are in a unique position to support greater energy efficiency in multifamily housing by potentially incentivizing these heating systems and construction techniques in funding opportunities, offsetting initial system costs through rebate programs, and expanding research opportunities into innovative technologies and processes.

GLOSSARY

Coefficient of performance (COP)—metric used to represent performance of a heat pump. It is the ratio of useful work output (e.g., heating) to input energy required. Typically, heat pumps have COPs greater than 1. The larger the COP, the better the performance.

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 ground level and can be electric or gas-fired.

Distributed or decentralized water heating system—system 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)—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, which is typically higher than 1. This means that it produces more energy in heat than it uses in electricity.

Factory-built or modular housing—where 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 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 do provide "free cooling" to the individual unit they are installed in during operation.

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 15 A circuit and share that circuit with other electrical loads in a residential setting.

Site-built construction—conventional style of construction where raw materials are ordered and shipped separately to be assembled and erected primarily onsite.

INTRODUCTION

The sustained rise in housing costs in many metropolitan areas across the U.S. 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 minimizing the environmental impacts of housing over its full life cycle, including both embodied carbon (in the materials used for construction) and occupancy. 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).

Without cost-saving processes and mechanisms to manage upfront construction costs, however, well-intentioned sustainability-focused building codes such as net-zero building requirements may inadvertently increase the cost of new housing construction (Raetz, et al., 2020); one Terner Center for Housing Innovation study found that green building codes in California increased upfront construction costs by up to 4 percent (Reid, 2020). Simultaneously, modular and other offsite construction methods are a response to the urgent need to lower the cost and time required for housing development. This is especially true in the multifamily housing sector in dense metropolitan cores, where housing demand and construction costs are high (Bertram, et al., 2019; Pullen, 2022). The success of these methods could improve the feasibility of urban infill housing, a generally more energy- and resource-efficient development pattern than urban sprawl, with positive implications for affordability and equity in many metropolitan regions (Echenique, et al., 2012; Güneralp, et al., 2017; Manville, Monkkonen, and Lens, 2022). Additionally, several recent, overlapping studies from the National Renewable Energy Laboratory (NREL), funded by the Department of Energy (DOE), found that modular construction is 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 a building (Podder, et al., 2020; Klammer, et al., 2021; Pless, et al., 2022).

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

HUD's support is instrumental for this research because both HPWHs 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. Though both technologies have higher adoption in some international contexts—such as Japan, Finland, and Sweden (Bertram, et al., 2019; Manley and Widén, 2019)—the U.S. market introduces novel risks, opportunities, and challenges (Pullen, Hall, and Lessing, 2019; Pullen, 2022). Thus, government-funded research can assess the viability and potential of coordinated technological interventions—in this case, modular construction and distributed HPWHs—to encourage and mitigate the risk of early adoption. Government interest and support also increases exposure to and comfort with new technologies and processes for industry practitioners and investors, promoting further research and knowledge sharing. **The more synergy between technologies, products, and processes that reduce the time, cost, and environmental impact of new housing, the more effectively the U.S. can address the dual challenges of housing affordability and climate change**. Government support and continued investment into research and program incentives and rebates will be critical for informed acceleration of sustainable housing development.

RESEARCH DESIGN

To conduct the energy 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) systems. They 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 centralized heating systems using either natural gas or HPWHs, as well as distributed (decentralized) systems with HPWHs with and without DWHR products in each unit. To test the results' sensitivity to climate, energy models were run using DOE's representative cities for the nine major climate zones in the U.S.

The modular housing collaborator Factory_OS provided construction cost estimates for the different water heating schemes based on the detailed Revit models and current factory operational information. They compared the expected costs of a distributed system built during in-factory modular assembly against the real-life costs for a centralized HPWH system (requiring field installation of the distribution loop) for one of their projects in the San Francisco Bay Area.

The energy modeling data, construction cost estimates, and energy cost information provided the basis for the combined life-cycle cost assessment. Additional factors assessed include system and regional grid impact on greenhouse gas emissions, as well as qualitative considerations such as indoor thermal comfort and potential benefits of factory-based housing production beyond the quantitative analyses.

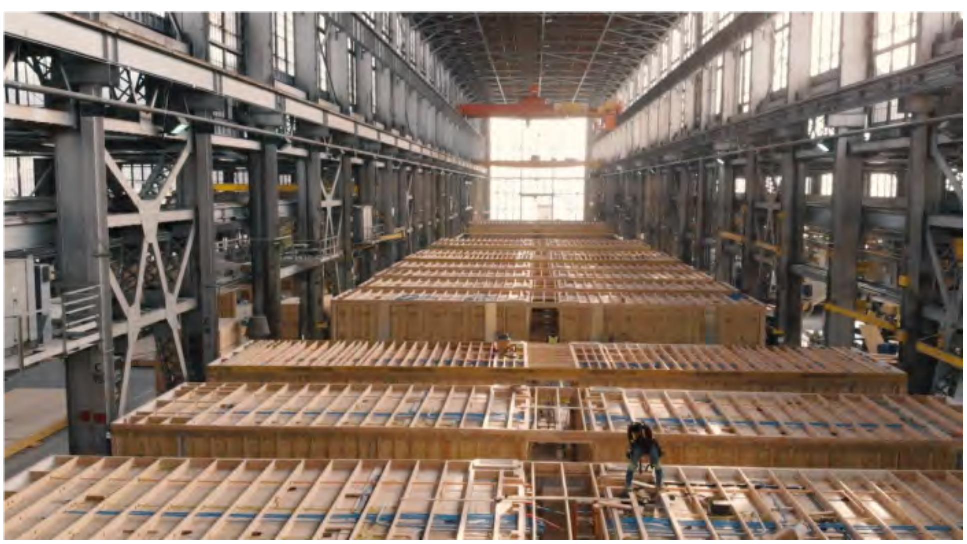
TECHNOLOGY / PRODUCT REVIEW

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

MODULAR CONSTRUCTION

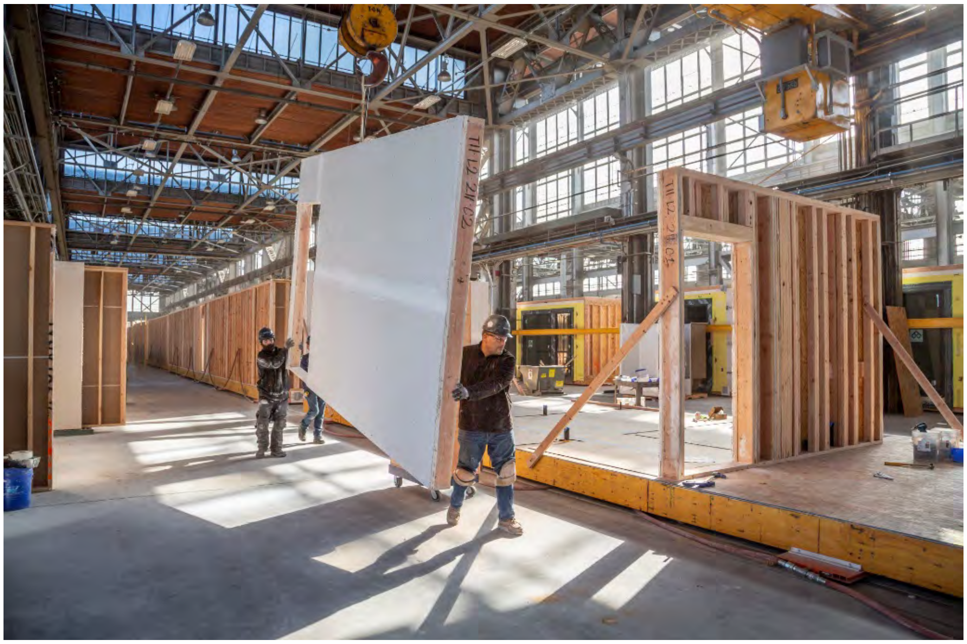
Volumetric modular construction is a specific method of offsite and industrialized construction that brings a substantial portion of construction work (as much as 90 percent of total construction value in some cases) into a controlled factory environment. This work often consists of major structural, mechanical, plumbing, and electrical work incorporated into a full 3-dimensional "box" that is then transported to and placed onsite. The module can be self-contained to comprise an entire apartment unit (such as a small studio), or several modules can be connected onsite to create larger apartment units. Exhibits 1–6 show snapshot examples of the modular construction processes in Factory_OS's facilities in Vallejo, California, and exhibit 7 portrays a typical two-bedroom apartment layout configured using two connected modules. The following section provides more detail on the unique aspects of Factory_OS business model and methods.

Exhibit 1. Factory_OS Assembly Line



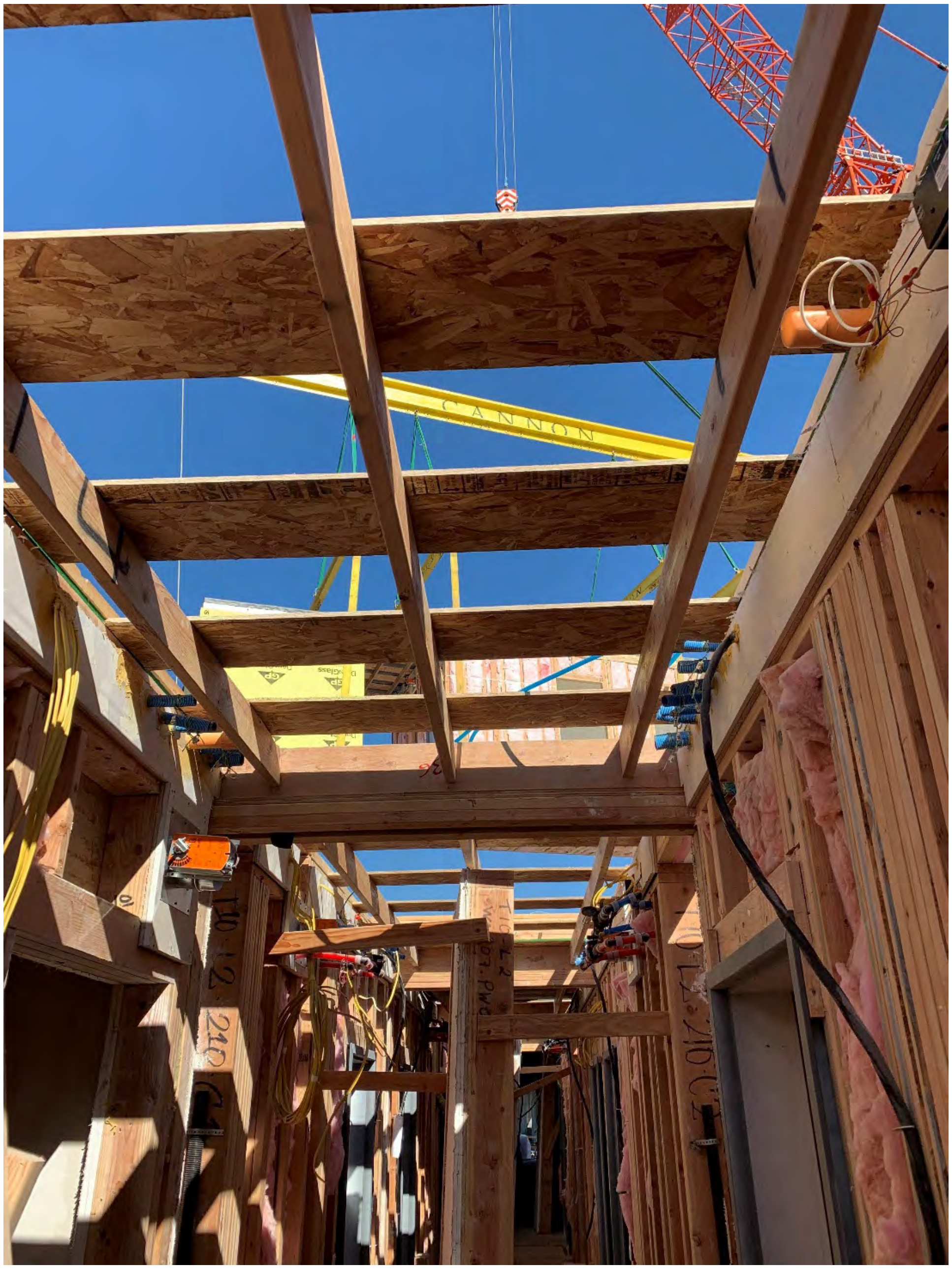
Overview of modules moving through the assembly line. Image courtesy of Autodesk.

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

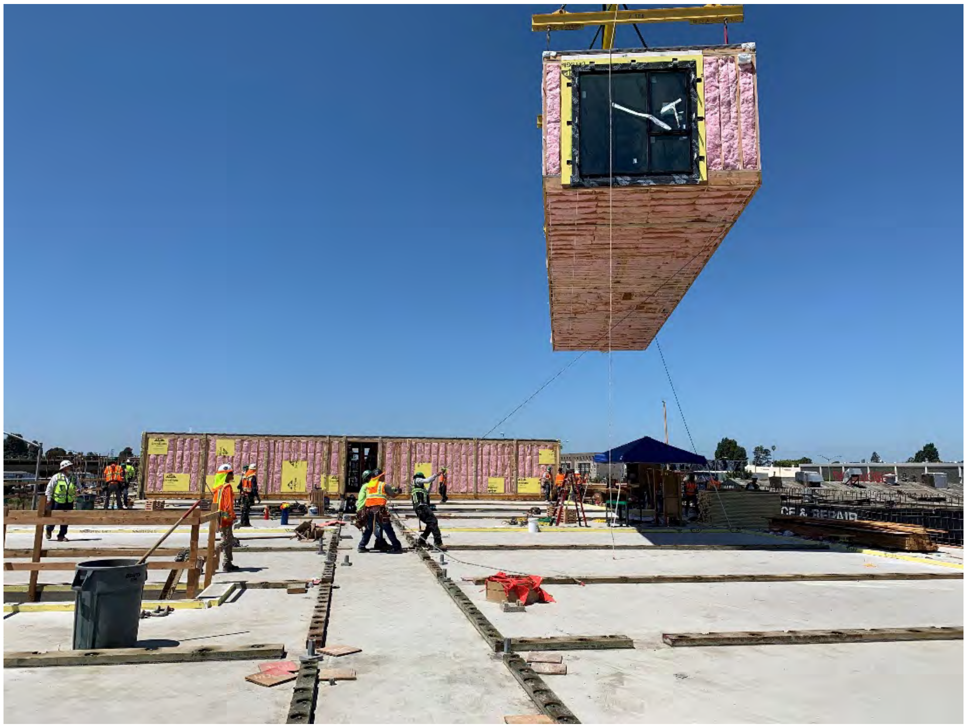


Hallway photo showing how site-built connections planned for corridors. Image courtesy of Factory_OS.

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

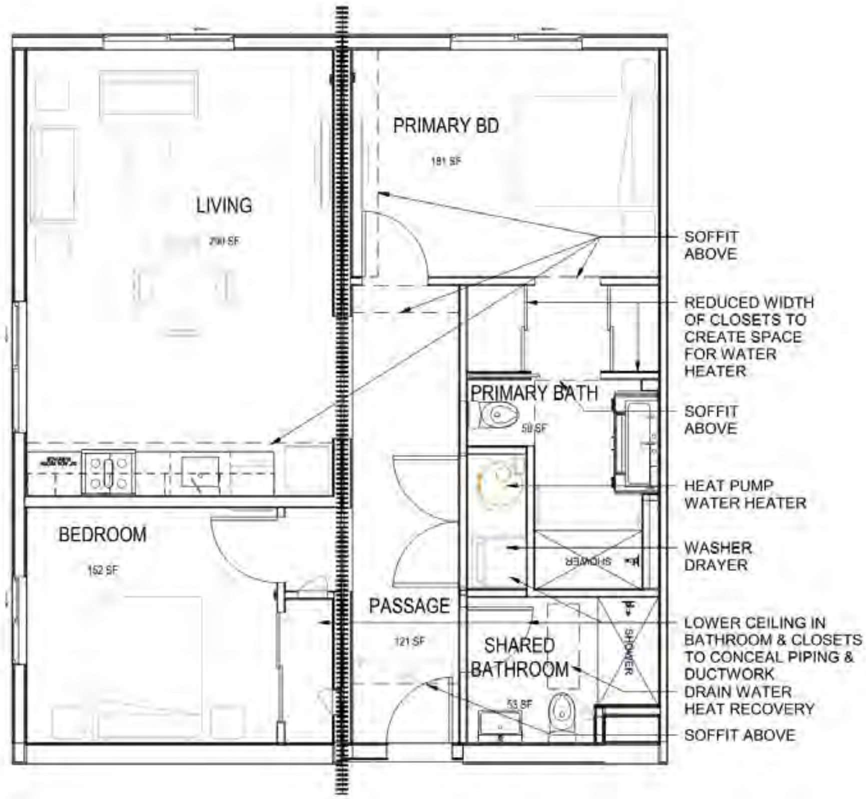


Setting factory-built modules on site-built concrete podium. Image courtesy of Factory_OS.

Exhibit 6. Onsite Placement of Factory_OS Module

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

Exhibit 7. Two-Bedroom Apartment Using Two Factory-Built Modules



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 are largely due to the parallel on- and offsite work streams that would otherwise need to happen in sequence; for example, onsite crews can begin excavation and foundation work while crews in the factory assemble the full interior of apartment units. Cost savings, when realized, are often found as a direct result of these time savings, as well as increases in labor productivity and material efficiency through optimized factory production (Pullen, 2022). Better quality control practices using manufacturing principles and practices may improve building quality and ultimate project performance as well, which has financial benefits during and after construction (Pless, et al., 2022). Finally, industry interviews and existing research find that factory production can simplify construction processes to be more ergonomic and accessible to a wide range of physical capabilities, lowering the barrier to entry for unskilled workers and increasing diversity in the workforce (Pullen, 2022).

In *proven* performance toward these potential benefits, a growing body of evidence suggests that offsite construction can offer total time savings in the range of 10–40 percent and cost savings in the range of 5–25 percent compared to traditional onsite construction (Smith and Rice, 2015); Decker, 2021; Pullen, 2022). 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, whereas cost savings are less predictable and more difficult to precisely measure (Pullen, 2022). In many cases, the successful fulfillment of cost savings depends on other, complimentary interventions, such as streamlined permitting and amenable funding structures (Decker, 2021). Other benefits, including construction quality and workforce development benefits such as increased diversity and safety performance, show promising anecdotal evidence that is likely to substantiate as adoption increases (Smith and Rice, 2015; Pullen, 2022). Nonetheless, interest and investment in offsite and industrialized construction practices continue to grow across the U.S., particularly in areas with high housing demand and skilled labor costs (Bertram, et al., 2019; Pullen, Hall, and Lessing, 2019).

A Note on Factory_OS

Factory_OS vertically integrates the core components of the development process into a comprehensive housing production model by combining development, design, and construction. In doing so, they can help bring down the cost and time it takes to produce housing while also leaning on its technology partnerships to increase quality and sustainability. Completed projects achieved total project cost savings of 20–40 percent compared to conventional onsite construction methods based on internal analysis. Highlights of the unique interventions of Factory_OS's approach to contextualize their role in this research study and respective applications include:

Design. A catalog of standardized plans for multiple unit types with façade customization available allows Factory_OS to balance optimal production line assembly, cost efficiency, and design flexibility. In-house architecture and engineering teams allow them to reach and service a broad range of industry partners.

Material and technology partnerships. Such partnerships allow Factory_OS reliability and certainty on supply budgets and production costs. Combined with the standardized unit layout offerings, this allows an early-stage budget certainty (unavailable through conventional construction), which is invaluable as developers apply for and secure funding, accelerating housing delivery overall.

Process. Factory_OS's portion of work makes up to 30–50 percent of overall construction costs, depending on site characteristics (e.g., slab-on-grade versus podium construction, exterior finish selections, auto parking requirements). The mechanical, electrical, and plumbing trade work in the unit interiors is completed at Factory_OS and "stubbed out" to the corridor. The site trades can complete their work without entering the residential units.

Research. Factory_OS promotes open knowledge sharing via research under existing grants with NREL through the DOE, the Terner Center for Housing Innovation, and other government agencies.

Even within the category of offsite and industrialized construction, strategies can vary greatly (Pullen, Hall, and Lessing, 2019; Pullen, 2022), and Factory_OS is only one of many new firms applying these strategies. However, data and estimates from Factory_OS provide a useful proxy for the general potential of these innovative methods.

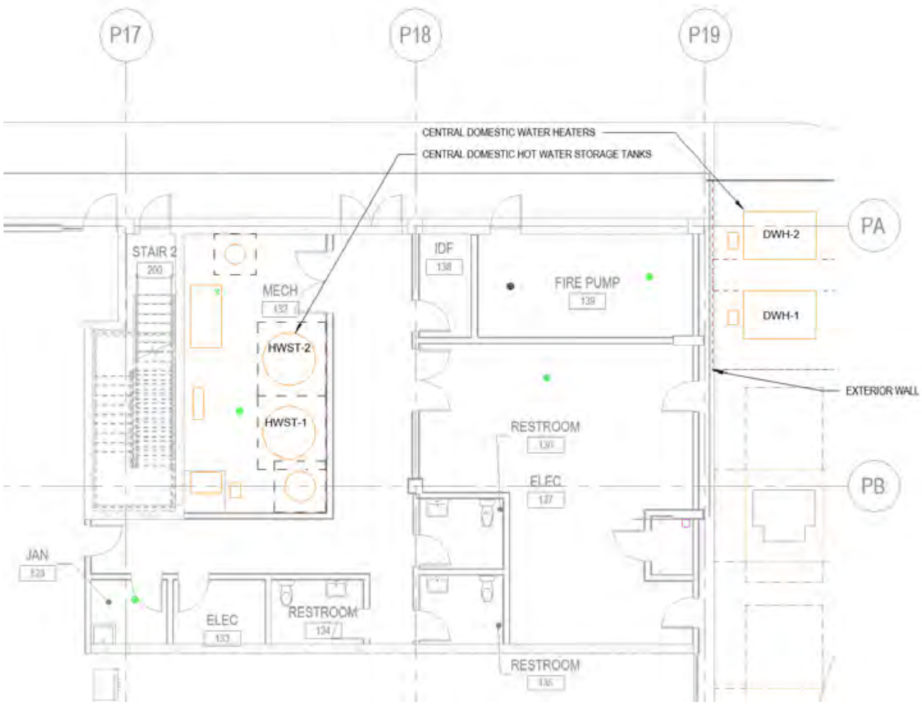
DOMESTIC HOT WATER HEAT PUMP WATER HEATERS (HPWH)

Heat pump systems are used commonly in heating ventilation and air conditioning systems (HVAC) as an all-electric option to heat or cool the air in residential or commercial buildings, also known as comfort heating and cooling. However, this technology can 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 with distribution piping throughout the building, highlighted in exhibit 8 below with drawings from the reference project used in this study. The design includes a large air-sourced heat pump and storage tank. In addition, a centralized heat pump design requires a lot of field-installed supply, recirculation piping with associated insulation, recirculation pumps, and balancing valves, some of which are often installed on roofs, as depicted in exhibit 9. The large amount of domestic hot water piping leads to energy losses as hot water is pumped through the building. These energy losses can be attributed to both heat loss from the long runs of distribution piping as well as the energy required to pump water through the recirculation loop. In the case of the reference project used for this study, the centralized HPWH system includes two air-sourced heat pumps located outside the building that extract heat from outdoor air and send it to hot water storage tanks inside the mechanical room. The hot water is then distributed from the storage tanks to the apartment units through vertical piping risers.

Exhibit 8. 2121 Wood Street First-Level Mechanical Room



DWH = central heat pump domestic water heater. HWST = domestic hot water storage tank.
Reference case 2121 Wood Street Centralized Heat Pump Water Heating System location indicated as DHW-1, 2 (outside building) and HWST-1, 2 (inside mechanical room). Distribution piping is hidden for clarity and PA, PB, P17, etc. represent grid lines to distinguish building sections for architectural work.
Source: Factory_OS

Exhibit 9. Typical Example of Central Domestic Hot Water System Before Insulation of Piping

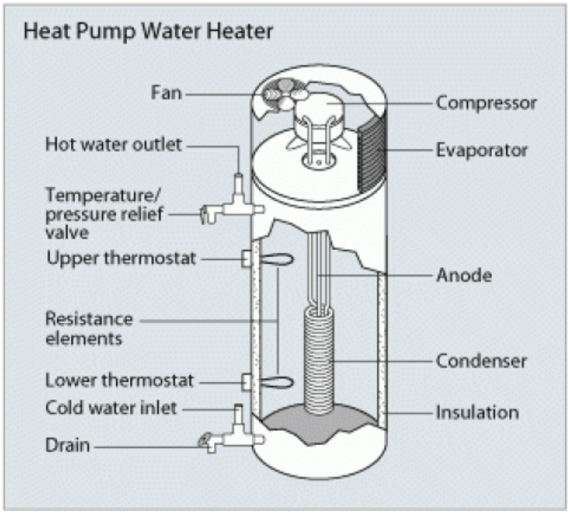
Large installations on roof are most common. Used with permission of Colmac WaterHeat.

Distributed Domestic Hot Water Heat Pump Water Heaters

Distributed (also known as decentralized) HPWHs utilize the same technology as the centralized systems, but provide smaller, separate heat pumps placed within each unit. The piping to support this system can be self-contained in an individual unit with only minor piping required between units to source domestic water. This reduces the overall amount of piping required and thus also reduces the energy lost to distribution of water through piping inherent to a centralized system. In contrast to distributed natural gas-fired water heaters, HPWHs do not require natural gas lines or flue gas venting.

In addition, a distributed HPWH system leverages prefabricated modular construction by allowing full installation of HPWH and domestic hot water (DHW) piping in the factory with reduced onsite connections required (e.g., for potable water, sanitary waste, vent connection). For this study, the all-in-one heat pump (which includes a storage tank) is located inside an enlarged closet in the prefabricated apartment modules and extracts heat from the air inside the occupied space to operate. Exhibit 10 portrays a representative diagram of an all-in-one heat pump device.

Exhibit 10. Representative All-in-One Heat Pump



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 to ensure realistic performance and cost estimates. The distributed HPWH market now includes shared circuit units—used as the basis of design (BOD) for this research—which has a smaller electrical load than other products and is designed to plug into a standard 120-volt, single phase outlet, sharing a 15-amp circuit with other electrical loads. HPWHs conventionally include a hybrid electrical resistance operating mode that is less efficient than heat pump operation and results in an increased electrical load. The shared circuit product used as the BOD, however, targets the retrofit market, which aims to simplify natural gas water heater replacement without requiring upgraded electrical service, thus its smaller loads. This all-in-one installation also aligns well with modular construction methods and allows for reduced installation times compared to its natural gas counterparts. One manufacturer that makes both gas and heat pump water heaters quoted 50 percent reduction in installation time between the distributed natural gas-fired and the shared circuit HPWHs.

The BOD model requires roughly 6 inches of clearance at the top of unit for filter access, and the manufacturer promotes "zero" rear and side clearance. Front clearance is required for unit removal and control panel access. If the more widely available hybrid heat pump with an electrical resistance backup was used in the reference project, then the collective impact of the 2,250-watt electrical resistance elements would have greater impact on the electrical system, including:

- Increase in electrical panel service required in each apartment.
- Additional circuit required for each apartment.
- Additional disconnect switch for each apartment.
- Increase in panel rating for all studio and one-bedroom units.
- Increase in panel feeder (conduit and wire) associated with increased panel rating.
- Increase in service transformer size.
- Change from conduit/wire to busway for increased service.
- Increase in service switchboard rating and main breaker.

In contrast, relative to a centralized HPWH system, the distributed, shared circuit design offers system savings such as:

- Removal of switchboard circuits (conduit and wire) for central HPWHs.
- Removal of disconnects for central HPWHs.
- Potential reduction of service switchboard sections for cost savings due to removal of central HPWH circuits.
- Potential reduction in transformer service size.

Assessing the upfront cost impact of these differences in installation complexity is one of the main goals of this study.

A Note on Distributed HPWH Tank Sizing

Although the hot water demand profile varies between studio, one-bedroom, two-bedroom, and three-bedroom apartments, cost advantages to scale occur. 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 can vary on a project-by-project basis based on climate zone and specific expectations of occupancy behavior.

Note that the specific BOD model used is available in 40-, 50-, 65-, and 80-gallon tank sizes, and increasing from a 50-gallon to 65-gallon tank would increase tank height by 3 inches and diameter by 2 inches.

The excess collective storage capacity of the tanks in a distributed system relative to a centralized system offer potential for enhanced electrical grid management through load-shifting. This could mitigate issues in the inconsistent timing and magnitude of renewable energy sources such as wind and solar (known as the "duck curve" problem in grid management). For instance, when renewable sources produce more electricity than needed (such as in the afternoon, during peak solar panel production), electricity providers or facilities managers can store some of that energy in the building's distributed water heating system. Then, later in the day, when electricity demand is higher than renewable source production (such as in the evening as the sun goes down), that stored energy can reduce the stress on the grid. This allows for more flexible and adaptive grid management overall, ultimately improving resilience on a per-unit and whole-building scale. If applied to the reference project, the total volume of domestic hot water storage—nearly 12,000 gallons for the distributed system compared to 2,700 gallons for the centralized system—equates to approximately 370 additional ton-hours of thermal energy storage for the distributed system relative to the centralized system.

DRAIN WATER HEAT RECOVERY (DWHR)

DWHR heat exchangers exchange heat between warm shower drain water and incoming domestic cold water. No direct mixing of flow streams occur: 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 provides a simplified diagram of DWHR function.

Exhibit 11. Horizontal Drain Water Heat Recovery

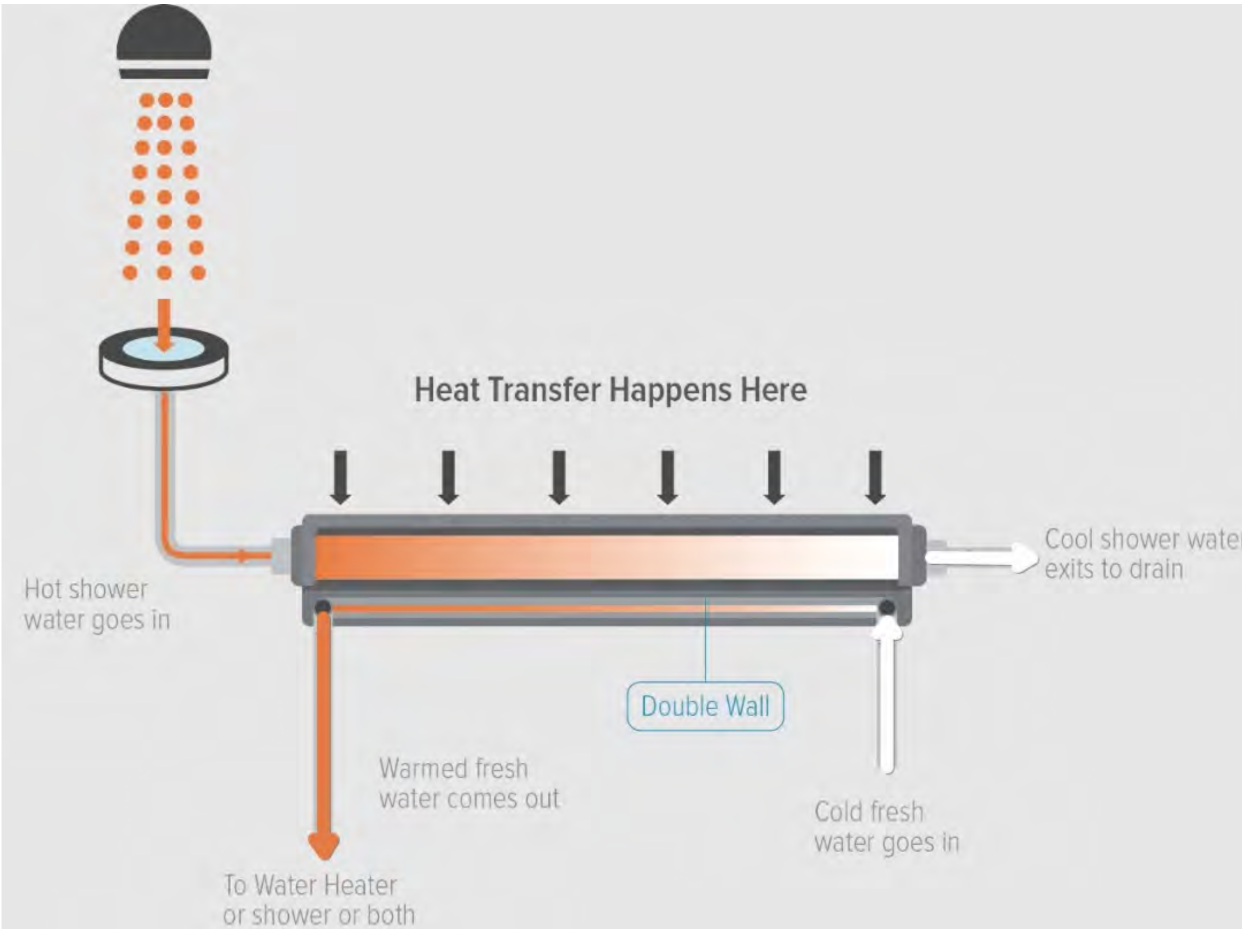


Diagram summary of drain water heat recovery system, which allows wastewater heat from shower to pre-heat incoming water. Source: EcoDrain

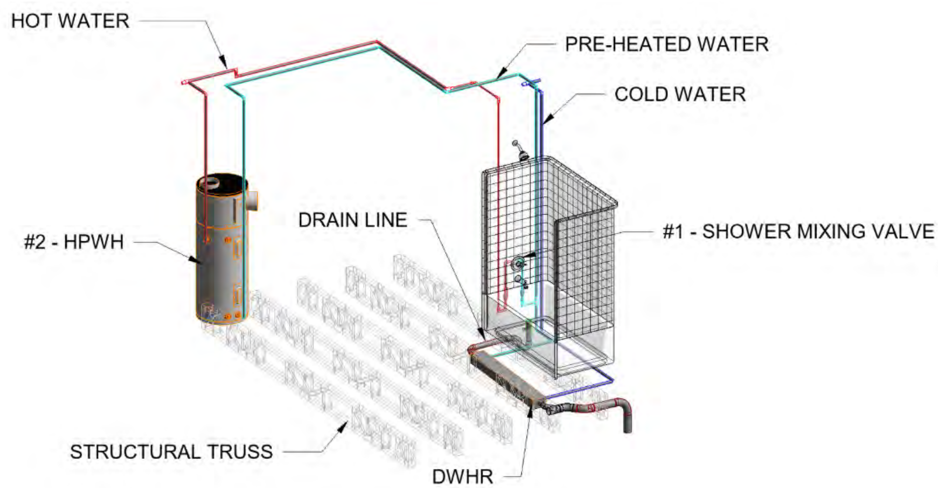
In traditional onsite stick-built construction, field-installed *vertical* drain water heat recovery devices are typically more common with a single heat exchanger serving multiple units. Vertical devices have higher heat transfer efficiency and are less likely to clog than horizontal designs. However, since they typically serve multiple apartments, the heat exchanger can be far removed from the water heater and fixtures, resulting in greater heat loss during distribution than a horizontal design installed more closely. For use in modular construction, horizontal devices allow full in-factory installation which avoids piping that crosses mate lines (i.e., points at which adjacent apartment modules are connected in the field), compared to a typical vertical DWHR installation.

To minimize risk of clogging the horizontal DWHR, the design applied in the research provided the heat exchanger with a dedicated drain line that only sees flow from the shower and avoids flow from the kitchen and clothes washer. In addition, the DWHR is not directly under the bathtub; it is placed in an accessible location with an upstream cleanout provided for easier maintenance. The DWHR device also is located close to the largest hot water consumer (in this case the shower) and close to the HPWH. This configuration enhances the benefit of the DWHR system by elevating cold-water temperature entering both the HPWH and cold-water inlet of the shower mixing valve. It also maximizes flow in both cold and hot heat exchanger fluid streams, which allows for greater heat transfer and, ultimately, energy savings.

Lastly, integrating the DWHR installation within the structural framing of a module produced in a factory allows for tighter installation tolerances and should minimize the risk of installation issues compromising device function.

Exhibit 12 highlights the HPWH and DWHR mechanical and plumbing configuration as described and used for this study.

Exhibit 12. Diagrams of HPWH and DWHR used in Research Model



DWHR = drain water heat recovery unit. HPWH = heat pump water heater.
The horizontal drain water heat recovery unit pre-heats incoming cold water that is then sent to the shower mixing valve and heat pump. DWHR coordination from Revit model shows slim profile of horizontal heat exchanger between structural framing and preheated water sent to shower mixing valve #1 and HPHW #2. Other building elements are hidden for clarity.

ENERGY MODELING METHODOLOGY

For the energy analysis, the research team created both a building-level energy model including residential units and retail space (as designed) and a single-zone energy model representing one-bedroom, two-bedroom and three-bedroom units. The overall energy model assesses the impact of centralized water heating systems and associated distribution losses, whereas single-zone energy models allow for sensitivity analysis of factors such as free cooling and varying energy usage across unit types. Energy models were created using the Energy Plus software, and the input assumptions for the model are in the appendix.

The model uses the reference project's California Title 24 2019 (the statewide codes for building energy efficiency) compliance energy model as a baseline, with a centralized HPWH system used for the cost comparison. The model assumes an N+1 occupant scenario for each unit type: studios and one-bedroom units have two residents, two-bedroom units have three residents, and three-bedroom units have four residents. The envelope characteristics include as-designed values. The envelope properties for the analysis include alterations based on the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) 90.1 2016 code, Table 5.5.0 to 5.5.8, for the different climate zones. Assumptions for interior lighting, plug loads, process loads, and schedules are based on California T24 2019 building energy code default values for high-rise residential buildings. The calculations do not include exterior lighting impacts. The residential units have operable windows to provide ventilation, and to provide a more realistic cooling energy usage for the building, the compliance model includes natural ventilation. The model assumes operable windows have a 25-percent openness factor, which means 25 percent of the window area allows for air movement. In the model, window operations provide cool air when desirable and avoid overheating of the space when the outside temperature is not desirable. The centralized dedicated outside air system (DOAS) provides ventilation to all the units, and in-unit fan coil devices cool and heat the space as per the design. For single-zone energy models, the capacity of the DOAS units was prorated based on the square footage of the individual bedroom units.

The centralized HPWH system provides domestic hot water to showers, sinks, dishwashers, and in-unit washing machines. The capacity and efficiency of the centralized HPWH is based on as-designed values. The efficiency for in-unit HPWH is assumed to be a coefficient of performance of 3. For natural gas water heaters, the efficiency reflects California Title 24 2019 building energy code values for natural gas fuel type. The flow capacity (in gallons per minute, or gpm) for individual fixture types, including shower and sinks, reflects the California Green building code requirements. The flow capacity for the dishwasher, washing machine, and dryer heating capacity reflect the California Title 24 multifamily housing example file from CBECC-Res software.

The default normalized shower schedule in the compliance model was modified to include a more realistic sub-hourly schedule, per the research paper, "Development of Realistic Water Draw Profiles for California Residential Water Heating Energy Estimation" (Kruis, et al., 2017). The total time of shower usage is based on the average daily water use for each bedroom type. For example, for a one-bedroom unit, the average daily shower uses 15.5 gpm, which translates to a 1.5 gpm shower running continuously for 9.5 minutes (1.5 gpm is the low flow fixture requirement for the state of California). The schedule for all other fixtures is based on default California Title 24 schedules.

The distribution losses for central water heating systems are calculated in a separate spreadsheet based on equations from CBECC-Com residential software referenced in the appendix.[1] The insulation for the piping system is as per the requirements of California Title 24 2019 code.

A gravity-film heat exchanger (GFX) serves as the baseline for the drain water heat exchanger. GFXs are generally vertical heat exchangers, commonly used for DWHR systems. The vertical heat exchanger has approximately 50–65 percent efficiency, varying based on surface area and material. The EcoDrain product studied for this project is a horizontal heat exchanger and has an approximate efficiency of 32 percent. In the energy model, the default efficiency of the GFX is 1500 UA (thermal conductivity times area). To represent the horizontal heat exchanger, the efficiency of the GFX shows a 50 percent (750 UA) reduction in the energy analysis.

Exhibit 13 documents the primary differences between the four cases considered for the energy modeling comparison.

[1] See link for reference: https://energycodeace.com/site/custom/public/reference-ace-2019/index.html#!Documents/b5hourlydistributionlossforcentralwaterheatingsystems.htm

Exhibit 13. Overview of Systems for Comparison Analysis

System Types	Description
Central Gas Water Heaters with recirculation (System 1)	HW System location = Mechanical Room Recirculation Distribution Losses = Yes (Central location to in-unit) Fuel Type = Natural Gas System Type = Traditional Water Heater Efficiency = Low Drain Water Heat Recovery = No
Central HP Water Heaters with recirculation (System 2)	HW System location = Mechanical Room (Water Storage) + Outside Bldg. (Heat Pumps) Recirculation Distribution Losses = Yes (Central location to in-unit) Fuel Type = Electric System Type = Heat Pump Water Heater Efficiency = High Drain Water Heat Recovery = No
Distributed HP-In-Unit (System 3)	HW System location = Inside the residential unit Recirculation Distribution Losses = No Fuel Type = Electric System Type = Heat Pump Water Heater Efficiency = High Drain Water Heat Recovery = No
Distributed HP-In-Unit with Drain Heat Recovery (System 4)	HW System location = Inside the residential unit Recirculation Distribution Losses = No Fuel Type = Electric System Type = Heat Pump Water Heater Efficiency = High Drain Water Heat Recovery = Yes

OVERVIEW OF REFERENCE PROJECT USED FOR ANALYSIS

To provide applicable and representative cost and energy use comparisons, the grant research focuses on the analysis of a prefabricated 235-unit multifamily building under construction in Oakland, California, for which SmithGroup provided the full engineering design of the mechanical, plumbing, and electrical systems. This project, located at 2121 Wood Street, Oakland, California, includes a centralized HPWH system that directly informed model assumptions and acts as a real-life reference point for energy use and construction cost comparisons (see exhibit 14). Throughout the report the 2121 Wood Street building is referred to as the reference case, project, or building.

Exhibit 14. Reference Project, 2121 Wood Street Architectural Rendering

Street-level rendering of reference project, 2121 Wood Street. Source: MBH Architects

The layouts used as the reference case for the studio, one-bedroom, and two-bedroom units were factory modules designed for the Wood Street project. Each unit type originally included a washer/dryer closet, which the research team enlarged slightly to accommodate the in-unit HPWH for the distributed system, a change highlighted in exhibit 15. Additional adjustments to the layout accommodate accessibility standards frequently required in affordable housing projects due to code and/or financing constraints; this adjustment was made at the independent recommendation of several industry professionals with experience in modular construction and affordable housing projects. None of the changes have a substantive impact on the leasable area of the unit, meaning there is no impact on the expected rent. In the following sections, exhibits highlight the studio layout to illustrate the changes made to the original design. A full set of designs is in the appendix.

Exhibit 15. Architectural Floor Plans of Studio Unit

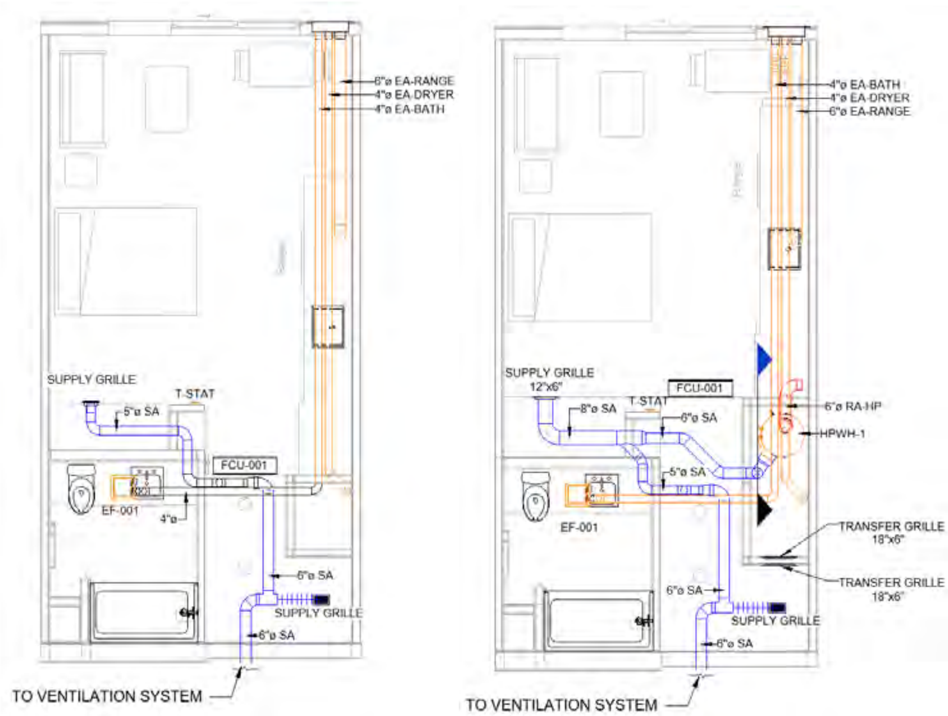
DWHR = drain water heat recovery. HPWH = heat pump water heater.
Architectural floor plans of studio unit comparing base case (left) to revised design with heat pump water heater and drain water heat recovery (right).

Changes to the HVAC system highlighted in exhibits 16 and 17 accommodate the HPWH, which requires two ductwork connections, a source-air inlet, and a discharge air outlet. To minimize the duct runs and keep the plumbing design compact, the HPWHs use the room air as the source air instead of outdoor air. To avoid dumping cool discharge air directly into occupied space, the cool air is ducted to mix with neutral temperature air from the central ventilation system. The design team created a pocket behind the refrigerator such that the HPWH could draw warm air from behind the refrigerator to further minimize energy use.

Downstream of the mixing point of the HPWH discharge and ventilation air, oversized ductwork accommodates the additional flow rate and lowers the risk of backpressure that may cause ventilation air to flow back through HPWH when it is not operating. Additional design adjustments mitigate the risk of nuisance sound from the HPWH's compressor and fan. Transfer grilles at the back of the closet, facing away from the sleeping area, provide a make-up air path for dryer exhaust in lieu of a louvered door. This layout, along with placing the HPWH in the closet with ducted connections with 90-degree elbows, reduces the risk of nuisance sound.

The in-unit HPWH in the closet replaces hot water previously provided from the central distribution system. The HPWH is located close to the shower because it is the fixture with the highest domestic hot water flow rate in the apartment. Other changes include the addition of the DWHR device and associated cold water and preheat water piping going to the shower, mixing valve inlet, and HPWH. No apartment level electrical system modifications were required due to the shared circuit HPWH. Building-level electrical system components that were serving centralized HPWHs are removed when applying the distributed system.

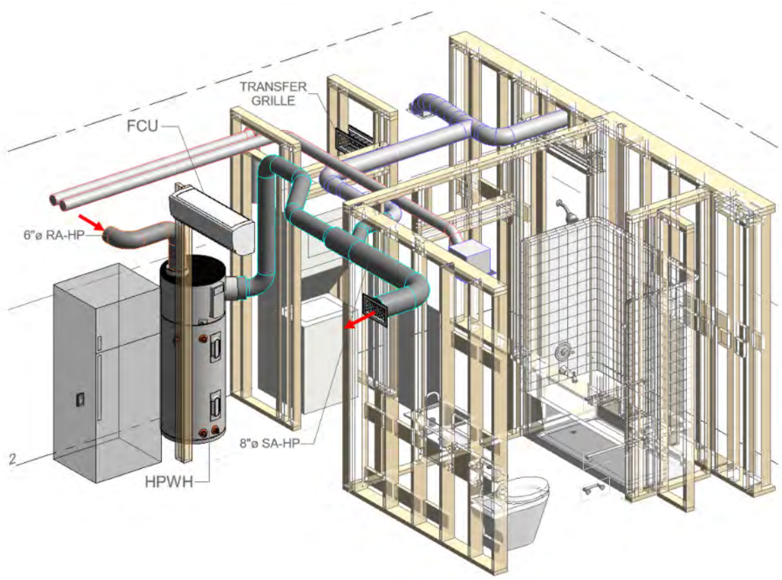
Exhibit 16. HVAC Floor Plans for Studio



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

HVAC floor plans highlighting changes between reference building (left) and modified building (right). The exhibit shows the two ductwork connections to the HPWH in the modified case. Because it is not allowed to use recirculation hoods in California, the kitchen hood, "Range" on plan, is exhausted directly to outdoors.

Exhibit 17. Warm Air Inlet and Cool Air Outlet

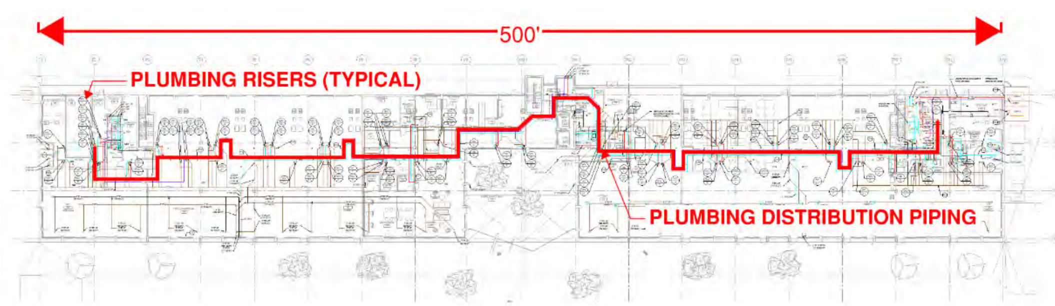


FCU = fan coil unit. HPWH = heat pump water heater. RA-HP = return air heat pump. SA-HP = supply air heat pump. Transfer grille = opening to transfer air into closet for mechanical equipment.
View showing warm air inlet (arrow in background) and cool air outlet of HPWH (arrow in foreground) as well as transfer air grille facing away from the occupied area.

Mechanical piping and plumbing-related modifications are the most extensive. Specifically, the entire centralized domestic water heating distribution system was removed. In the reference project, a six-story building with 235 units, the system comprised approximately 5,000 linear feet of domestic hot water recirculation piping. A sample of the central domestic water heating system piping is in exhibit 18. The main horizontal distribution runs on the underside of the first-floor ceiling, with vertical mains running upward at each plumbing stack.

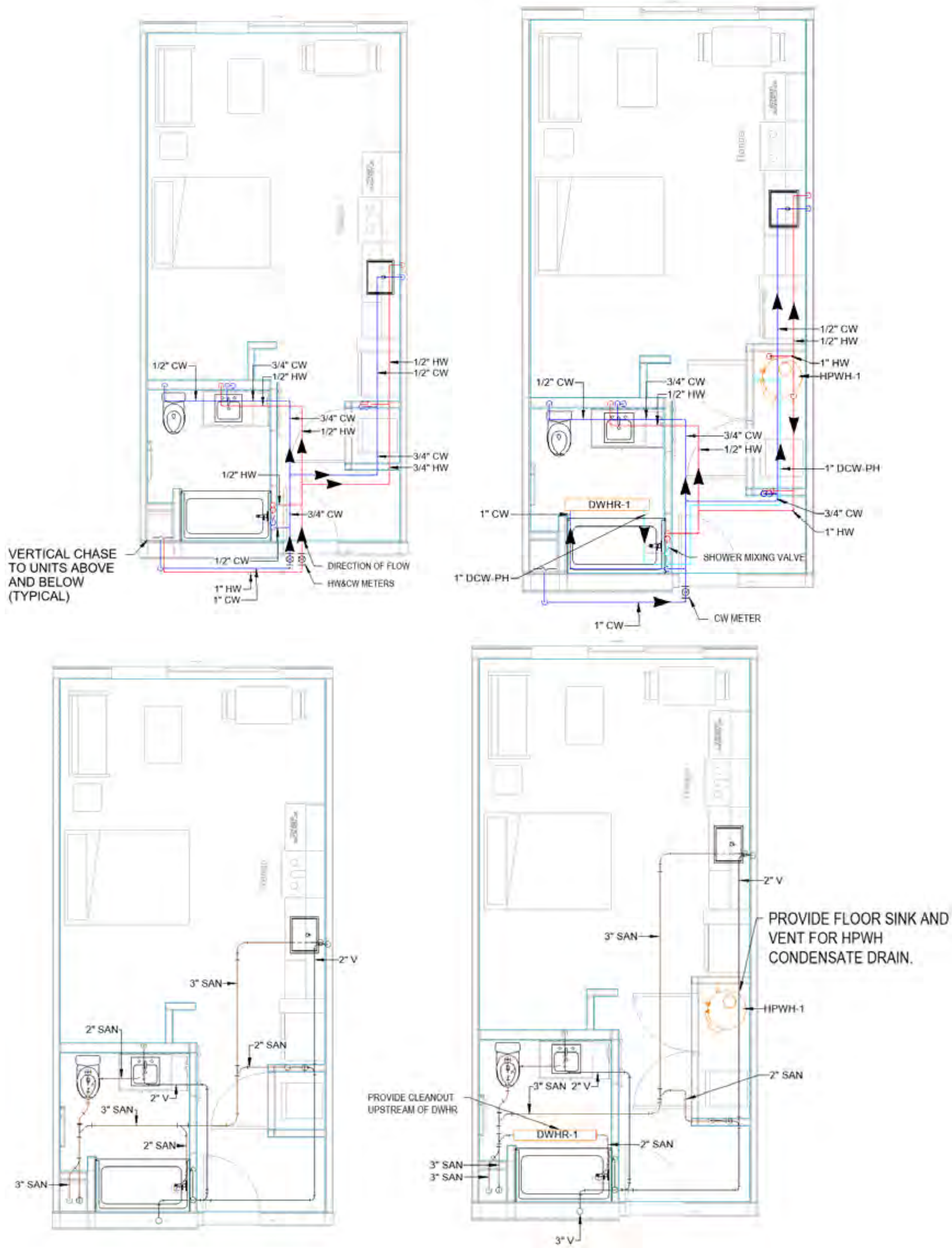
Exhibit 19 highlights the main adjustments made to plumbing and mechanical systems for this study.

Exhibit 18. Plumbing Plan for One Floor of Building with Centralized System



Ground level plumbing plan highlighting the domestic water heating distribution and recirculation piping that serves apartment units on upper floors through vertical risers. This hot water piping scope is removed in the modified building with distributed heat pump water heaters.

Exhibit 19. Plumbing and Mechanical Plans for Studio, Baseline (left) and Modified (right)



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

Hot and cold water plumbing plans (top) with direction of flow indicated and sanitary plumbing plans (bottom) with reference cases on left and modified cases 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 to the shower mixing valve and HPWH.

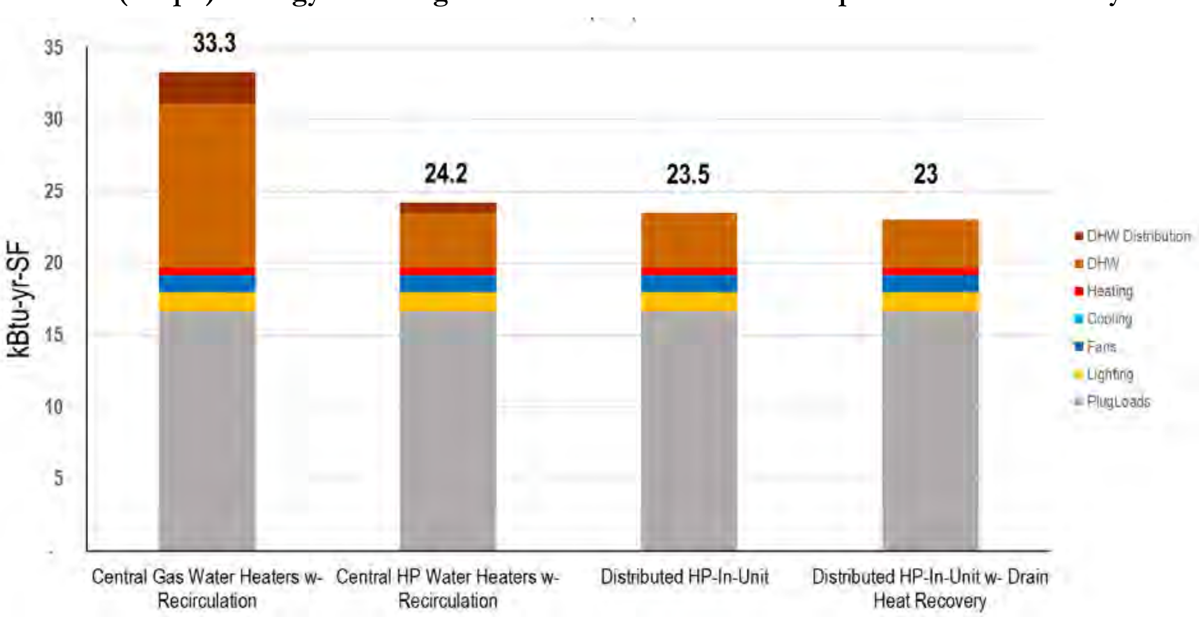
FINDINGS

ENERGY ANALYSIS FINDINGS

The annual simulation results of the whole building energy model from the reference case 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. Both heat pump water heating options, centralized and distributed, outperform a traditional gas-fired central water heater domestic hot water system. Compared to centralized HPWHs, most of the energy savings for the distributed HPWHs came from the removal of the hot water distribution recirculation system. Even when insulated to current code requirements, a centralized distribution network results in significant heat loss, with the circulating hot water acting functionally as a radiator along the full piping system (in the interior of the building).

In numerical terms, the centralized HPWH resulted in a 29-percent annual total energy use savings over the gas-fired domestic water heating system. The distributed HPWHs, accounting for impacts to heating and cooling loads (e.g., free cooling), resulted in a 3-percent total energy savings compared to the centralized HPWH system. The DWHR system provided an additional 2-percent savings. If all measures were combined, the **distributed HPWHs with the free cooling and DWHR produced a 31-percent savings compared to the centralized gas-fired water heating system.** Exhibit 20 shows a visual comparison of energy use by system and use type for the Oakland case.

Exhibit 20 (Graph). Energy Modeling Results for 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. w- = with.
Example energy modeling results from an actual project located in Oakland, California. Notice the reduction in DHW-related energy end use from left to right in the exhibit.

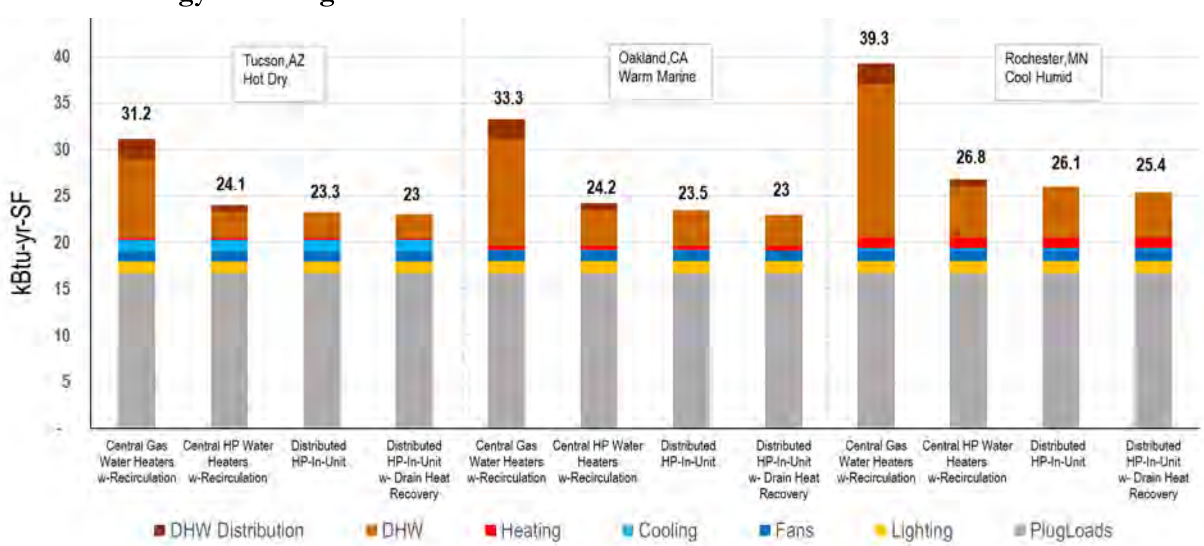
To analyze the effect of varied climate types on energy savings, the team compared their analysis in three different climate types, as defined by ASHRAE's climate zones (listed in exhibit 23): Oakland, California (the reference case), a Warm Marine climate (zone 3C); Tucson, Arizona, a Hot and Dry climate (zone 2B); and

Rochester, Minnesota, a Cool Humid climate (zone 6A). The model localizes both envelope characteristics (per ASHRAE 90.1 2016) and design day files for each climate zone. The incoming site water temperature is calculated based on annual average outdoor temperature and maximum difference in monthly temperature range for different climate zones. All other inputs were kept consistent between the runs. The primary impact in different climates zones is whether the free cooling produced by the distributed HPWHs is beneficial or harmful to annual energy use. This relationship is complex to model, as it requires an understanding of hourly cooling and heating demands as well as the behavioral impacts of when an occupant uses domestic hot water. Domestic hot water fixture draw profiles were altered to represent a realistic day-to-day operation in reference to the research paper from the International Building Performance Simulation Association (Kruis, et al., 2017).

Exhibit 21 provides a visual summary of the analysis, and exhibit 22 highlights the major difference in energy performance across systems. In a cooling-dominated climate such as Tucson, Arizona, the overall cooling energy is less than 6 percent of the total energy consumption of the building. Similarly, in a heating-dominated climate such as Rochester, Minnesota, the annual heating energy accounts for 4 percent of the total energy consumption. The distributed HPWHs, accounting for impacts to heating and cooling loads (e.g., free cooling) during DHW generation, resulted in a 3-percent total energy savings in Tucson and a 2.75-percent savings in Rochester. The slightly higher savings in Tucson reflect a higher cooling energy ratio and free cooling.

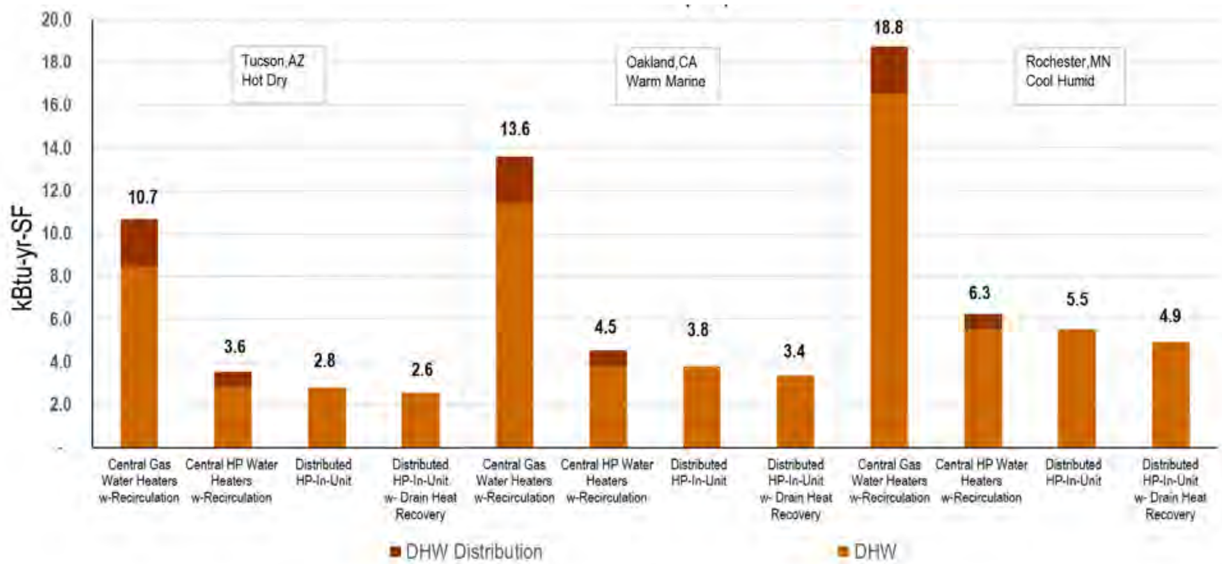
The DWHR system provided 1.2-percent savings in Tucson, 2-percent savings in Oakland, and 2.5-percent savings in Rochester. The higher savings in colder climates are due to higher domestic hot water energy consumption resulting from colder incoming water temperatures. If all measures were combined, the **distributed HPWHs with the free cooling and DWHR produced savings of 26 percent in Tucson, 31 percent in Oakland, and 35 percent in Rochester compared to the centralized gas-fired water heating system.** The higher energy savings in cool climates shows that the increased benefit of the DWHR in cool climates outweighs the detrimental effect of the additional heating load due to HPWH "free cooling."

Exhibit 21. Energy Modeling Results Across Various Climate Zones



DHW = direct 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. w- = with.
Chosen climate zones for three representative cases across the United States, highlighting energy savings of modeled systems.

Exhibit 22. Modeled Distribution Losses Across Systems, Climates



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. w- = with
Highlights savings specifically within the hot water system, with dark-shaded bars representing total energy lost in distribution.

The results are somewhat intuitive. In hot, warm, and mild climates, 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 because the distributed HPWH effectively steals heat from the interior space, which must then be made up by the space heating system. Exhibit 23 shows the total annual energy impact of free cooling for a typical one-bedroom unit. In the table, the percentage of total energy offset with free cooling represents the difference in annual energy with the HPWH being inside the unit versus outdoors. The HPWH inside the unit models the distributed water heating system interaction with the indoor space, whereas the HPWH located outdoors excludes this effect from the analysis. The results reflect a general trend of free cooling benefiting hot climate zones, but the impact is not unanimous, and all impacts are relatively minor. The largest impact is in the coldest climate in the model—Fairbanks, Alaska—with a 2.8-percent increase in annual energy use.

Exhibit 23. Impact of Free Cooling from Distributed HPWHs in Various Climates*

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.
**Positive percentages reflect beneficial free cooling from a heat pump water heater, while negative percentages indicate that cool air from a heat pump water heater increases energy use. There are outliers in the results from some of the climate zones (e.g., climate zones 0A, 2A, 3A, and 5C) that need further investigation; however, the trend remains even with outliers removed.*

Another finding is that, **regardless of the climate zone, the distributed HPWH outperforms a centralized HPWH system**. In all climate zones in which distributed HPWHs had detrimental impacts on annual energy use, it was less than the distribution loss inherent to a centralized system's recirculation loops.

Several additional sensitivity analyses were conducted to study the impact on building annual energy use, free cooling, and drainwater heat recovery. The following sensitivity analyses assume the reference case in Oakland, California.

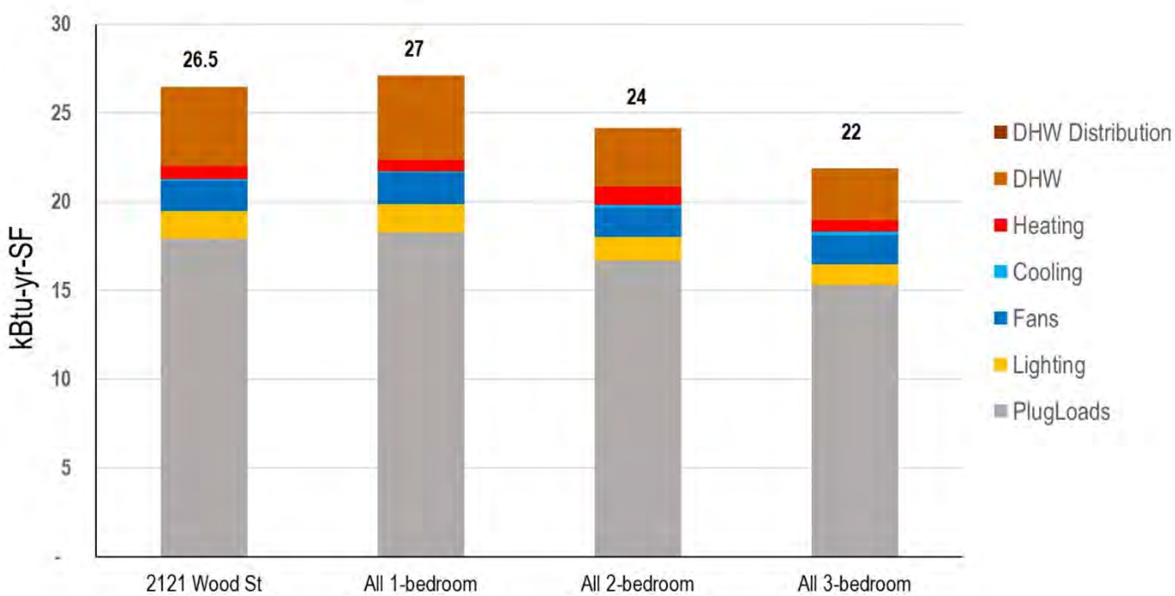
Shower Flowrate and Duration

One further analysis highlights the impact of shower flow rate and duration of the shower on free cooling and DWHR systems. The reference project energy analysis assumes a 1.5 gpm shower fixture, dictated by California's green building standards. The analysis suggests that the higher gpm shower and the increased duration of shower increases the domestic hot water usage and, in turn, increases the DWHR capability and free cooling. ASHRAE 90.1 2016 code, for example, requires a 2.2 gpm shower fixture. Using a 2.2 gpm shower fixture for the same duration shows an additional 2-percent savings in cooling energy in comparison to the 1.5 gpm shower fixture. Further, shower duration was increased in 5-minute increments from 10 to 15 minutes and from 15 to 20 minutes. A 1.5 gpm shower with a 15-minute shower duration increases free cooling by an additional 2.2 percent, and a 20-minute shower duration provides an additional 1-percent increase in free cooling energy. Similarly, for DWHR systems, a 2.2 gpm shower fixture shows additional 1.3-percent heating energy savings in comparison to a 1.5 gpm shower fixture. Further, a 2.2 gpm shower fixture running for 15 and 20 minutes provides additional 3.7- and 4-percent heating energy savings, respectively. The results imply that DWHR devices and free cooling impacts will have larger impacts with less water-efficient fixtures and occupancy behavior.

Number of Bedrooms

The real-life reference project has a mix of bedroom types: 78 percent of total units are studio and one-bedroom units, and the remaining 22 percent are two-bedroom units. There are no three-bedroom units in the reference case. In the analysis, the building square footage is kept constant, and unit mix was changed based on how many apartment units of a certain type would fit into the overall building area. The first option showcases the reference project model with a combination of studio, one-bedroom, and two-bedroom units; the second option is all one-bedroom units; the third option is all two-bedroom units; and, lastly, the fourth option is all three-bedroom units. Exhibit 24 compares the hypothetical projects based on total annual energy usage per square foot of floor area.

Exhibit 24. Modeled Energy Use Based on Mix of Bedrooms



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.
Relative energy use based on mix of bedrooms, with lower per-square foot energy for higher bedroom counts. Note: Reference project includes 235 units, with 78% studio and one-bedroom units, and 22% two-bedroom units.

Results show that the energy increases as the ratio of studio and one-bedroom units increases. This increase is due to higher energy usage from one-bedroom units because all appliance loads (dishwasher, refrigerator, washer and dryer) are concentrated in a small square footage area. The three-bedroom unit, meanwhile, includes the same amount of appliance load concentrated over a much larger area. Ultimately, the total building energy usage would be roughly 20 percent lower if the building consisted of all three-bedroom units compared to a project with only one-bedroom units.

Occupant Density Sensitivity

Increasing occupant density increases domestic hot water consumption, which in turn increases free cooling capacity and DWHR savings. If occupant density increases from two people in each studio and four people in a one-bedroom unit, the overall building annual energy use decreases by 1.3 percent, mainly due to savings in heating energy and 0.012-percent savings in free cooling energy. In effect, occupant density (as measured by residents per bedroom) would dramatically reduce per person energy use while minimally impacting overall building energy use.

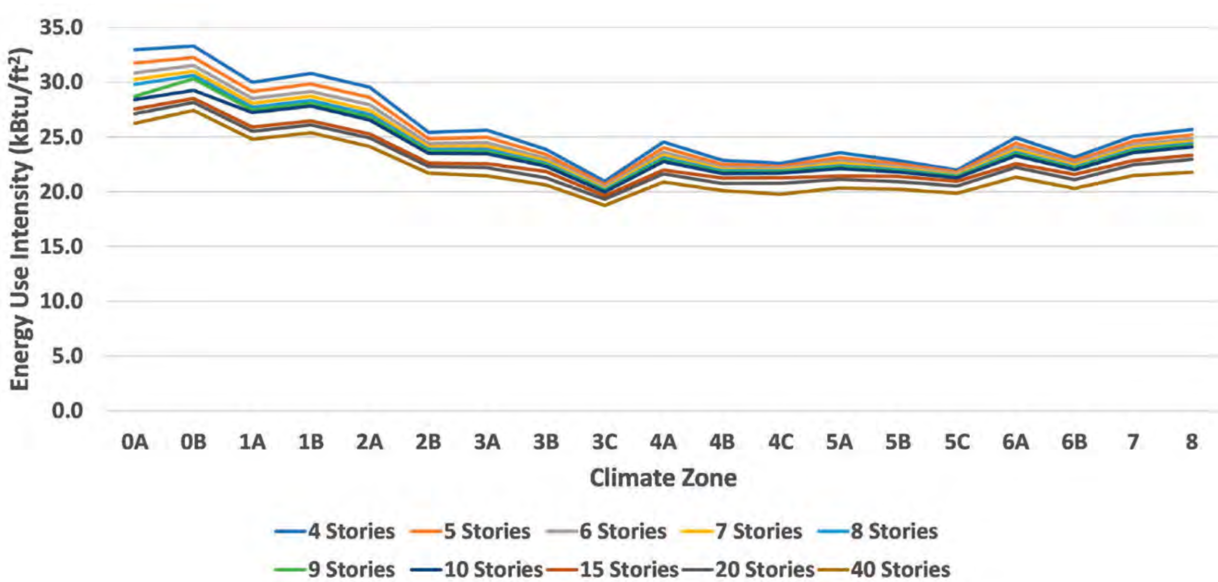
Envelope Sensitivity

Envelope properties for wall and glazing were improved from code minimum values to R-30 insulation and triple-paned glazing to verify if free cooling can offset the overall cooling needs of the unit. For the studios and one-bedroom units in mild climates, improvement in envelope properties reduced the cooling energy by 30 percent and overall annual energy usage by 0.5 percent. Because the ratio of cooling energy to the total energy is small, the impact on the overall annual energy is minimal.

Building Height Sensitivity

In the reference project, the first floor is a commercial space, whereas the rest of the floors are for residential use. Because the ratio of building floor area from upper residential floors to the commercial ground floor increases, there is a decrease in annual energy consumption due to residential floors having lower energy use intensity (EUI) relative to the commercial space. Exhibit 25 diagrams this relationship as per the Advanced Energy Guide for Multifamily Buildings.

Exhibit 25. Energy Use Across Building Heights and Climate Zones



kBtu-yr-ft2 = kilo-British thermal units per year per square foot, a measure of energy use normalized for time and building size. Note: First floor is assumed commercial, and upper floors are assumed residential.

CONSTRUCTION COST FINDINGS—CENTRALIZED VS. DISTRIBUTED HPWHs

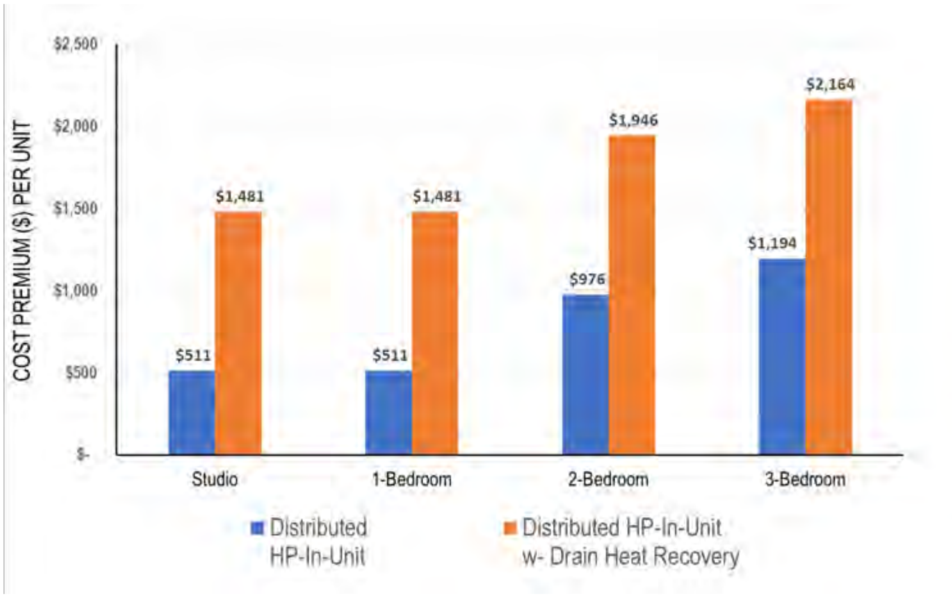
Using modular construction, an in-unit HPWH will necessarily increase the material and labor cost of the individual prefabricated module compared to a centralized system with a whole-building HPWH and no DWHR (as with the reference project). The analysis thus compares this *in-factory* installation cost with the expected savings on total project costs from the reduction in an onsite, centralized system installation, normalized on a per-unit basis using the reference project. The site-built scope deduction includes the plumbing and electrical scope associated with the centralized domestic water heating system: large central HPWHs, storage tanks, distribution piping and insulation, and the recirculation pump. The estimate reflects prices provided by Factory_OS, including quotes from external contractors and labor rates in Oakland, California, in the summer of 2022; these values can vary significantly by 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 not enough to increase the domestic cold water piping size and thus did not add plumbing cost.

One additional consideration in the reference case is that California law requires the use of individual hot water meters at each apartment when apartments source from a centralized water heater. Switching to a distributed HPWH system allows for the removal of hot water meters at each unit entrance, reducing cost and operational complexity of hundreds of water metering devices. This may also make distributed HPWH systems more appropriate than centralized systems for all-electric and energy efficiency retrofits (of public housing units, for example) by reducing installation complexity.

The estimate considers the electrical system impact of centralized and distributed domestic water heating systems as well. There are two centralized heat pumps in the reference project with significantly larger compressor and electrical loads than any of the individual in-unit HPWHs, 235 of which would be in the distributed system. These HPWHs would be on a general-purpose receptable circuit (as opposed to kitchen appliances, for example, which require dedicated circuits). The latter approach offers increased electrical load diversity and results in approximately 130 amps less in site electrical loads when compared to the centralized system. In the case of the reference project, this was not enough load reduction to reduce overall service size (e.g., the size or quantity of required transformers); however, a potential reduction is a benefit of the distributed approach and could allow for service reductions on projects with a different electrical load profile.

Exhibit 26 summarizes the cost comparison analysis, broken down by bedroom type.

Exhibit 26. Upfront Cost Comparison by Bedroom Type



HP = heat pump. w- = with
Emphasizes per unit cost premiums for higher bedroom counts. Note: Graph shows only cost premium from the reference case's centralized HPWH system.

Factoring in the site-built scope deduction, the cost premium of the distributed system varies from approximately $500 to $2,200, increasing with the number of bedrooms and addition of the DWHR. For the reference project (and its respective unit mix), the combined HPWH and DWHR system would result in an approximate $370,000 premium to the total project cost of $72M; this is an approximate 0.5 percent increase to total upfront project cost.

The limitations section addresses additional salient and significant considerations regarding these cost estimates, including potential energy efficiency programs and rebates, as well as ancillary benefits for modular construction integration not captured in the analysis above.

LIFE CYCLE COST (LCC) FINDINGS

Life cycle cost (LCC) analysis combines the energy modeling and construction cost findings. LCCs often inform capital investment when considering mechanical or plumbing system alternatives with varying operational costs. The LCC represents the total discounted dollar costs, or net present value, of purchasing, operating, maintaining, and disposing of a building or building system over a certain study period.

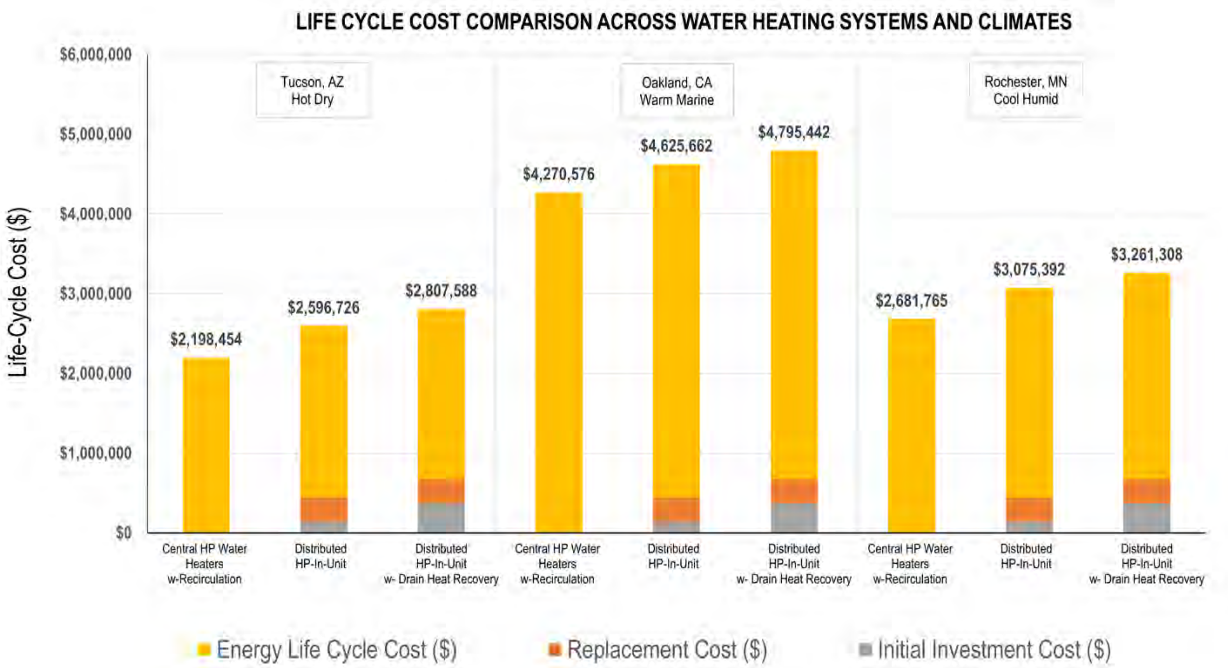
The LCC uses assumptions documented in Exhibit 27 and are based on the National Institute of Standards and Technology (NIST) Building Life Cycle Cost program, BLCC5-3-22. The LCC was calculated for each of the all-electric domestic water heating system options; cost information on a central natural gas water heating system was unavailable and is outside the scope of this study. Each system LCC follows a constant dollar analysis (omitting general inflation impacts), and the discount factor and energy escalation are predicted values. Additionally, due to lack of available information, the LCC analysis is simplified by omitting maintenance and disposal costs as well as the schedule impact of assembling the water heating systems primarily in an offsite facility. For example, a factory-built, distributed water heating system offering time savings in the construction phase would reduce investment cost and its LCC. The assessment includes upfront investment, replacement, and annual energy costs relative to the central HPWH design included in the reference project. Simulated energy costs are derived from the last 12 months of available data to include recent price increases and are escalated annually, per DOE's annual projections for each year of the study period. The study period of 24 years matches the expected service life of a commercial water-to-air heat pump, which was used to approximate the air-to-water central HPWH. The distributed HPWHs are predicted to have a shorter expected service life than the central HPWHs; therefore, they are replaced during the analysis period. Due to lack of available service life estimate on distributed HPWHs, the model used the service life of an electric domestic hot water heater.

Exhibit 27. Overview of Assumptions into Life Cycle Cost Analysis Model

LCC Inputs	Description
Real Discount Rate: 3.6%	Discount rate is also known as the Minimum Acceptable Rate of Return (MARR). Nominal rate was 6%, per Factory_OS, which was converted to real rate of 3.4% assuming 2.3% rate of inflation, which is historic average.
Study Period: 24 Years	Study period is matched to expected service life of central HPWH.
Expected System Service Life: Central HPWH = 24 Years Distributed HPWH = 12 Years	Commercial Water-to-Air Heat Pump Median Service Life = 24 years. Electric Domestic Hot Water Heater Median Service Life = 12 years. ASHRAE 2019 HVAC Applications Handbook, Ch. 38 Owning and Operating Costs, Table 4 Comparison of Service Life Estimates.
Energy Cost: Varies by State	Referenced from U.S. Energy Information Administration (EIA) on October 13, 2022. Average of each state's monthly commercial retail prices over the last available 12 months of data (August 2021–July 2022).
	Electricity Price (Cents/kWh)
	Arizona = 10.51
	California = 20.29
	Minnesota = 11.76
Real Annual Energy Price Escalation: Varies by State and by Year	Per DOE, projections incorporated into BLCC5.3-22, which includes latest Energy Price Indices from 2022 Annual Supplement to Handbook 135. Additionally, per NIST, based on how DOE projects energy price escalation values, the assumed values are considered conservative, or low. Future adoption of carbon tax policy or increases in fossil fuel scarcity could increase actual future energy cost.
Investment and Replacement Cost: Constant Across States	Construction costs are based on 2121 Wood Street, which is located in Oakland, California. Cost information was provided by Factory_OS and held constant for each system type across each geographic location.

Exhibit 28 illustrates the results of the LCC for three representative climate zones. These climate zones range from cool to warm to hot. Lower total LCCs represent more attractive economic options, reflecting the system that offers the most cost savings over the 24-year study period.

Exhibit 28. Life Cycle Costs Across Heating System and Climate



HP = heat pump. w- = with.
Emphasizes higher life cycle costs of distributed system and drain heat recovery units (as modeled). Notes: Energy life cycle cost is the majority of total life cycle cost. The investment cost of the reference case central HPWH system is $0 because it represents the baseline, and other system investment costs are relative to the reference case. The central HPWH system does not include a replacement cost because the central HPWH is not expected to be replaced during study period.

The central HPWH system is the most cost-effective option across all three climate zones, according to the LCC. This indicates that **according to the as-modeled estimates and assumptions, the relative energy cost savings of the distributed HPWH and DWHR systems compared to the central HPWH are not sufficient to overcome their construction cost premium**. More precisely, compared to the combined distributed HPWH and DWHR systems, the centralized HPWH system has an 11–22-percent lower life cycle cost across the three climate zones shown in exhibit 28. The differential is smallest in Oakland, California, due to the higher baseline magnitude of the LCC, which reflects the higher cost of electricity in this region. Note that the total LCC and energy cost savings will vary based on building unit mix and overall building shape.

The second-best system according to the LCC is the system with the distributed HPWH only (excluding the DWHR device). This means that through the lens of LCC, the DWHR assumed in the reference project is not worth the additional installation cost, a finding emphasized in exhibit 29. It shows the LCC increase of the distributed systems over the reference case, highlighting that the distributed HPWH system alone is under $400,000 of additional life cycle cost, whereas adding the DWHR brings this to over $500,000. The impact of the DWHR on LCC results will vary project-to-project. In the scope of this research, the DWHR device needed to be a horizontal type to enable it to be installed in the factory. A vertical-style DWHR, with heat exchanger in vertical orientation, would have higher heat transfer effectiveness, which means more energy recovered from drain water, higher temperature preheated water being sent to the water heater, and potentially more energy cost savings.

Exhibit 29. Highlight of Life Cycle Cost Premium Comparisons

HP = heat pump. w- = with.
Full-project life cycle increase of the distributed systems relative to the reference case with a centralized HPWH system.

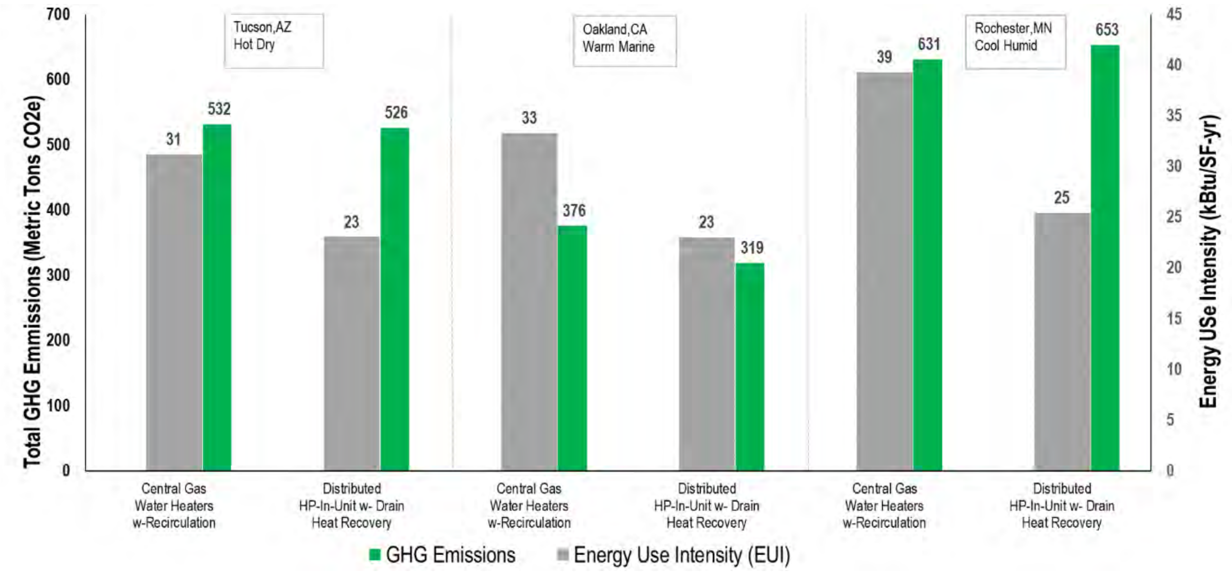
Another takeaway from the results is that energy cost—shown in yellow in exhibit 28—dominates the overall LCC when compared to the investment and replacement costs. However, in each of the three climate zones, the life cycle construction cost premium, or upfront installation cost plus present value of the replacement cost, of the distributed systems over the central system is greater than the energy life cycle cost savings achieved. This means that the cost premium of the distributed HPWH system would need to be reduced by approximately 85 percent for the LCC to match that of the centralized system, which could be achieved through green building program incentives or rebates that address upfront costs or through more extensive ground-truthing of the conservative cost premium estimate or energy performance of distributed systems (detailed further in the Limitations section).

ADDITIONAL FINDINGS

Greenhouse Gas (GHG) Emissions

The team compared the greenhouse gas (GHG) emissions produced by the building for centralized natural gas hot water system and distributed HPWH with DWHR cases and compared the impact of local grid status (i.e., the proportion of clean energy comprising local generation capacity). Exhibit 30 summarizes the results. The GHG emissions for distributed HPWH with DWHR cases (all electric) in Tucson, Arizona, and Rochester, Minnesota, is higher compared to centralized natural gas hot water system cases. This is due to a fossil fuel-heavy energy mix of the source grid. Although this study eliminated natural gas at the site level, the source grid fuel mix has an impact on the overall GHG emissions. The study team also compared the relation between EUI and GHG emissions in different climates. EUI for the proposed cases in Tucson, Arizona, and Oakland, California, has the same value of 23. However, due to the cleaner grid in California, the GHG emissions in Oakland are 40 percent lower than in Tucson.

Exhibit 30. GHG Emissions Comparison Across System Type and Climate

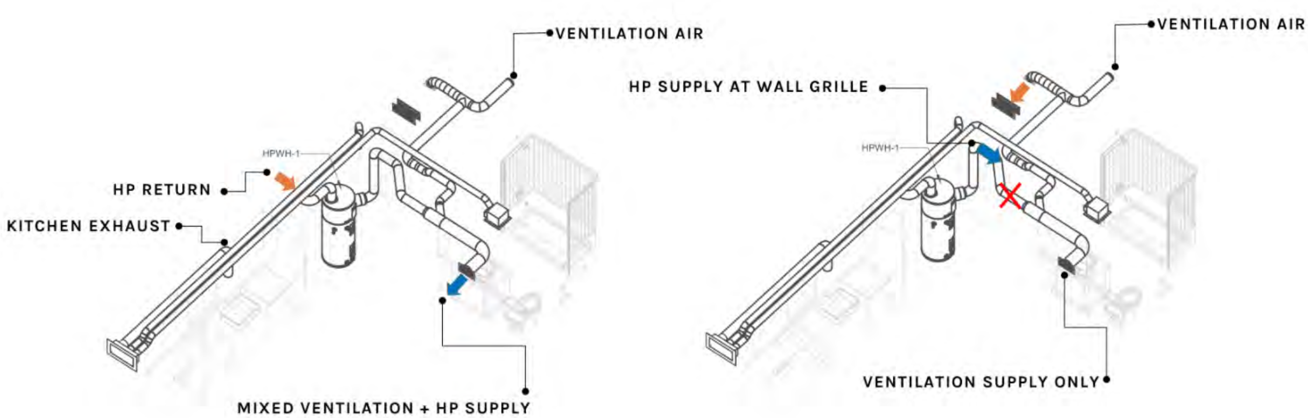


CO2e = carbon dioxide equivalents, a normalized measure of climate change impact. HP = heat pump. kBtu-yr-SF = kilo-British thermal units per year per square foot, a measure of energy use normalized for time and building size. w- = with. Graph shows comparison between GHG emissions (left) and energy use intensity (EUI) (right) for distributed HPWH with DWHR systems across climate zones.

Indoor Thermal Comfort Evaluation

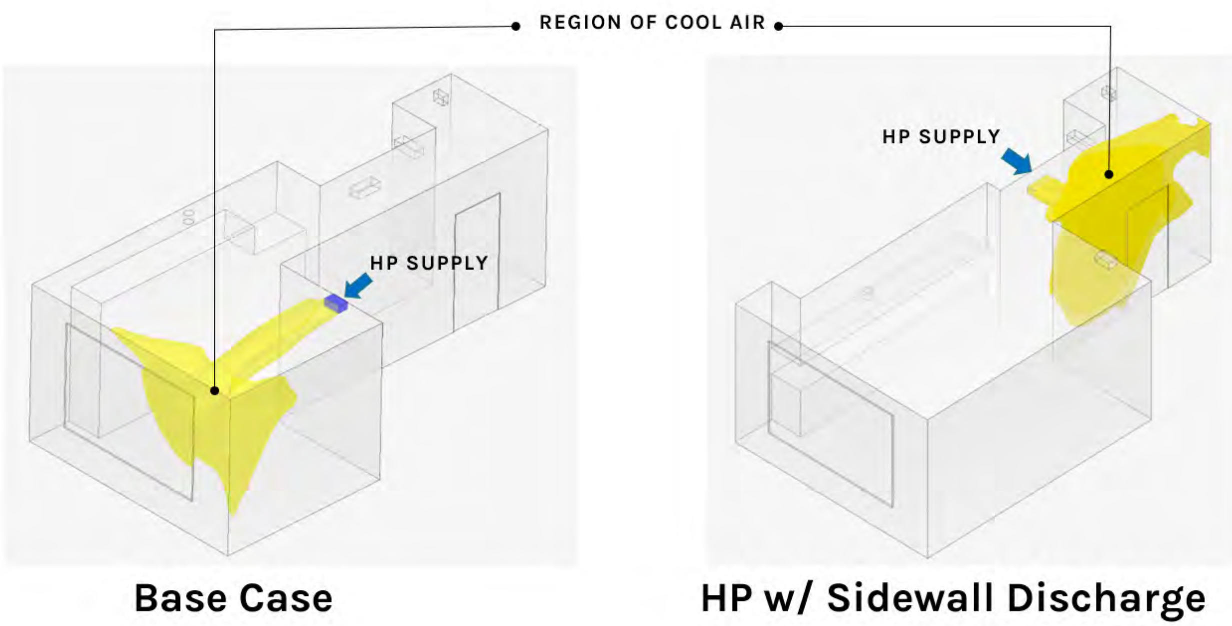
The team conducted an evaluation of indoor environmental quality regarding the thermal comfort of residents. A computational fluid dynamics model was created to evaluate the impact of heat pump discharge and return locations on occupant comfort. One finding from this work was that future designers need to consider the heat pump discharge location because local cold air release impacts comfort within the apartment. Exhibits 31 and 32 display two layouts: one that concentrates cold air in the living space and the other in the corridor. This research project used the former as the basis of design in the modified building.

Exhibit 31. 3D View of Mechanical Layouts



HP = heat pump.
Basis of design in the modified building (left) with alternative with HP discharge in corridor (right). Images from computational fluid model.

Exhibit 32. Fluid Dynamics Model Results



HP = heat pump.
Temperature isovolume (yellow) depicting fluid temperature region between 55 °F and 70 °F (i.e., cool air). This highlights the local region of cooling from HP while it is in operation.

LIMITATIONS OF THE RESEARCH

ENERGY MODELING ANALYSIS

The weather files used for the energy modeling use historic data from a "typical" meteorological year. However, because climate change impacts are expected to worsen in the near- and mid-term future, a high potential exists for an increased frequency of extreme weather events that will have unpredictable impacts on energy performance (of *all* buildings).

Predictive energy modeling results also depend on estimated building use profiles with assumptions about how residents use the space (e.g., lighting, appliance usage, water consumption). Actual metered energy use will vary based on occupant and respective behavior, which may differ across regions, household income, and other demographic factors. This could impact certain project types more than others, such as affordable, family-centric, or senior housing projects.

COST ANALYSIS

A principal limitation to the generalizability of the cost analysis in this report is the availability of information for products and services, as well as the temporal and local specificity of costs in the construction industry. Many line-item costs have high variability over time and in different housing markets, especially for products such as shared circuit HPWHs that are still relatively new in the U.S. market. For reference, the research team could only find and procure price quotes from one shared circuit HPWH manufacturer. This situation may present challenges to projects under requirement to procure more than one competitive bid for certain products (a requirement for some projects utilizing public subsidies). According to industry expert interviews, the San Francisco Bay Area also has uniquely high labor rates for on- *and* offsite scopes of work compared to other regions, which could have uncertain impacts on the relative costs of the systems analyzed in this report. Furthermore, Factory_OS is only one offsite housing producer, whose approach (and estimate) will inevitably differ from other firms.

While the research team finds a cost differential to the raw material and labor cost of the distributed system, prefabricated modules with distributed HPWH systems offer potential *time* savings to the project by dramatically reducing onsite construction scope. This impact could result in holistic upfront cost reductions for a distributed system, but this is difficult to precisely measure due to the multiple overlapping onsite trades and numerous subcontractors involved with centralized system installations. Thus, this potentially significant consideration remains quantitatively outside of the scope of these estimates.

Potential quality control improvements of factory-built housing also exist that are of particular interest for distributed HPWH systems. The research team's industry interview feedback and own experiences indicate that installation problems can frequently undermine the performance (and promised energy savings) of HPWH systems (centralized and otherwise). Modular construction techniques, however, can pursue an optimal design and installation process for in-unit HPWHs incorporated during module assembly, ensuring consistent and reliable installation and inspection practices. Doing so can also integrate in-unit water heating capabilities into a standardized set of apartment units offered on *multiple* projects, which could reduce the upfront design *and* onsite construction scope (and related costs) when compared to centralized heating systems for multifamily housing projects (which must be designed uniquely for each project). The impacts of these advantages are difficult to quantify or verify for a singular and hypothetical project.

The cost estimates reflect one-time cost quotes from contractors and suppliers. One advantage to modular construction is the economy of scale in factory production that allows for long-term supply chain partnerships and resulting discounts through bulk purchasing that cannot be met through one-off projects. The ultimate potential cost savings available here are difficult to estimate outside of realistic business negotiations.

Lastly, the cost estimates in this report do not factor in potential rebate or other incentive programs that may be available because of the passage of the Inflation Reduction Act or through other state and local energy efficiency programs, which could ultimately reduce or eliminate cost premiums for a distributed HPWH system.

These considerations render the cost estimates for distributed HPWH systems highly conservative in this report, implying that real-world applications of such designs may reduce or eliminate the cost premium reflected in the findings.

LIFE CYCLE COST ANALYSIS

The LCC depends on energy costs projected into the future, thereby carrying an appreciable margin of uncertainty to the findings. One instance of uncertainty is in the escalation of energy cost and its sensitivity to the social cost of carbon, which could be implemented through new policy. Additionally, the LCC analysis assumes approximate service lives of equipment and does not include expected maintenance costs due to limited information availability, particularly for newer products like the central HPWH and shared circuit HPWH. The all-in-one installation of in-unit HPWHs, standardized and optimized through factory production, may allow for easier maintenance and repairs, extending the useful life of HPWHs in a distributed system and reducing this system's life cycle costs; alternatively, facility managers may fully replace smaller appliances rather than pay for servicing, which could increase a distributed system's life cycle costs. Actual, longitudinal operational data are required to confirm the ultimate impact of maintenance for distributed systems. Similarly, quantitative estimates of long-term operations and maintenance costs for multifamily housing built through modular construction methods *could* favor the simplified in-unit HPWH installation, but this information is unavailable at present.

AREAS FOR FUTURE RESEARCH

HPWH—EQUIPMENT SIZE REFINEMENT

One area for research expansion is in traditional versus non-traditional domestic hot water system sizing methods. Metered domestic hot water consumption data across geographic regions are required to select the right size of domestic water heaters, whereas traditional methods of sizing are often based on outdated fixture flow rates. The benefits of using modern trend data to size equipment could include smaller water heater and storage tank minimums to meet domestic hot water demand, thereby reducing upfront installation costs. This could also enable nontraditional water heater options, including integrated refrigerator and hot water heaters or water heaters with wall-mounted storage tanks, which would increase usable floor area compared to larger, floor-mounted water heaters.

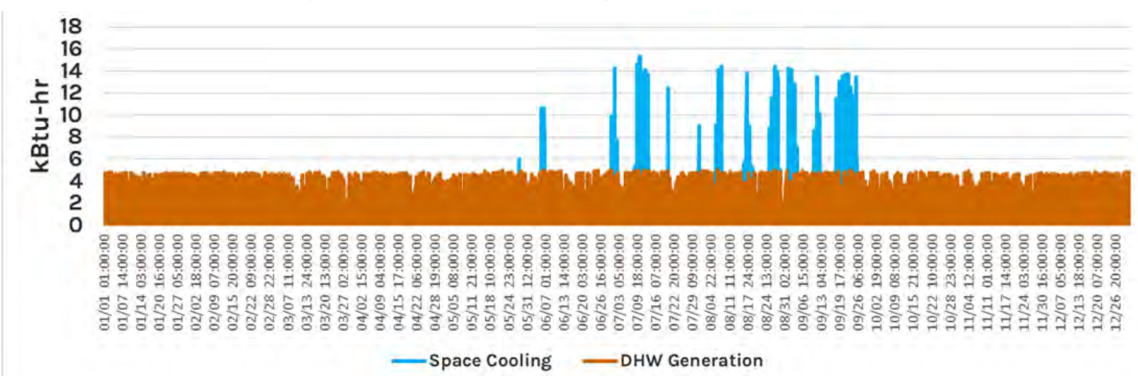
RESILIENCE ANALYSIS—ELECTRIC LOAD SHIFTING

HPWHs could serve as a thermal battery for individual units and whole buildings. Benefits include potential improvements to the per-unit and whole-building resilience against power outages, as well as better alignment with the needs of energy grids using large proportions of clean sources like wind and solar. Future research could bear out these impacts, assessing the practicality of distributed storage in residential buildings for integration with smart grid technology and management.

Future work could also evaluate HPWHs models with both inlet and outlet connections at the top of the unit rather than the side of unit. Equipment with top outlets would result in minor space savings when compared to units with side connections because the side connection elbow requires additional lateral clearance, potentially improving the feasibility of in-unit HPWH systems.

Optimized free cooling management research could assess the relative impact on comfort and energy use when controlling heat pump cool air rejection location. For instance, providing occupant or automated controls to discharge the air to the indoor or outdoor environment, depending on overall heat balance of the room, could be useful. By avoiding cool discharge to occupied space, this could reduce the heating load, increase comfort, and reduce energy use in cold climates. Exhibit 33 displays the complex, time-dependent impact of free cooling across an average year in Oakland, California. This strategy would also require mechanical design changes, however, alongside additional controls and ductwork (for potentially sending discharge outdoors). Potentially, this could be done by upsizing the toilet exhaust ductwork and mixing cool heat pump discharge air downstream of the toilet exhaust fan. To maintain air balance in the room, especially with other room exhaust equipment running, additional makeup air to the room may be required. Locating the HPWH near the perimeter of the building would reduce the distribution impact. The layered considerations and impacts of these decisions require further research but could improve the energy performance of distributed HPWH systems even further and improve occupant comfort.

Exhibit 33. "Free Cooling" Impact Across Average Year in Oakland, California



kBtu-hr = kilo-British thermal units per hour, a measure of energy use. DHW = domestic hot water.
Temporal overview of free cooling from HPWH and DHW savings across a full calendar year for Oakland, California.

VALIDATION OF PREDICTED ENERGY MODEL

To extend and validate the findings presented in this report, future grants could fund projects across diverse climate zones that directly compare metered energy data between a centralized and distributed heat pump system. This would add context and precision.

COMPARING ON- VERSUS OFFSITE CONSTRUCTION COSTS

This report does not compare on- and offsite construction costs directly. The purpose was instead to assess the viability of distributed HPWH systems for modular construction integration using a centralized HPWH project that was *also* built using similar methods. The research team firmly believes that the upfront cost difference between these systems is likely similar to or even exaggerated for fully onsite construction approaches. Further research could provide deeper analysis into this and other questions comparing conventional versus offsite and industrialized construction. For example, estimates would improve with additional detailed cost estimates from other factories supporting the industrialized construction of housing, as well as offering more scrutiny of the onsite construction costs from general contractors. Other supportive efforts could more deeply assess the purported qualitative advantages of offsite and industrialized construction, including superior quality control, as-built precision, and actual building performance. Pending further validation of this report's findings, the research team believes that factory-produced housing remains uniquely capable of standardizing and proliferating highly energy efficient and resilient designs.

CONCLUSION

The research findings are promising. Both centralized and distributed HPWHs can dramatically reduce domestic water heating and overall building energy use compared to natural gas systems in multifamily housing. As many states and cities legislate for all-electric construction (Iaconangelo, 2022), and especially as electric grids themselves increasingly source energy from clean and renewable sources, the findings are useful validation for HPWHs. Distributed HPWH systems have modest per-unit cost premiums, but there are also benefits to project schedule and installation reliability through industrialized construction approaches that this preliminary research does not capture. However, integrating distributed HPWH systems into modular building methods is not without unique challenges *and* opportunities to consider when translating research toward industry adoption, some of which include:

Building codes. Increased adoption of performance-based (also known as outcome-based) building codes could improve the viability and application of innovative, cost-saving, and energy efficient technologies. Prescriptive building codes, pervasive across the U.S., establish minimum requirements for each individual building element (e.g., windows, insulation, plumbing fixtures) to a high degree of specificity. But they tend to limit innovation in the built environment because they have embedded assumptions about the conventional means and methods of building design and construction; new technologies and processes may render some of these prescriptive standards obsolete, which may be the case for both offsite construction processes and HPWH systems. For instance, a recent white paper from the Advanced Building Construction Collaborative (funded by the DOE) found that building codes are often written with only *onsite* construction in mind, presenting complications in applying existing building codes to units built predominantly offsite (Colker, et al., 2022). Even more minor products such as a horizontal DWHR device may not be recognized by existing local codes, requiring amendments or exceptions because they are different from conventional plumbing systems. States such as California, Washington, and Florida already offer performance-based codes for energy efficiency compliance (though compliance varies), and the federal government could standardize and encourage performance-based code structures for more states to unlock cost-effective innovation (Senick and Abramson, 2013).

In the U.S., building codes are highly localized. The International Codes Council (ICC) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) are two primary standards-setting organizations that iteratively revise the base codes that many states and local jurisdictions eventually adopt. Although the federal government requires states and local jurisdictions to use these codes as a minimum standard, they often adopt different versions at different times and can amend or adjust them in various ways that can undermine the power of standardization.[2] This is a challenge for designers, builders, and others attempting to provide products or services across multiple jurisdictions, and especially difficult for offsite housing producers trying to provide standardized products and unit designs. HUD already sets a nationwide code standard and inspection process for manufactured ("mobile") homes and could consider adopting a similar model for modular construction. For HPWHs, the federal government could also steer more states toward these highly energy efficient products by making them the *baseline* technology in the codes sent to states for adoption, potentially modeling after California's (Arellano and Zilliac, 2021).

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 maximum potential benefits regarding affordability and sustainability goals. This is especially true for strategies such as modular construction that depend on consistent production pipelines to "keep the lights on" in the factory. Procedural improvements to permitting could include:

- *Single-agency review*. Developers submit plans through only one local government agency rather than separate submissions and sequential reviews by planning, fire, building, and/or public works departments (among others). Single-agency review can greatly simplify permit submission and processing for developers, and it could require local jurisdictions to improve inter-agency coordination and communication to accommodate the change.
- *Limits on local discretionary review*. Discretionary review can be time-consuming and unpredictable because it often allows planning commissions and departments to assess projects based on subjective review standards. The adoption of *objective* review standards in the zoning code, time limits on permit review periods, or other interventions to limit discretionary review could increase the predictability of housing delivery overall, benefiting the industry at large and unlocking deeper synergy with industrialized construction methods.
- *Interventions that limit local jurisdictions' ability to fall behind housing production needs*. Many of the metropolitan regions across the country have fragmented regional governance and other mechanisms that can contribute to a chronic undersupply of new housing to meet demand (Kingsella and MacArthur, 2022). State or regional incentive structures to mitigate this issue can, for example, impose restrictions to local control for jurisdictions out of compliance with their housing goals. Massachusetts 40B, a state law passed in 1969, does exactly this, and Terner Center for Housing Innovation research 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).

HUD does not have the direct authority to control local permitting procedures, but it could provide structured guidance for implementation of the suggested improvements (through technical assistance and other resources), and it could possibly make certain state or local funding (especially for housing) contingent on compliance with one or more of the above interventions.

[2] For reference, see the status of residential energy code efficiency adoption across states and large metropolitan areas in the U.S., as presented using DOE data in 2022: https://public.tableau.com/app/profile/doebecp/viz/Top100MetroDatabase-PrimaryCityCode-V4/MetroResidentialCode.

Sustainability-focused policies and programs. New and existing tax credits and rebate programs that incentivize and reward 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, for instance, include over $50 billion for building electrification and energy efficiency, primarily through tax credits and rebate programs (Jenkins, et al., 2022). Products such as HPWHs (distributed and otherwise) may be eligible for many of these programs, but states will likely determine the ultimate terms of eligibility. However, complications remain for developers and owners of multifamily rental properties who may not see the cost savings from upfront investments into energy efficiency. New programs will likely need to pay for part or all of HPWH installation and minimize administrative burden in order to achieve meaningful industry participation (without potentially increasing construction costs).

In addition, existing subsidies for affordable housing at multiple levels of government could incorporate scoring criteria that reward high energy- and cost-efficient designs and construction methods to support uptake of progressive energy efficiency funding. These criteria would tangibly incentivize adoption of cost-effective, high quality new construction, *and* they would send a prominent signal to researchers and practitioners able to improve and proliferate processes and products to further accelerate the trend. At the federal level, HUD can add such criteria to programs such as Choice Neighborhoods. States and local programs can follow early examples such as those from Seattle's 2030 Challenge, which provides concessions to the existing zoning code for developers designing for substantial energy efficiency.

A related incentive in public funding and programs could reward designs and building methods that promote resilience. As highlighted by HUD's own recent *Evidence Matters*, energy efficiency and affordability are important components of household- and community-level resilience in general (HUD, 2022). More specifically, distributed HPWH systems offer self-contained water heating and energy storage for each unit, providing redundancy that can improve resilience in the event of an emergency or energy insecurity (such as when the power is out). Industrialized and offsite construction techniques, meanwhile, insulate a substantial portion of construction work—*and workers*—from increasingly prevalent extreme weather events such as high heat hazards. The controlled indoor factory environment thus mitigates some of the consequences of climate change on housing development by improving the safety and stability of the workforce and reducing the impact of environmental hazards on project schedules and budgets.

Learning curves. Practitioners across all the phases of housing development—including investors, developers, architects, general contractors, subcontractors, the skilled trades, and facilities management—will require new knowledge and practices for any new technology or process in housing construction. These barriers require coordinated engagement across historically fragmented stakeholder networks (including multiple levels of government and the agencies within them). One promising effort to accelerate adoption of environmentally forward and cost-conscious technologies such as HPWHs and industrialized construction is the Advanced Building Construction (ABC) Collaborative, a DOE-funded initiative to connect and grow viable solutions to many of the challenges facing the built environment industry. HUD also hosted the Innovative Housing Showcase in the summer of 2022 in Washington, D.C. in anticipation of the release of its Offsite Construction Roadmap. These early but promising initiatives—as well as funding for research projects such as this one—will be instrumental in overcoming the barriers to innovation in the built environment, but they could be better coordinated between governmental agencies to align efforts and resources.

The research team's broader initiatives in and outside this report will continue to explore the barriers and opportunities for unlocking the potential in design and construction innovations. Industrialized and offsite construction methods and distributed HPWHs are just one example of critical synergies needed to deliver high-performing, multifamily housing cost-effectively. This and similar work demands continued collaboration between industry stakeholders, researchers, and local, state, and federal government agencies. To meet the enormous and urgent demand of the housing and climate crises in the U.S., standard practices need to be developed for of quality, affordable, environmentally sensitive design and construction.

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APPENDIXES

APPENDIX A—ENERGY MODELING INPUTS

	1-Bedroom Unit	2-Bedroom Unit	3-Bedroom Unit
Building/Zone Area (As designed for Reference Project)			
Square Footage (SF)	488	951	1333
Front Wall Width (FT)	15.0	29.3	41.0
Depth (FT)	32.5	32.5	32.5
Orientation	South	South	South
WWR Main Orientation	30.0%	30.5%	23.5%
Sill Height (FT)	1	1	1
Orientation Other	NA	West	East
WWR Other Orientation	NA	21.5%	27.5%
Shading	Not Included	Not Included	Not Included
Building Envelope (As designed for Reference Project)			
Wall (Btu/h·ft²·°F)	U-0.066	U-0.066	U-0.066
Roof (Btu/h·ft²·°F)	Adiabatic	Adiabatic	Adiabatic
Glazing	U-0.36 Btu/h·ft²·°F SHGC-0.22/VLT-0.51	U-0.36 Btu/h·ft²·°F SHGC-0.22/VLT-0.52	U-0.36 Btu/h·ft²·°F SHGC-0.22/VLT-0.53
Infiltration			
Design Flow Rate (m3/s-m2) (As per DOE Multifamily prototype Bldg.)	Flow/ExteriorWallArea 0.000682752	Flow/ExteriorWallArea 0.000682753	Flow/ExteriorWallArea 0.000682754
Internal Gains			
People (No. of People)	2	3	4
Activity Level (As per Residential Living)	117 W/Person	117 W/Person	117 W/Person
Lighting (W/SF) (As designed for Reference Project)	0.5	0.5	0.5
Non Regulated Lighting (W/SF) (As per T24 2019 NonRes Code-High Rise Res Example)	0.9	0.8	0.6
Plug Loads (W/SF) (As per T24 2019 NonRes Code-High Rise Res Example)	4.7	4.3	3.9
Process Loads/Cooking (W/SF) (As per T24 2019 NonRes Code-High Rise Res Example)	5.3	4.4	3.7
Washer (In Unit) (As per T24 2019 Res Code-Multifamily Example)	3.7	3.7	3.7
Electric Dryer (In unit) (As per T24 2019 Res Code-Multifamily Example)	1.1	1.1	1.1
Ventilation			
Outdoor Air (CFM)	29.6	51	70
Setpoints			
Heating Setpoint (F)	68	68	68
Cooling Setpoint (F)	78	78	78

Cont.	1-Bedroom Unit	2-Bedroom Unit	3-Bedroom Unit
Internal Gains Schedule			
People	CA T24 2019 NonRes Code (High Rise Residential)	CA T24 2019 NonRes Code (High Rise Residential)	CA T24 2019 NonRes Code (High Rise Residential)
Lighting	CA T24 2019 NonRes Code (High Rise Residential)	CA T24 2019 NonRes Code (High Rise Residential)	CA T24 2019 NonRes Code (High Rise Residential)
Non Reg Lighting	CA T24 2019 NonRes Code (High Rise Residential)	CA T24 2019 NonRes Code (High Rise Residential)	CA T24 2019 NonRes Code (High Rise Residential)
Plug Loads	CA T24 2019 NonRes Code (High Rise Residential)	CA T24 2019 NonRes Code (High Rise Residential)	CA T24 2019 NonRes Code (High Rise Residential)
Process Loads	CA T24 2019 NonRes Code (High Rise Residential)	CA T24 2019 NonRes Code (High Rise Residential)	CA T24 2019 NonRes Code (High Rise Residential)
Infiltration	CA T24 2019 NonRes Code (High Rise Residential)	CA T24 2019 NonRes Code (High Rise Residential)	CA T24 2019 NonRes Code (High Rise Residential)
Washer	CA T24 2019 Res Code (Multifamily Example)	CA T24 2019 Res Code (Multifamily Example)	CA T24 2019 Res Code (Multifamily Example)
Dryer	CA T24 2019 Res Code (Multifamily Example)	CA T24 2019 Res Code (Multifamily Example)	CA T24 2019 Res Code (Multifamily Example)
HVAC System (As designed for Reference Project)			
System Type	Dedicated Outdoor Air System w/ Variable Refrigerant Flow(VRF)	Dedicated Outdoor Air System w/ Variable Refrigerant Flow(VRF)	Dedicated Outdoor Air System w/ Variable Refrigerant Flow(VRF)
Cooling Capacity (Btu-hr)	24,000	24,000	30,000
Heating Capacity (Btu-hr)	27,000	27,000	33,750
Cooling EER	12.5	12.5	12.5
Cooling SEER	22.0	22.0	22.0
Heating COP	4	4	4
Fan Flow (Max) CFM	406	565	724
Fan Flow (Min) CFM	265	452	639
Fan Power (TSP)	0.25	0.1	0.1
Fan Motor HP	0.5	0.67	0.67
Domestic Hot Water System (As designed for Reference Project)			
System Type	Heat Pump Water Heater	Heat Pump Water Heater	Heat Pump Water Heater
Heat Pump Unit COP	3	3	3
DHW Heat Recovery System Type	Horizontal Flow	Horizontal Flow	Horizontal Flow
DHW Heat Recovery System Effectiveness	32%	32%	32%
Shower Duration (Minutes)	10.25	14.25	17
Average Daily Shower Hot Water Use (Gal/day)	15.5	21.4	25.3
Shower Flow Rate (GPM)	1.5	1.5	1.5
Bath Flow Rate (GPM)	4.4	4.4	4.4
Faucet Flow Rate (GPM)	1.1	1.1	1.1
Dishwasher Flow Rate (GPM)	0.01	0.01	0.01
Clothes Washer Flow Rate (GPM)	0.025	0.025	0.025
Fixture Schedules			
Shower & Bath (Modified based on "Development of Realistic Water Draw Profiles for California Residential Water Heating Energy Estimations" paper)	Morning- 1st Shower 10 Min.	Morning- 1st Shower 8 Min. Morning-2nd Shower 6 Min.	Morning-1st Shower 6 Min. Morning-2nd Shower 6 Min. Evening-3rd Shower 5 Min.
Faucet	CA T24 2019 NonRes Code (High Rise Residential)	CA T24 2019 NonRes Code (High Rise Residential)	CA T24 2019 NonRes Code (High Rise Residential)
Dishwasher	CA T24 2019 NonRes Code (High Rise Residential)	CA T24 2019 NonRes Code (High Rise Residential)	CA T24 2019 NonRes Code (High Rise Residential)
Clothes Washer	CA T24 2019 Res Code (Multifamily Example)	CA T24 2019 Res Code (Multifamily Example)	CA T24 2019 Res Code (Multifamily Example)

APPENDIX B—HOURLY DISTRIBUTION LOSSESS FOR CENTRAL WATER HEATING SYSTEM

	Hourly Distibution Losses for Central Water Heating Systems	https://www.energycodeace.com/site/custom/public/reference-ace-2019/index.html#!Documents/b5hourlydistributionlossforcentralwaterheatingsystems.htm		

Equation 15

$$HRDL_k = NLoop_k \times HRLL_k + HRBL_k$$

HRDL k with Branch Losses			**64,500**	**Btu-hr**
HRDL k without Branch Losses			**38,424**	**Btu-hr**
N Loop	1			
HRLLk	Loop Losses	Equation 16		is the hourly heat loss from all six pipe sections.
HRBLk	Branch Losses	Equation 24		
PLWF	38,424			Equation 17- Hourly pipe heat loss with non-zero water flow (Btu/hr)
PLCD	0		0	Hourly pipe heat loss without water flow (Btu/hr)

Equation 16

$$HRLL_k = \sum_n [PLWF_n + PLCD_n]$$

HRLL k	**38,424**	**Btu/hr**

Equation 17

$$PLWF_n = Flow_n \times (1 - f_{noflow.n}) \times \rho \times C_p \times (T_{n.in} - T_{n.out})$$

PLWF n	**38,424**	**Btu/hr**	
Flow n	1433	gph	
Flow recirc	360	gph	assumption that the recirculation flow rate is 6 gpm
$f_{noflow,n}$	0		
Flow n x (1- f noflow n)	1433		
p	8.345	lb/gal	Density of water, 8.345 (lb/gal)
Cp	1	Btu/lb-oF	Specific heat of water, 1 (Btu/lb-oF)
T n, in	140		
T n, out			

Equation 19

$$T_{out.n} = T_{amb.n} + (T_{in.n} - T_{amb.n}) \times e^{-\frac{UA_n}{\rho C_p Flow_n}}$$

T Out n	**136.8**	**F**
T Amb n	75	
UA n	606.3	
Len n	4850	
U bare n		R-11
f UA	0.5	R-2
U insul n	0.125	R-11
Dia	2	inches
Dia o	3.5	inches
Dia X		
Thick	1.5	inches
h	0.091	R-11

Uinsul

Equation 20

UA n	**606.3**

Cont.	**Hourly Distibution Losses for Central Water Heating Systems**	https://www.energycodeace.com/site/custom/public/reference-ace-2019/index.html#!Documents/b5hourlydistributionlossforcentralwaterheatingsystems.htm		

Equation 24 HRBL k $HRBL_k = Nbranch_k \times (HBUL + HBWL)$ **26,076 Btu-hr**

N branch k		234	Number of branches in water heating
HBUL =	Hourly pipe loss for one branch when water is in use (Btu/hr)		
HBWL =	Hourly pipe loss for one branch due to hot water waste (Btu/hr).		

$$HBUL = \left(\frac{GPH_k}{NBranch_k}\right) \times \rho \times C_p \times (T_{b,in} - T_{b,out})$$

7.1 Btu-hr

GPH k		1433
Tb in		136.79
Tb out		

Equation 26 T b Out $T_{b,out} = T_{amb,b} + (T_{b,in} - T_{amb,b}) \times e^{-\frac{UA_b}{\rho \times C_p \times Flow_b}}$ **136.648** F

T amb b		75	F
UA b			
Flow b		120	

Equation 27 UA b $UA_b = Len_b \times U_{insul,b}$ **2.25**

Equation 35 Len b $Len_b = 4 + H_{floor} \times Nfloor/2$ **4.5** (ft) Branch pipe length

Constant		4	
H Floor		1	ft
N Floor		1	
Constant		2	

$$U_{insul} = \frac{\pi}{\frac{ln\left(\frac{Dia_x}{Dia_o}\right)}{\frac{2 \times Cond}{12}} + \frac{12}{h \times Dia_x}}$$

Hb 0.5

Equation 28 HBWL **104 Btu-hr**

$$HBWL = N_{waste} \times SCH_{waste,m} \times f_{vol} \times 7.48 \times \pi \times \left(\frac{Dia_b - 0.125}{24}\right)^2 \times Len_b \times \rho \times C_p \times (T_{b,in} - T_{inlet})$$

N waste		11.50636202	
SCH waste		0.041	m
f vol		1.4	Assumed
T in b			
T inlet			

Annual Energy Calculations

	Annual Distributed Losses (Btu-hr)	Annual Distributed Losses (kbtu-hr)	Annual Distributed Losses per Unit (kbtu-hr)
With Branch Losses	447,310,026	447,310	**1912 kbtu-hr**
WithOut Branch Losse	266,470,689	266,471	**1139 kbtu-hr**

For annual energy calculations, annual distributed losses per unit (kBtu-hr) with branch lossess value is assumed

Annual Distributed Losses per Unit **1912 kBtu-hr**

APPENDIX C—ENERGY ANALYSIS FINDINGS

The following provides energy analysis conducted across all climate zones.

Energy Use Intensity (kBtu/SF-yr)						
			Heating Hot Water System Type			
ASHRAE Climate Zone	Climate Condition	Representative City	Central Gas Water Heaters w- Recirculation (Sys. 1)	Central HP Water Heaters w- Recirculation (Sys. 2)	Distributed HP -In-Unit (Sys. 3)	Distributed HP-In-Unit w- Drain Heat Recovery (Sys. 4)
0A	Extremely Hot Humid	Ho Chi Minh City	29.7	25.2	24.5	24.4
0B	Extremely Hot Dry	Abu Dhabi	28.2	23.5	22.8	22.7
1A	Very Hot Humid	Honolulu	28.8	23.5	22.7	22.6
1B	Very Hot Dry	New Delhi	29.5	23.9	23.1	22.9
2A	Hot Humid	Tampa	30.6	24.2	23.5	23.2
2B	Hot Dry	Tucson	31.2	24.1	23.3	23.0
3A	Warm Humid	Atlanta	33.2	24.7	24.0	23.6
3B	Warm Dry	El Paso	33.0	24.6	23.8	23.5
3C	Warm Marine	San Diego	33.3	24.2	23.5	23.0
4A	Mixed Humid	New York City	35.7	25.6	24.9	24.4
4B	Mixed Dry	Albuquerque	35.3	25.2	24.5	24.0
4C	Mixed Marine	Seattle	35.8	25.5	24.8	24.2
5A	Cool Humid	Buffalo	38.0	26.3	25.6	25.0
5B	Cool Dry	Denver	37.6	26.1	25.4	24.8
5C	Cool Marine	Port Angeles	37.6	26.1	25.4	24.8
6A	Cool Humid	Rochester	39.2	26.8	26.1	25.4
6B	Cool Dry	Great Falls	39.3	26.8	26.1	25.4
7	Very Cold	International Falls	41.0	27.3	26.6	26.0
8	Subarctic/Arctic	Fairbanks	42.2	27.7	27.0	26.3

RESEARCH IN HOUSING AND TECHNOLOGY

SHEET INDEX

SHEET NUMBER	SHEET NAME
G0.00	COVER SHEET
A2.1.1	FLOOR PLAN - STUDIO AND ONE BED
A2.1.2	FLOOR PLAN - TWO BED
A2.1.3	FLOOR PLAN - THREE BED
MP2.1.1	FLOOR PLAN - STUDIO
MP2.1.2	3D VIEWS - STUDIO
MP2.1.3	FLOOR PLAN - ONE BED
MP2.1.4	3D VIEWS - ONE BED
MP2.1.5	FLOOR PLAN - TWO BED
MP2.1.6	FLOOR PLAN - TWO BED
MP2.1.7	3D VIEWS - TWO BED
MP2.1.8	FLOOR PLAN - THREE BED
MP2.1.9	FLOOR PLAN - THREE BED
MP2.1.10	FLOOR PLAN - ALTERNATES
MP7.1	SCHEDULES AND DETAILS

RENDERING OF REFERENCE CASE PROJECT LOCATED AT 2121 WOOD STREET IN OAKLAND, CALIFORNIA BY MBH ARCHITECTS IN PARTNERSHIP WITH SMITHGROUP AND FACTORY_OS

LEVERAGING MODULAR CONSTRUCTION WITH INTEGRATED HOT WATER SYSTEMS TO INCREASE EFFICIENCY AND REDUCE COST

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OFFICE OF POLICY DEVEOPMENT AND RESEARCH
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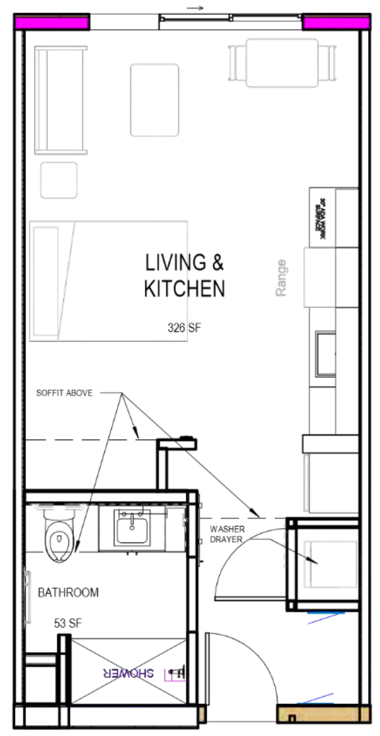

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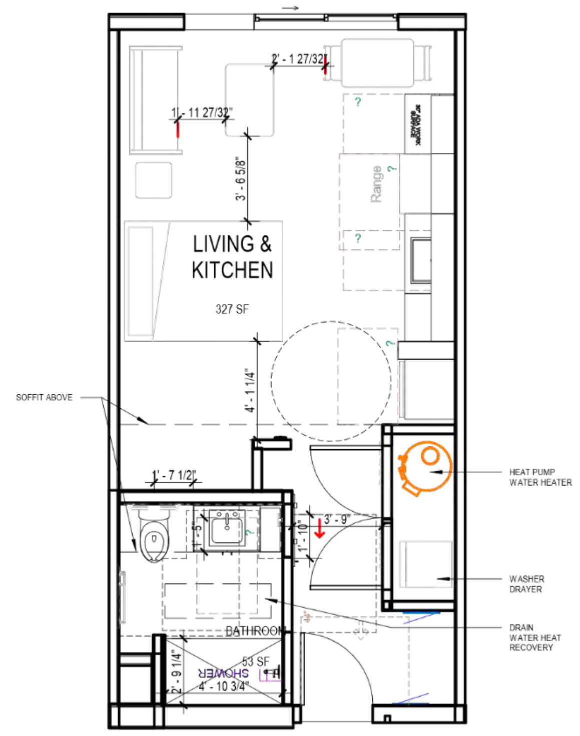

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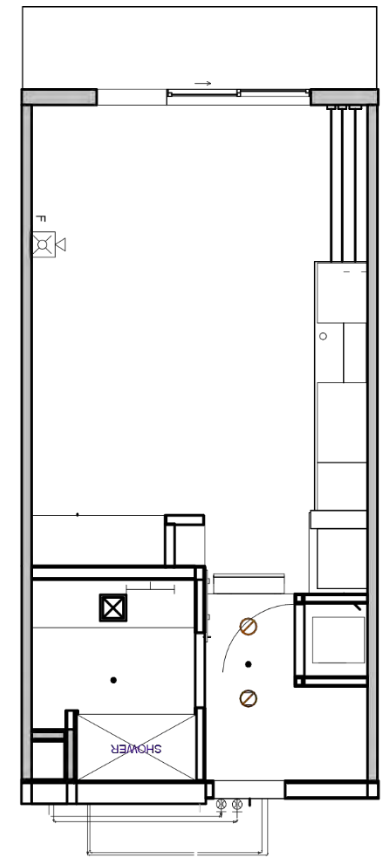

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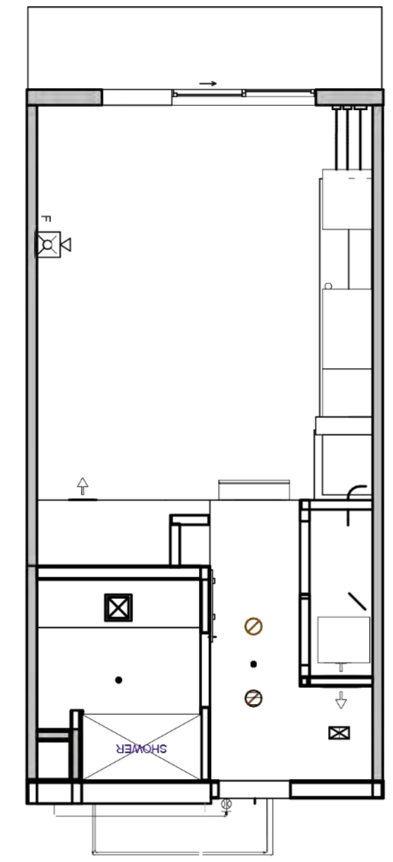

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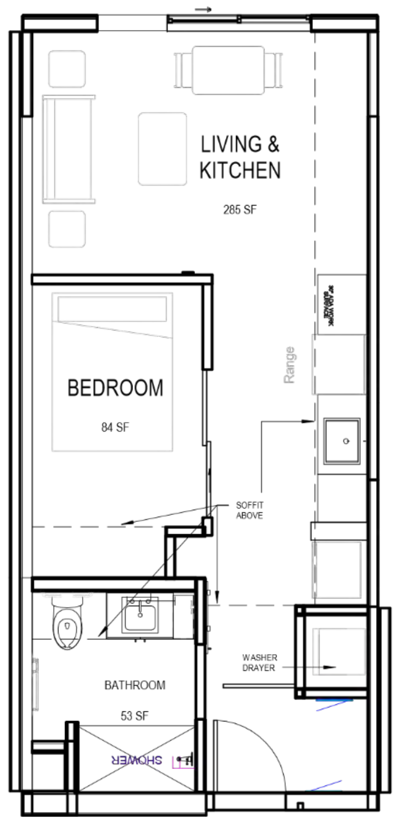

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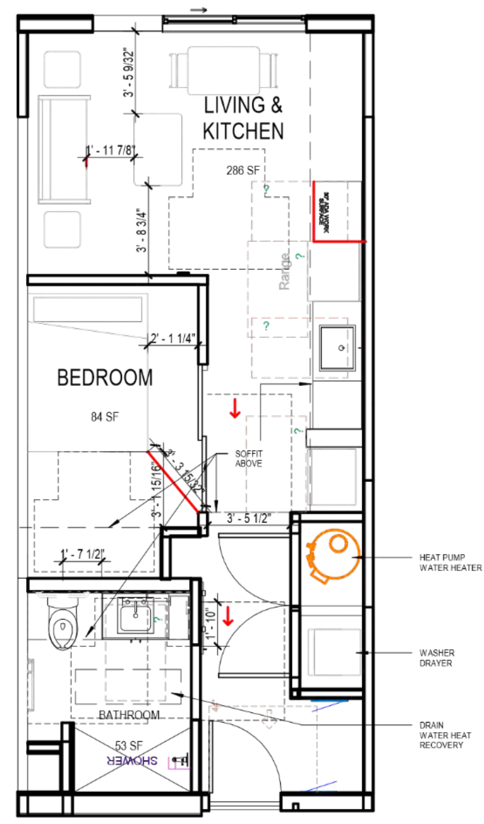

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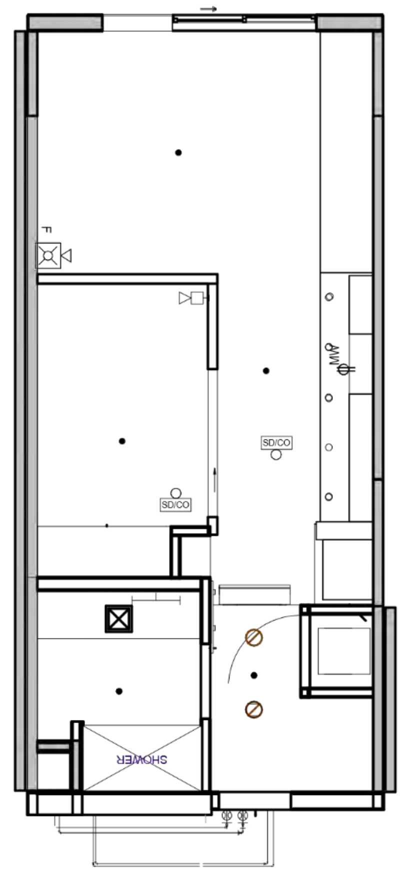

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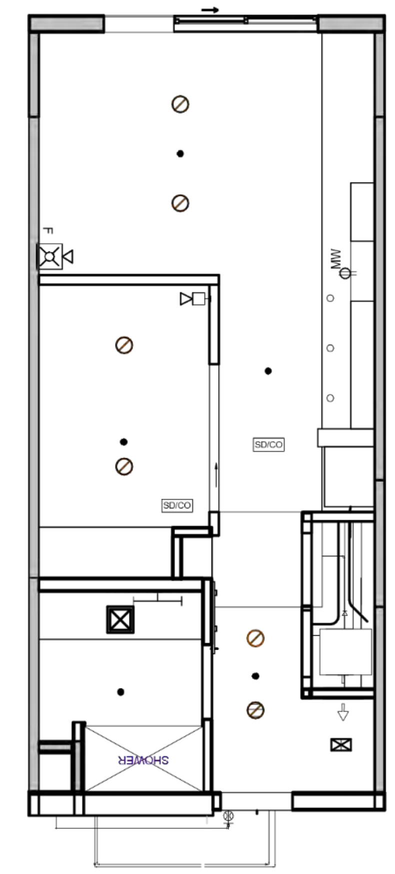

8 RCP - ONE BED - MODIFIED CASE
SCALE: 1/4" = 1'-0"

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FLOOR PLAN - STUDIO AND ONE BED

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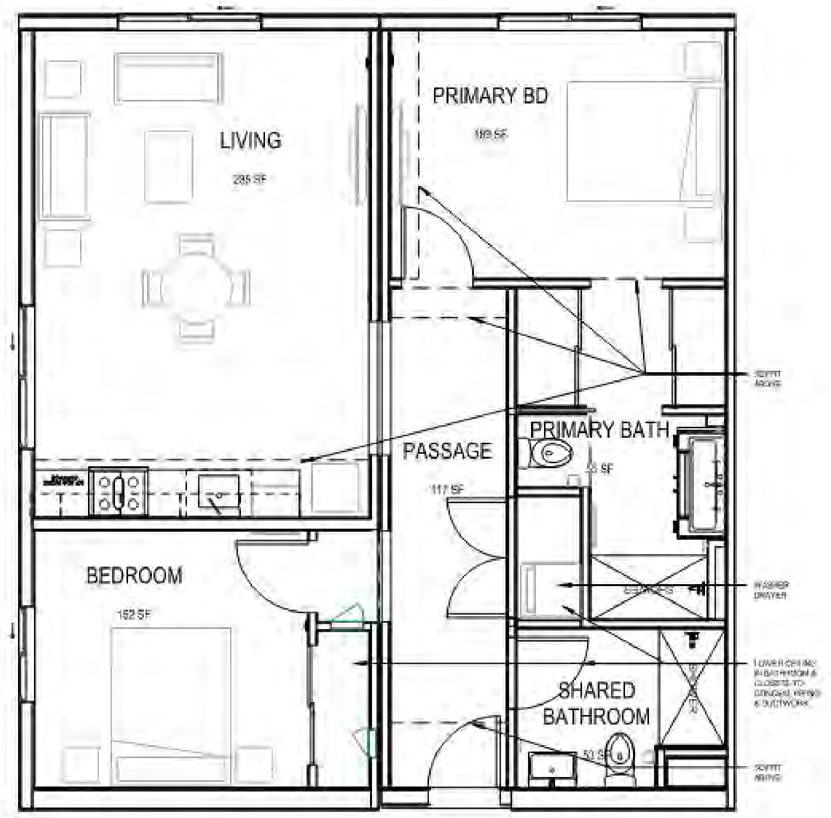

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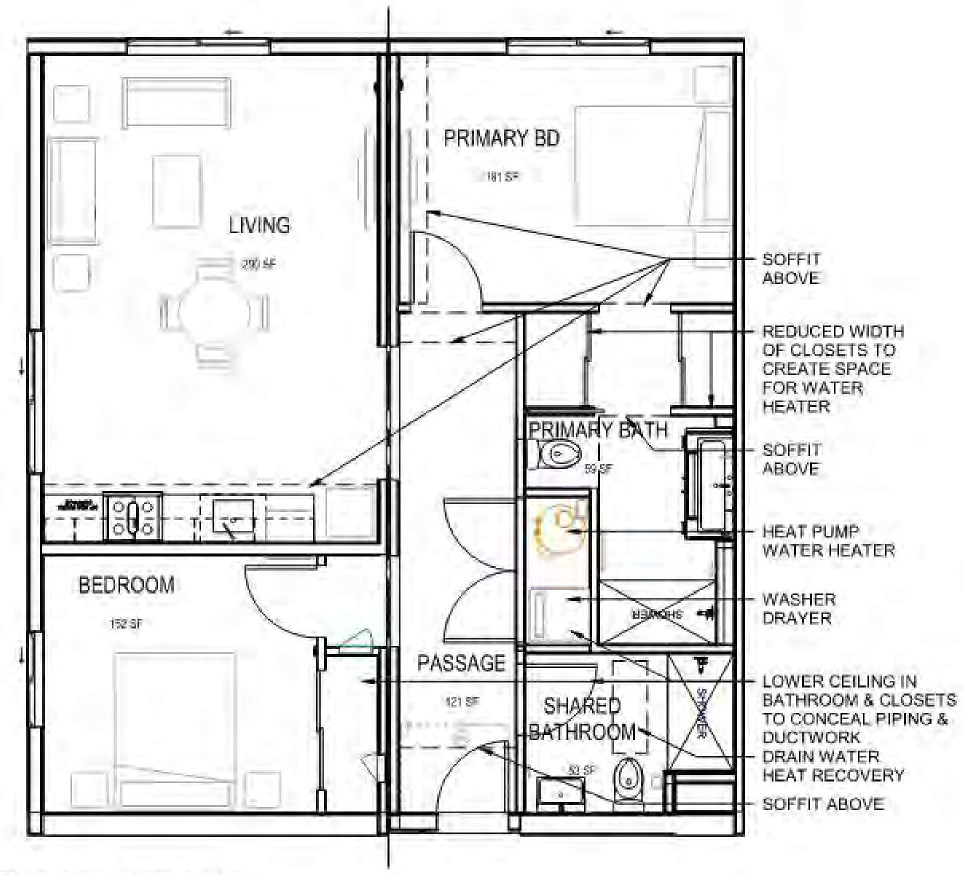

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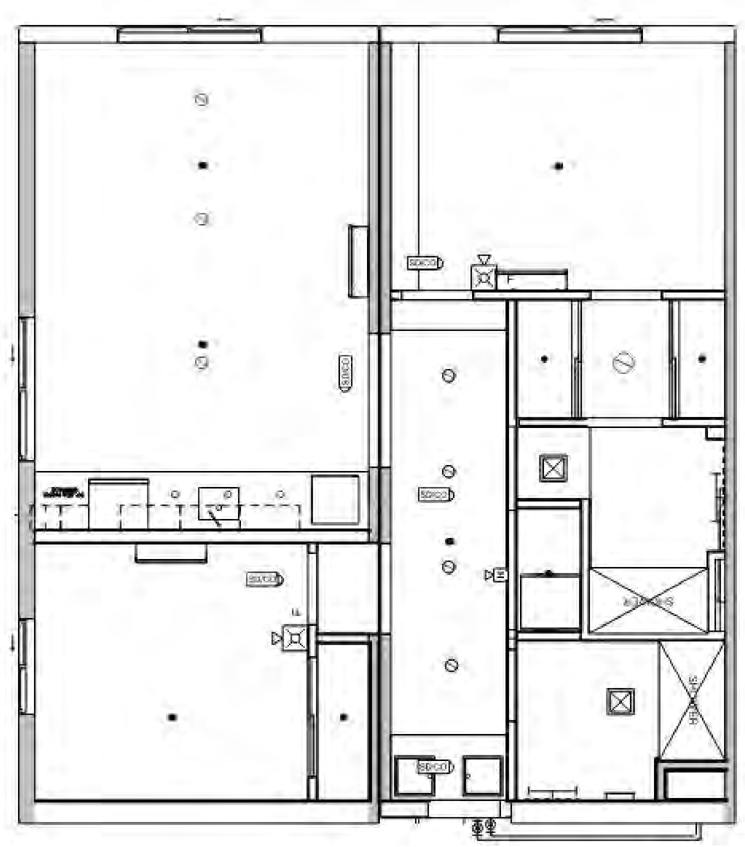

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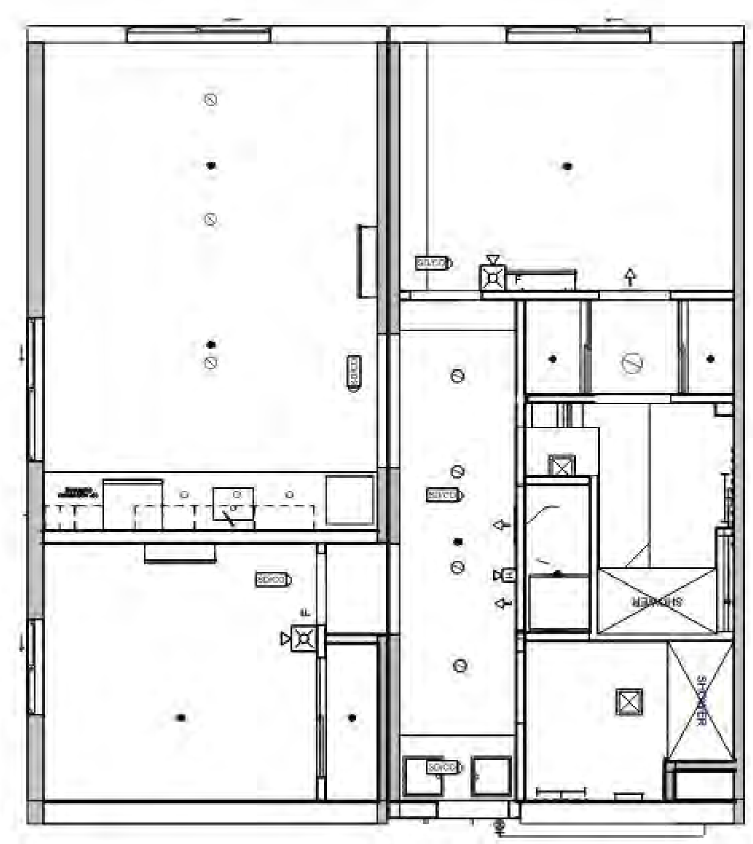

4 RCP - TWO BED - MODIFIED CASE
SCALE: 1/4" = 1'-0"

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SHEET TITLE

FLOOR PLAN - TWO BED

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A2.1.2

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3 THREE BED - REFERENCE CASE
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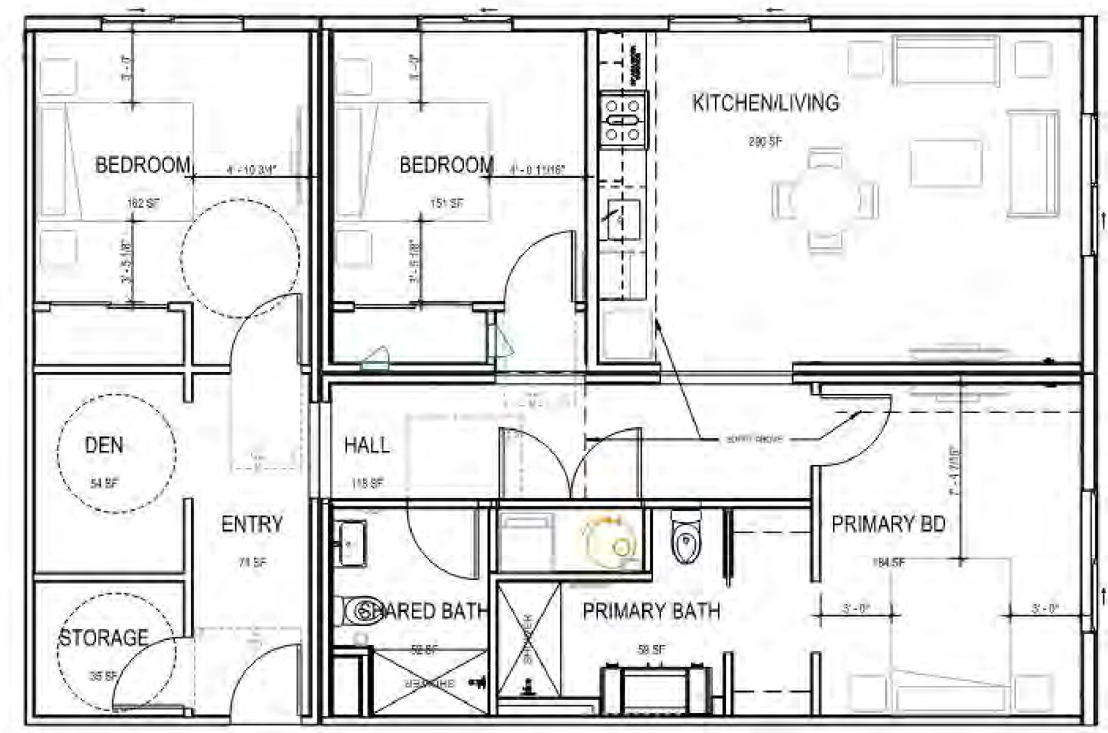

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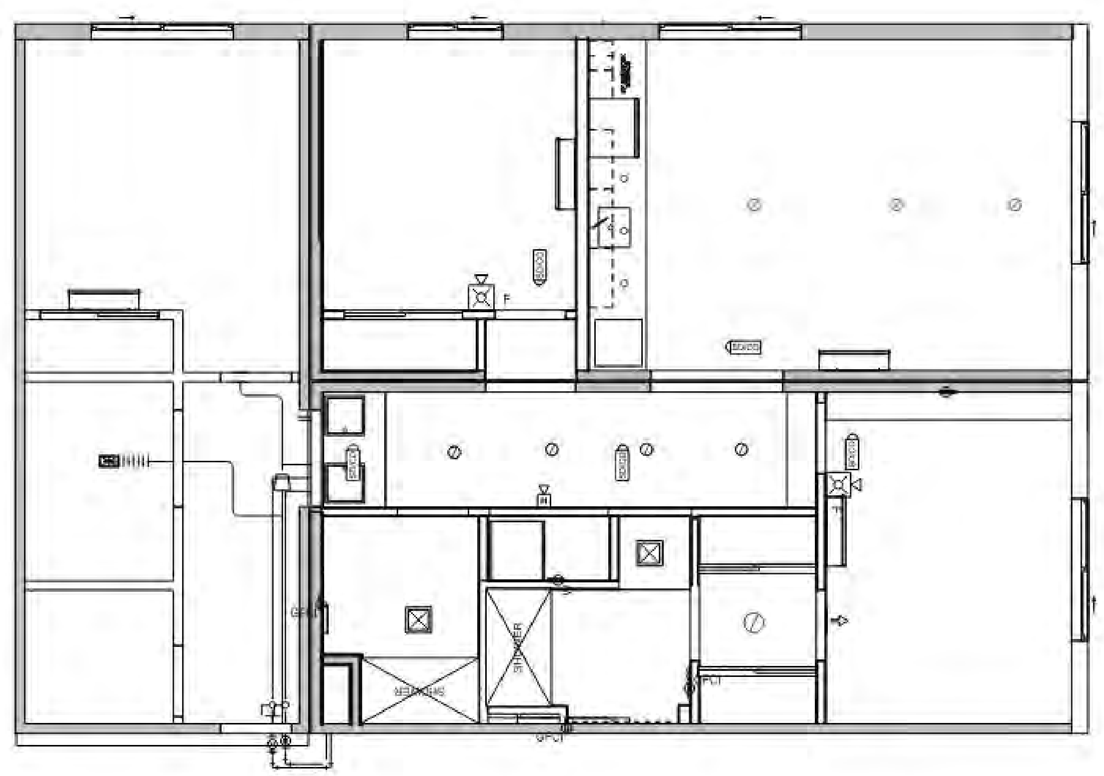

1 RCP - THREE BED - REFERENCE CASE
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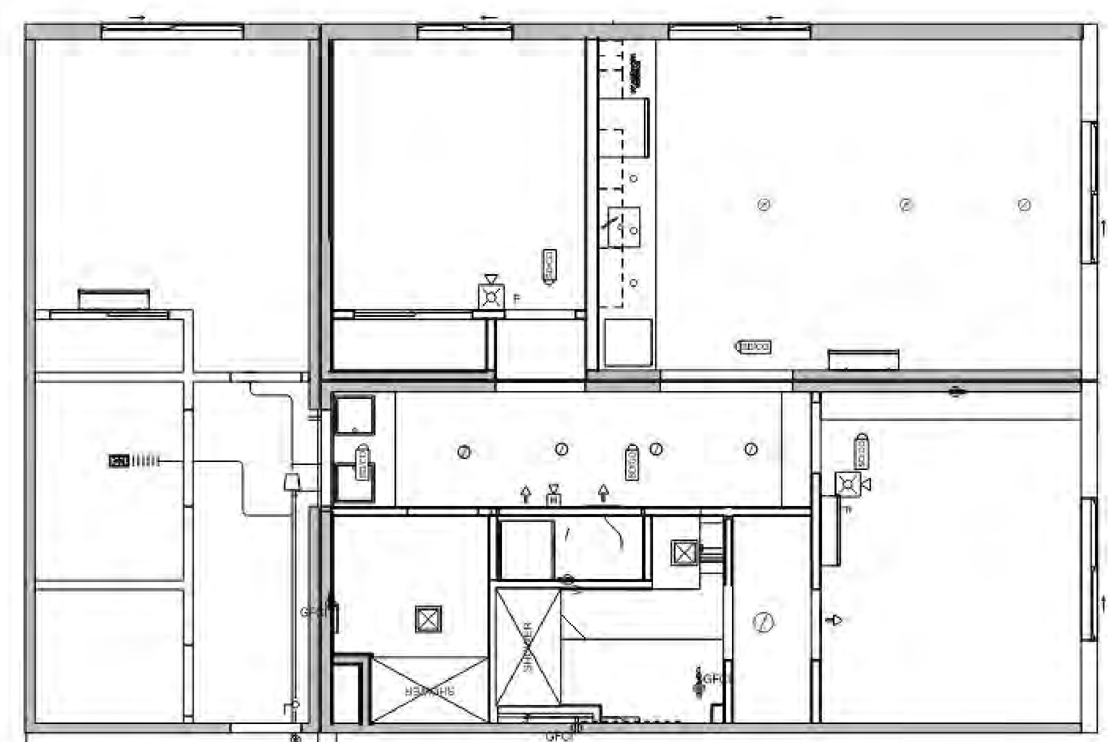

4 RCP - THREE BED - MODIFIED CASE
SCALE: 1/4" = 1'-0"

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FLOOR PLAN - THREE BED

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A2.1.3
SHEET NUMBER

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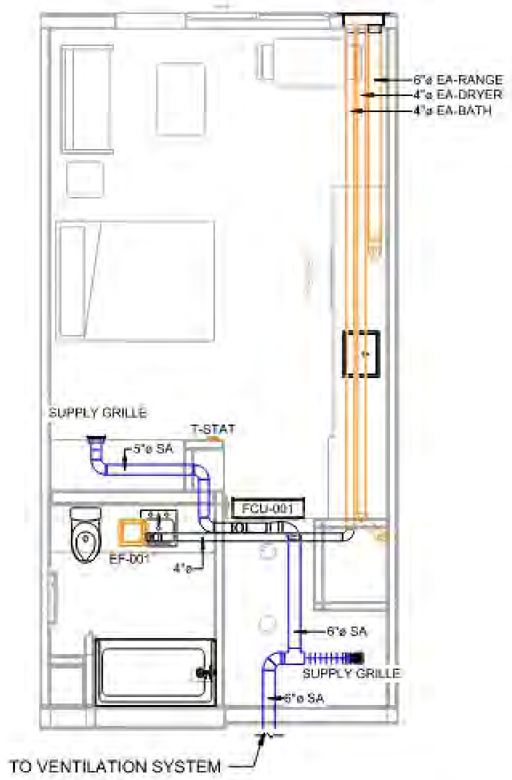
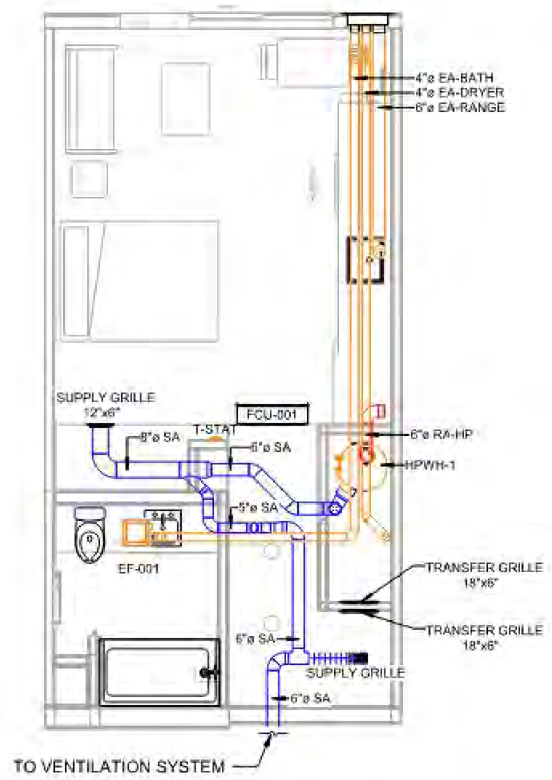
GENERAL SHEET NOTES



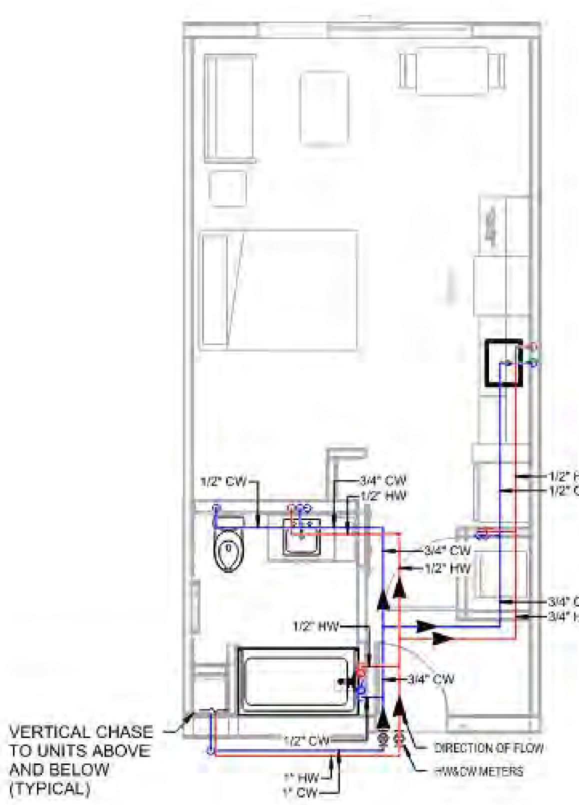
1 STUDIO - REFERENCE CASE - MECHANICAL
SCALE: 1/4" = 1'-0"



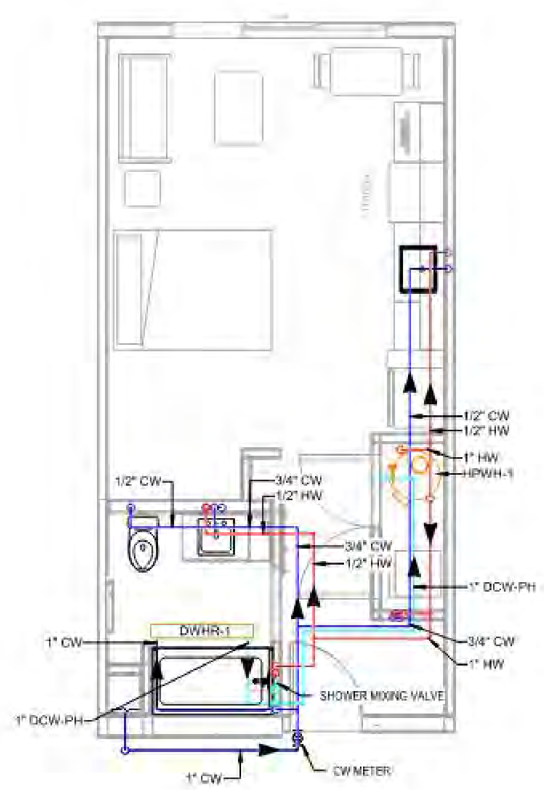
2 STUDIO - MODIFIED CASE - MECHANICAL
SCALE: 1/4" = 1'-0"

LEGEND

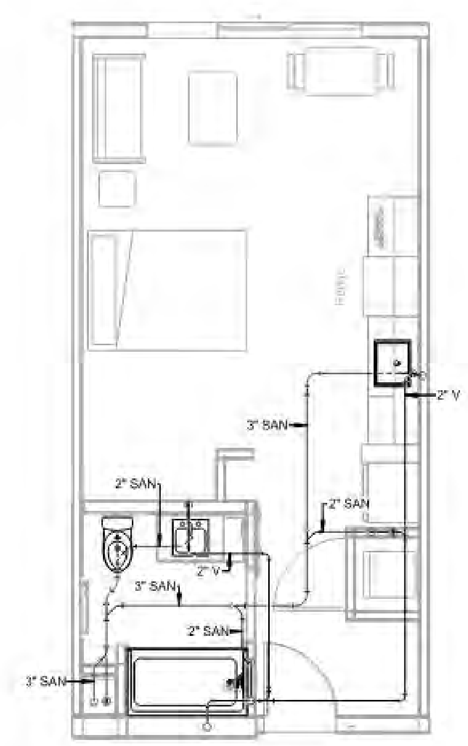
ABBREVIATION	DESCRIPTION
MECHANICAL	
SA	SUPPLY AIR
RA	RETURN AIR
RA-HP	RETURN AIR TO HEAT PUMP
EA	EXHAUST AIR
EF	EXHAUST FAN
FCU	FAN COIL UNIT
T-STAT	THERMOSTAT
PLUMBING	
CW	DOMESTIC COLD WATER
DCW-PH	PREHEATED DOMESTIC COLD WATER
HW	DOMESTIC HOT WATER
SAN	SANITARY DRAIN
V	SANITARY VENT
MECHANICAL AND PLUMBING EQUIPMENT	
DWHR	DRAIN WATER HEAT RECOVERY UNIT
HPWH	HEAT PUMP WATER HEATER



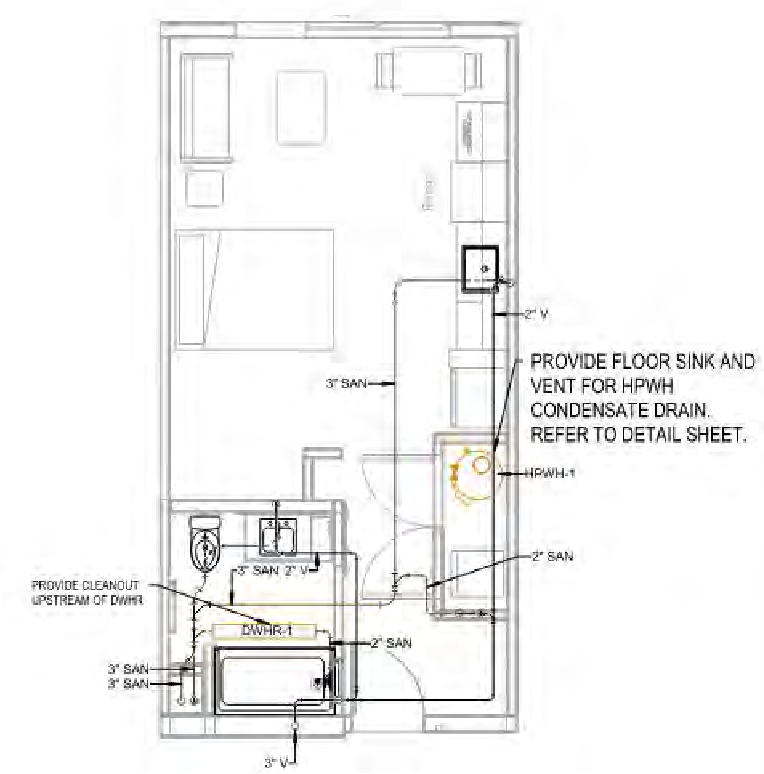
3 STUDIO - REFERENCE CASE - PLUMBING - HW/CW
SCALE: 1/4" = 1'-0"



4 STUDIO - MODIFIED CASE - PLUMBING - HW/CW
SCALE: 1/4" = 1'-0"



5 STUDIO - REFERENCE CASE - PLUMBING - DWV
SCALE: 1/4" = 1'-0"



6 STUDIO - MODIFIED CASE - PLUMBING - DWV
SCALE: 1/4" = 1'-0"

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PRICING SET		04/22/2022

SEALS AND SIGNATURES

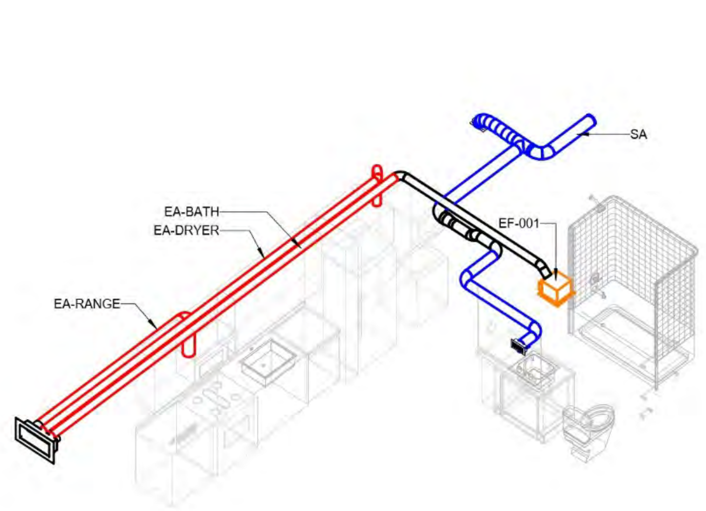
NOT FOR CONSTRUCTION

SHEET TITLE
FLOOR PLAN - STUDIO

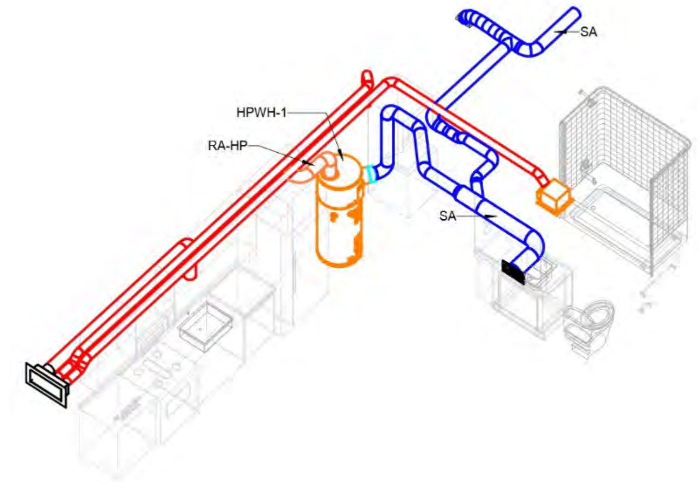
H21687CA
PROJECT NUMBER

MP2.1.1
SHEET NUMBER

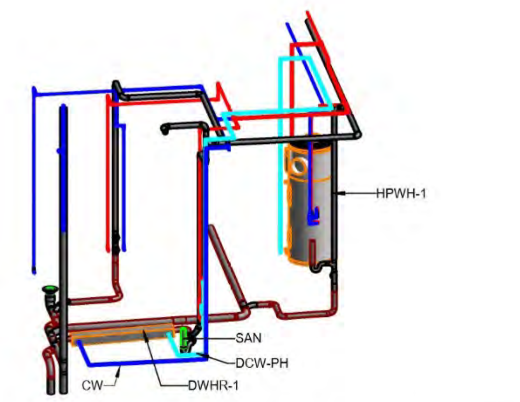
Plot Date: 12/17/2022 10:45:55 AM Author



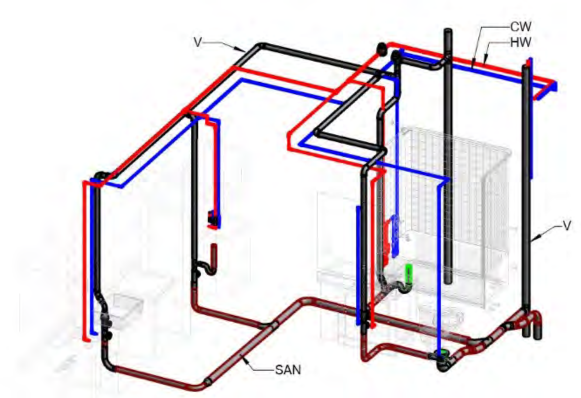
STUDIO - REFERENCE CASE - MECHANICAL 3D



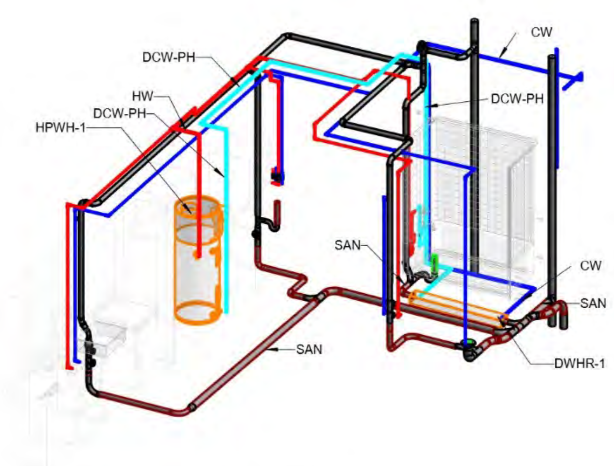
STUDIO - MODIFIED CASE - MECHANICAL 3D



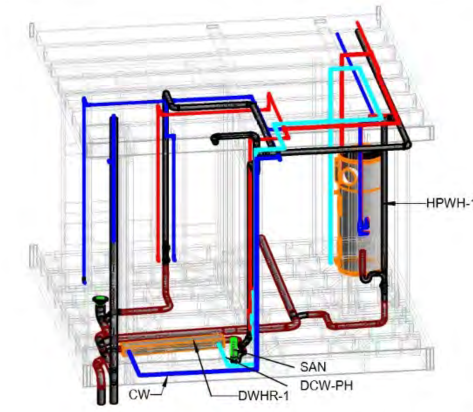
STUDIO - MODIFIED CASE - DWHR COORDINATION - NO FRAMING



STUDIO - REFERENCE CASE - PLUMBING 3D



STUDIO - MODIFIED CASE - PLUMBING 3D



STUDIO - MODIFIED CASE - DWHR COORDINATION

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SEALS AND SIGNATURES

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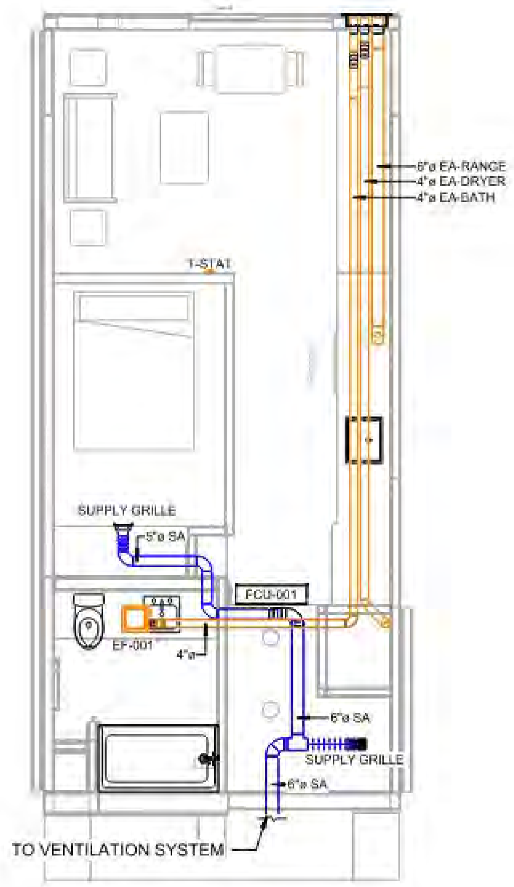
SHEET TITLE
3D VIEWS - STUDIO

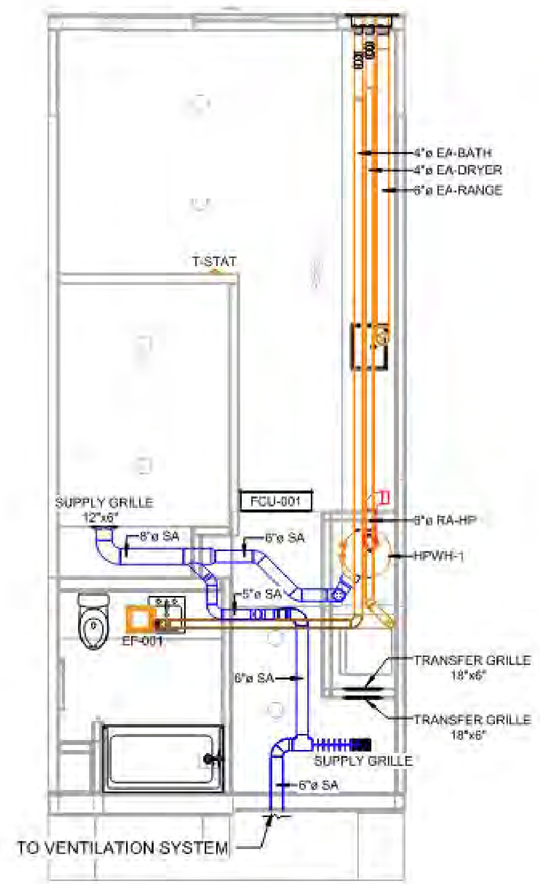
H21687CA
PROJECT NUMBER

MP2.1.2
SHEET NUMBER

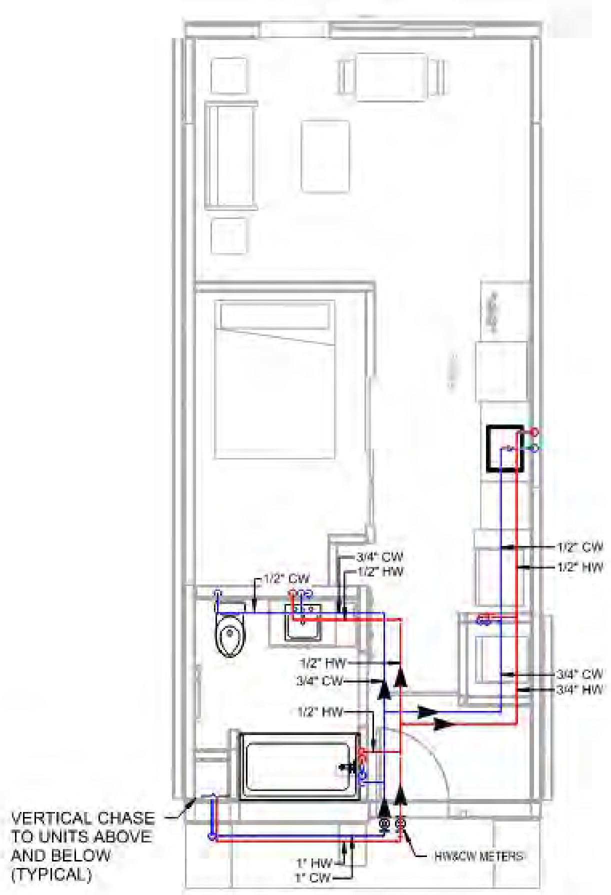
Plot Date: 12/15/2022 5:22:09 PM Author



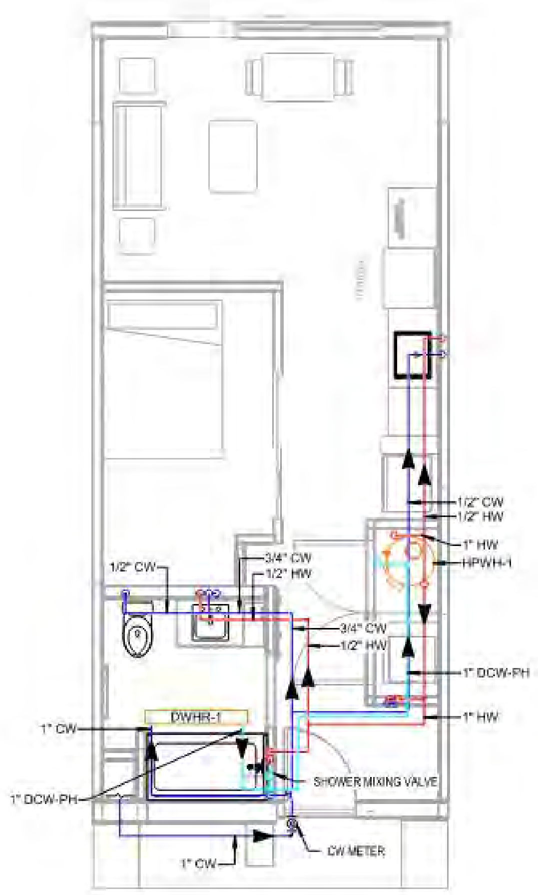
1 ONE BED - REFERENCE CASE - MECHANICAL
SCALE: 1/4" = 1'-0"



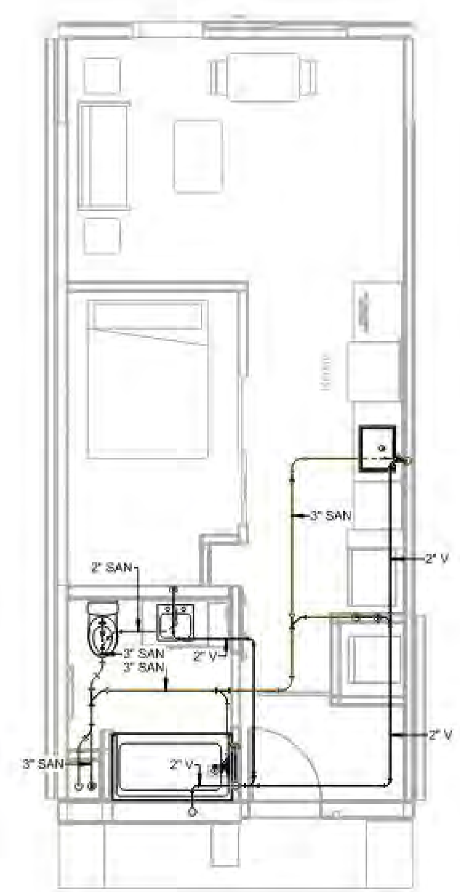
2 ONE BED - MODIFIED CASE - MECHANICAL
SCALE: 1/4" = 1'-0"



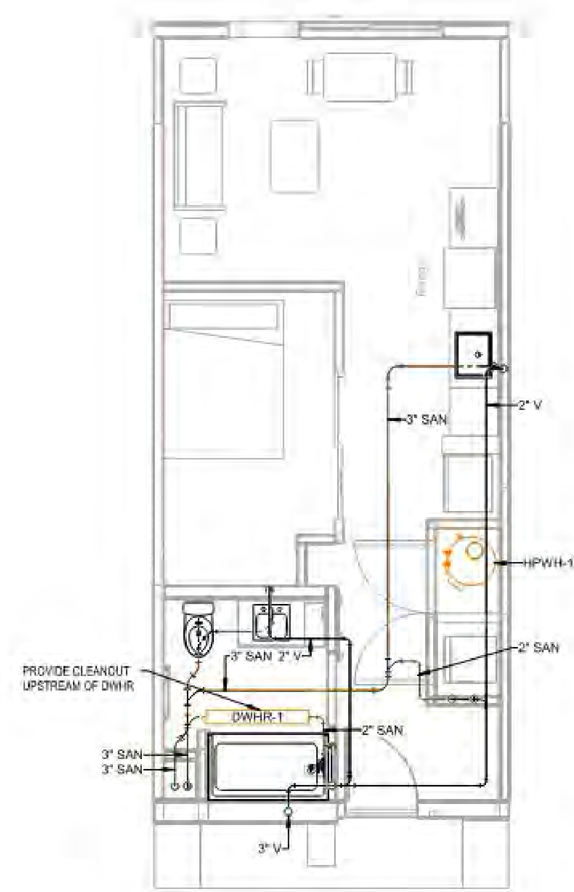
3 ONE BED - REFERENCE CASE - PLUMBING - HW/CW
SCALE: 1/4" = 1'-0"



4 ONE BED - MODIFIED CASE - PLUMBING - HW/CW
SCALE: 1/4" = 1'-0"



5 ONE BED - REFERENCE CASE - PLUMBING - DWV
SCALE: 1/4" = 1'-0"



6 ONE BED - MODIFIED CASE - PLUMBING - DWV
SCALE: 1/4" = 1'-0"

GENERAL SHEET NOTES

LEGEND

ABBREVIATION	DESCRIPTION
MECHANICAL	
SA	SUPPLY AIR
RA	RETURN AIR
RA-HP	RETURN AIR TO HEAT PUMP
EA	EXHAUST AIR
EF	EXHAUST FAN
FCU	FAN COIL UNIT
T-STAT	THERMOSTAT
PLUMBING	
CW	DOMESTIC COLD WATER
DCW-PH	PREHEATED DOMESTIC COLD WATER
HW	DOMESTIC HOT WATER
SAN	SANITARY DRAIN
V	SANITARY VENT
MECHANICAL AND PLUMBING EQUIPMENT	
DWHR	DRAIN WATER HEAT RECOVERY UNIT
HPWH	HEAT PUMP WATER HEATER

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SEALS AND SIGNATURES

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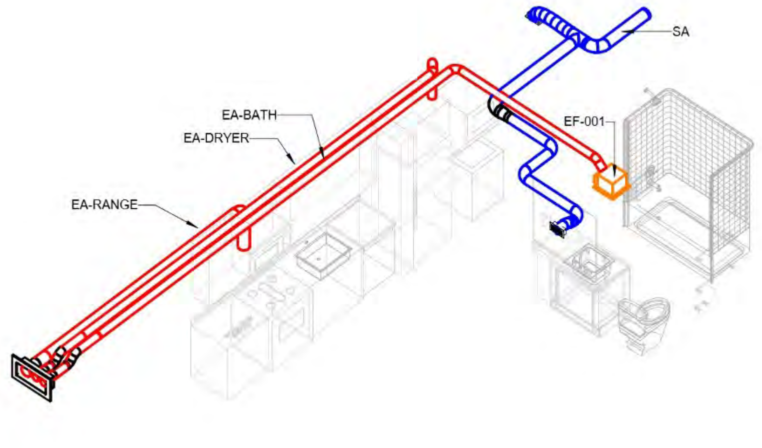
SHEET TITLE
FLOOR PLAN - ONE BED

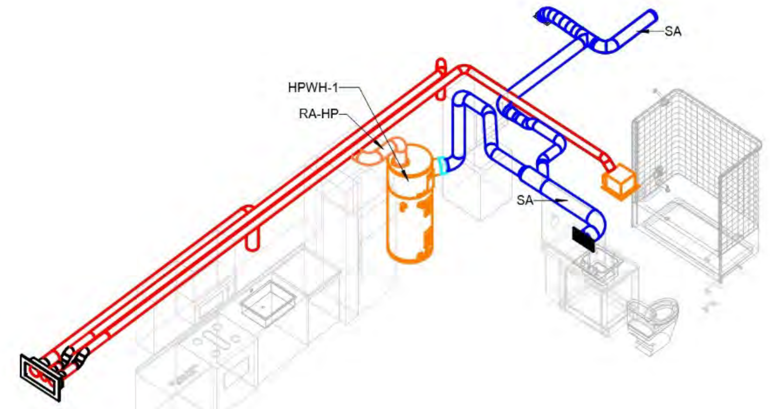
H21687CA
PROJECT NUMBER

MP2.1.3
SHEET NUMBER

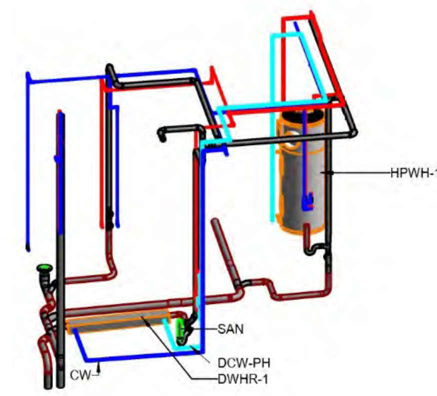
Plot Date: 12/15/2022 5:22:20 PM
Author



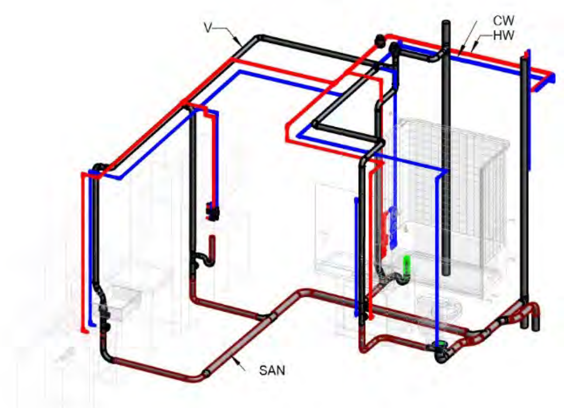
ONE BED - REFERENCE CASE - MECHANICAL 3D



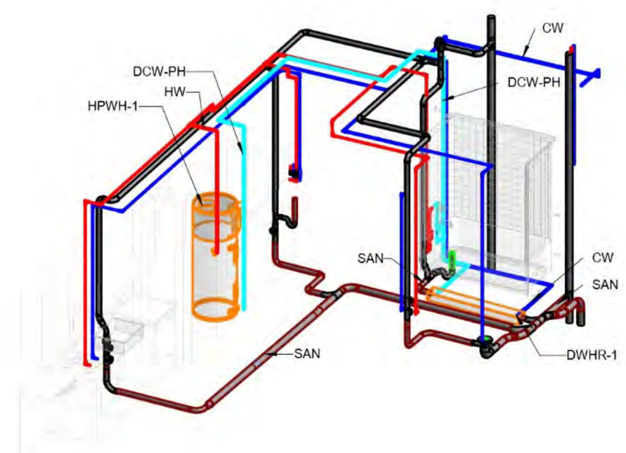
ONE BED - MODIFIED CASE - MECHANICAL 3D



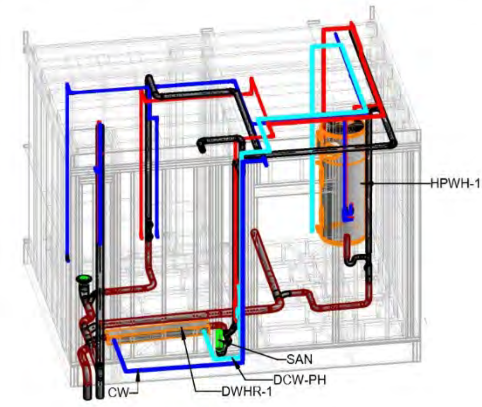
ONE BED - MODIFIED CASE - DWHR COORDINATION - NO FRAMING



ONE BED - REFERENCE CASE - PLUMBING 3D



ONE BED - MODIFIED CASE - PLUMBING 3D



ONE BED - MODIFIED CASE - DWHR COORDINATION

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U.S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT

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SEALS AND SIGNATURES

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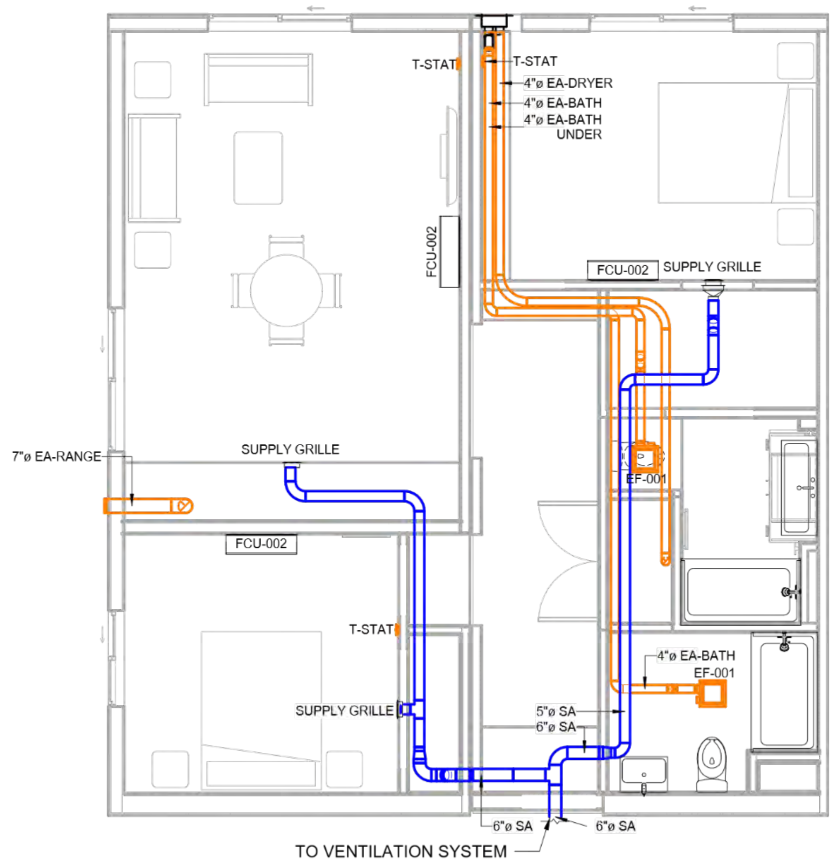
SHEET TITLE
3D VIEWS - ONE BED

H21687CA
PROJECT NUMBER

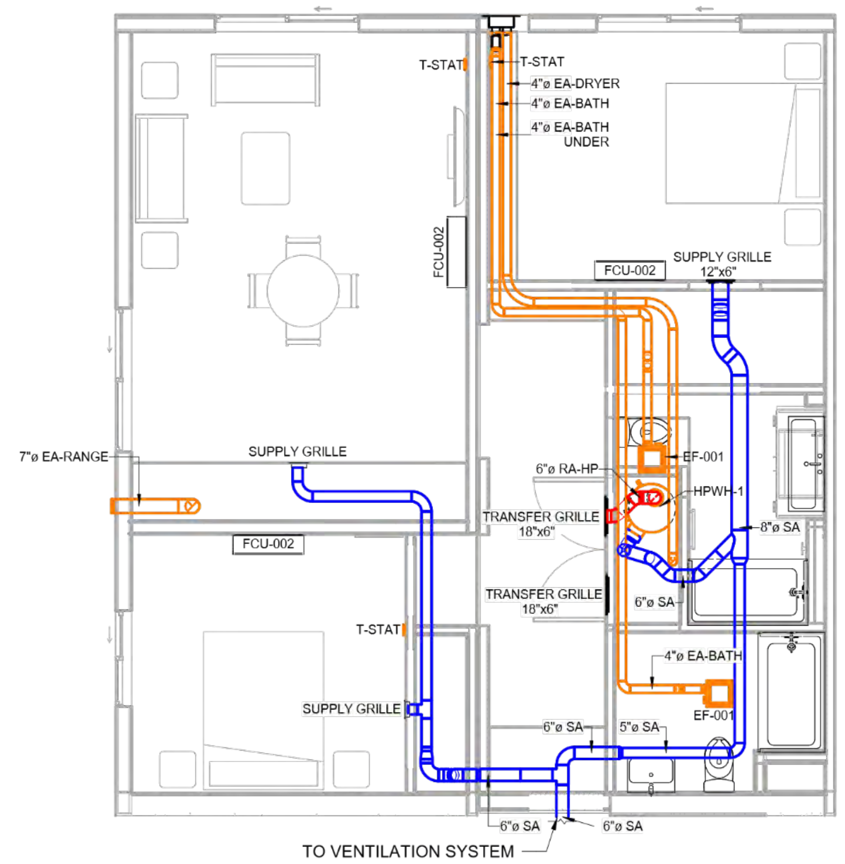
MP2.1.4
SHEET NUMBER

Plot Date: 12/15/2022 5:22:30 PM Author

GENERAL SHEET NOTES



1 TWO BED - REFERENCE CASE - MECHANICAL
SCALE: 1/4" = 1'-0"



2 TWO BED - MODIFIED CASE - MECHANICAL
SCALE: 1/4" = 1'-0"

LEGEND

ABBREVIATION	DESCRIPTION
MECHANICAL	
SA	SUPPLY AIR
RA	RETURN AIR
RA-HP	RETURN AIR TO HEAT PUMP
EA	EXHAUST AIR
EF	EXHAUST FAN
FCU	FAN COIL UNIT
T-STAT	THERMOSTAT
PLUMBING	
CW	DOMESTIC COLD WATER
DCW-PH	PREHEATED DOMESTIC COLD WATER
HW	DOMESTIC HOT WATER
SAN	SANITARY DRAIN
V	SANITARY VENT
MECHANICAL AND PLUMBING EQUIPMENT	
DWHR	DRAIN WATER HEAT RECOVERY UNIT
HPWH	HEAT PUMP WATER HEATER

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SEALS AND SIGNATURES

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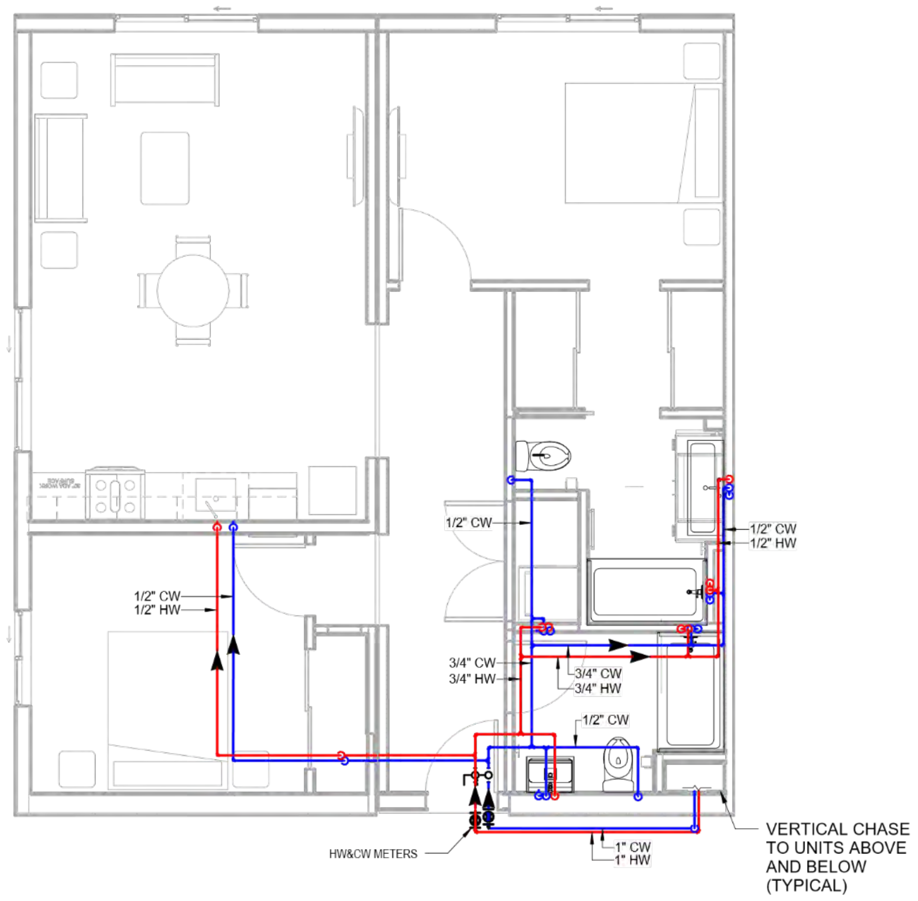
SHEET TITLE
FLOOR PLAN - TWO BED

H21687CA
PROJECT NUMBER

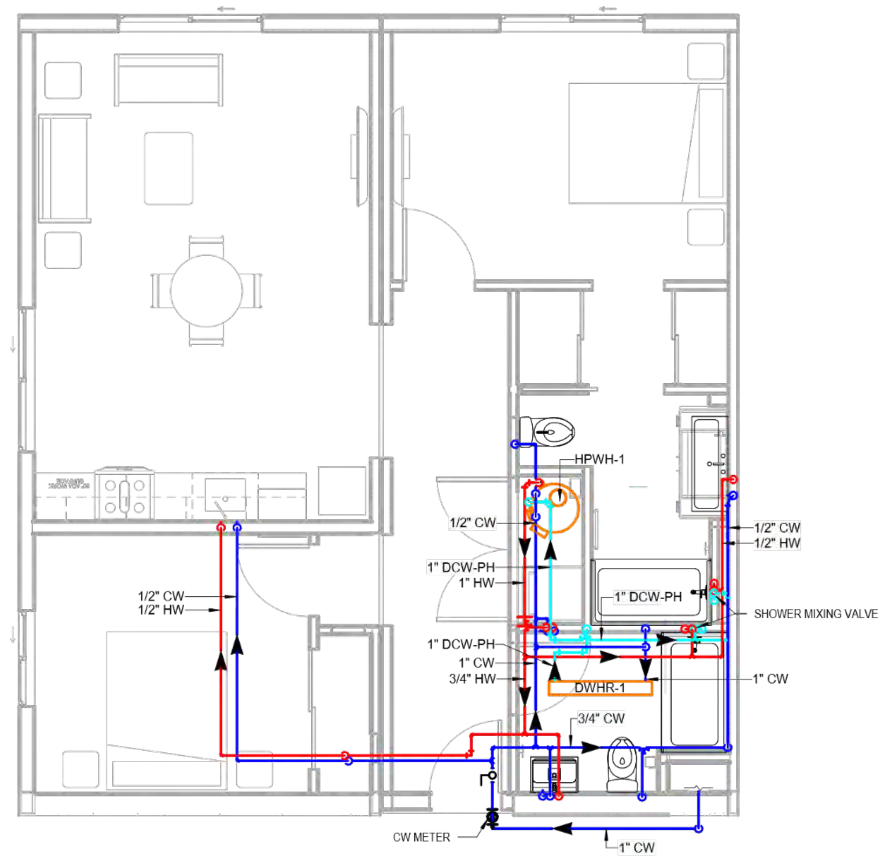
MP2.1.5
SHEET NUMBER

Plot Date: 12/15/2022 5:22:35 PM Author

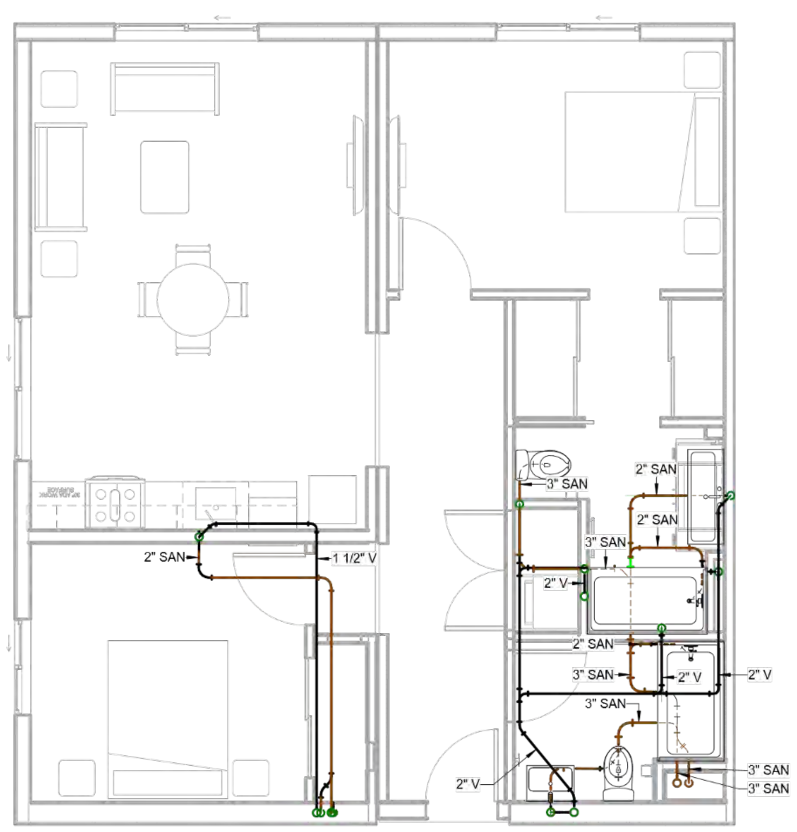
GENERAL SHEET NOTES



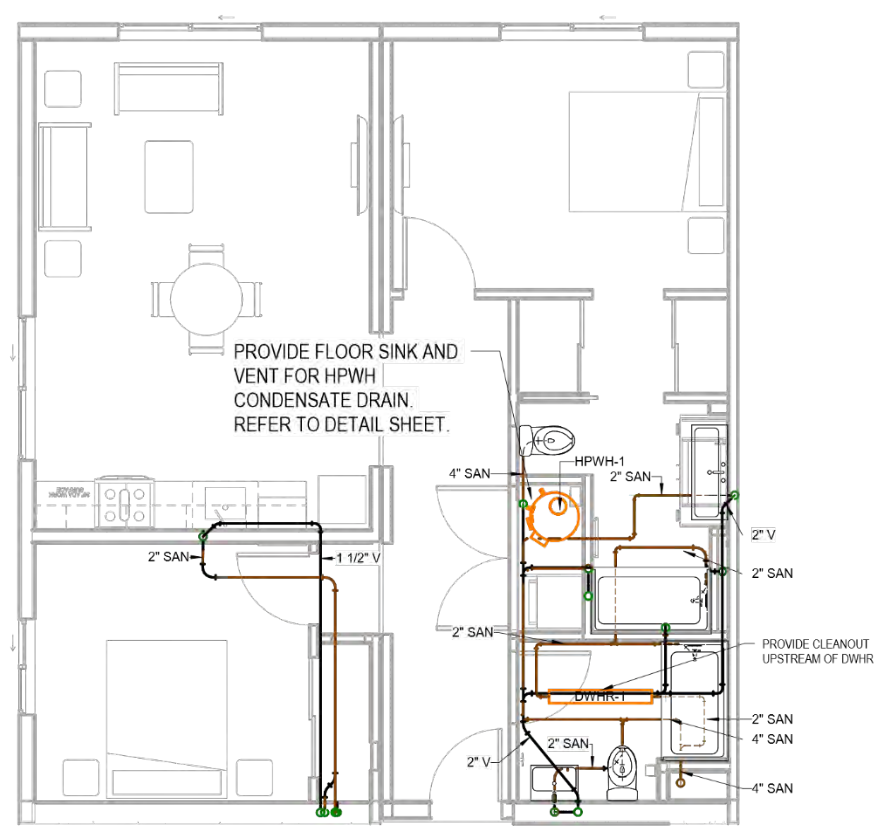
1 TWO BED - REFERENCE CASE - PLUMBING - HW/CW
SCALE: 1/4" = 1'-0"



2 TWO BED - MODIFIED CASE - PLUMBING - HW/CW
SCALE: 1/4" = 1'-0"



3 TWO BED - REFERENCE CASE - PLUMBING - DWV
SCALE: 1/4" = 1'-0"



4 TWO BED - MODIFIED CASE - PLUMBING - DWV
SCALE: 1/4" = 1'-0"

LEGEND

ABBREVIATION	DESCRIPTION
MECHANICAL	
SA	SUPPLY AIR
RA	RETURN AIR
RA-HP	RETURN AIR TO HEAT PUMP
EA	EXHAUST AIR
EF	EXHAUST FAN
FCU	FAN COIL UNIT
T-STAT	THERMOSTAT
PLUMBING	
CW	DOMESTIC COLD WATER
DCW-PH	PREHEATED DOMESTIC COLD WATER
HW	DOMESTIC HOT WATER
SAN	SANITARY DRAIN
V	SANITARY VENT
MECHANICAL AND PLUMBING EQUIPMENT	
DWHR	DRAIN WATER HEAT RECOVERY UNIT
HPWH	HEAT PUMP WATER HEATER

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SEALS AND SIGNATURES

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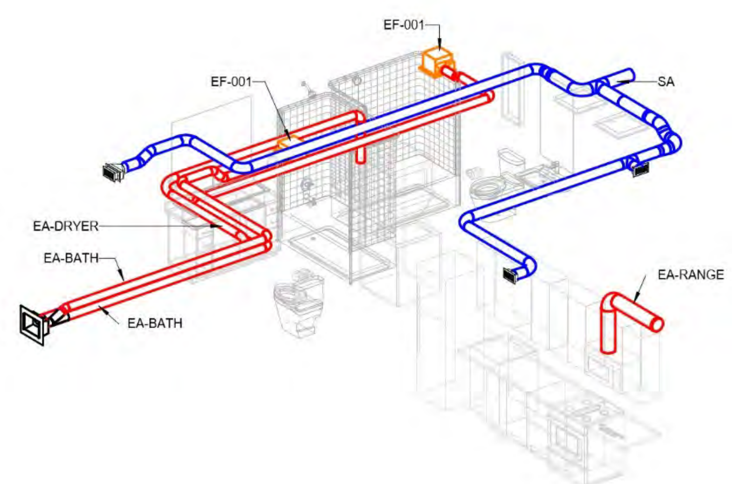
SHEET TITLE
FLOOR PLAN - TWO BED

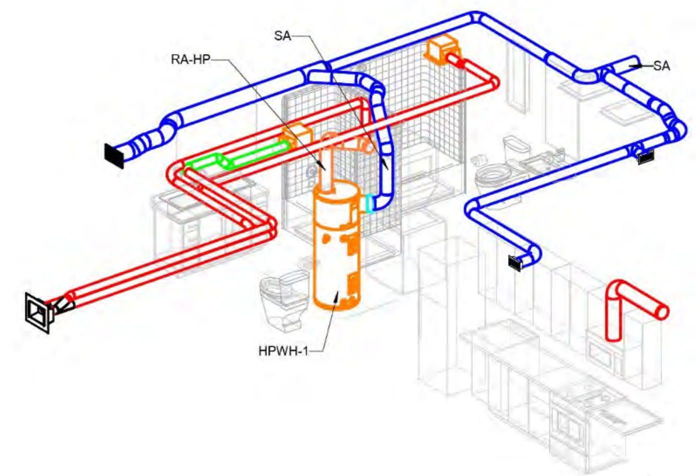
H21687CA
PROJECT NUMBER

MP2.1.6
SHEET NUMBER

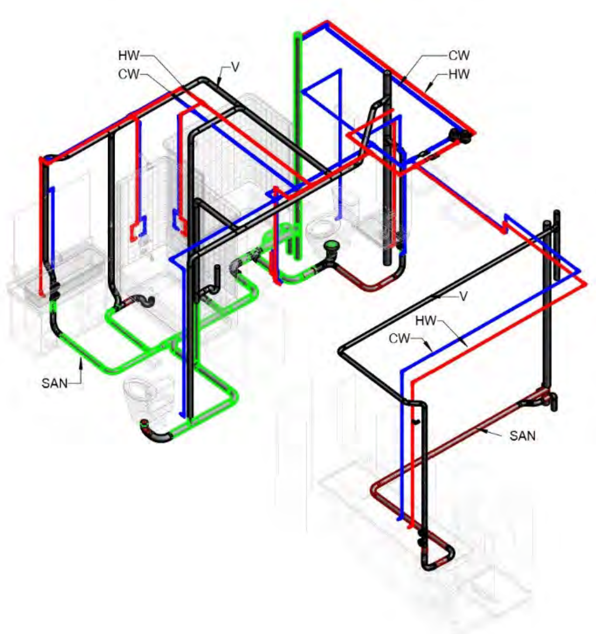
Plot Date: 12/15/2022 5:22:41 PM
Author



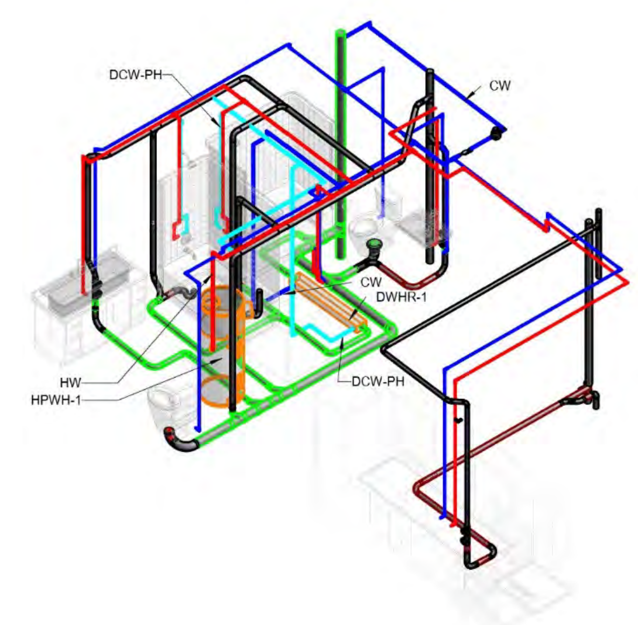
TWO BED - REFERENCE CASE - MECHANICAL 3D



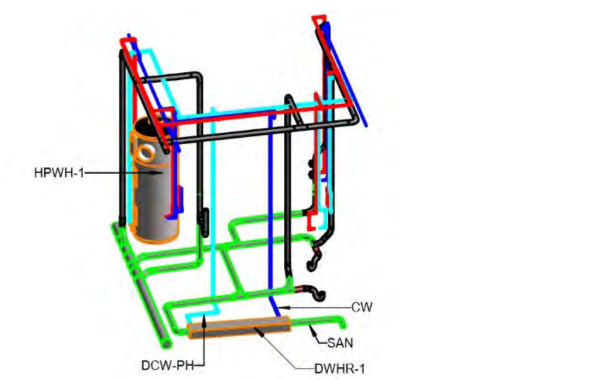
TWO BED - MODIFIED CASE - MECHANICAL 3D



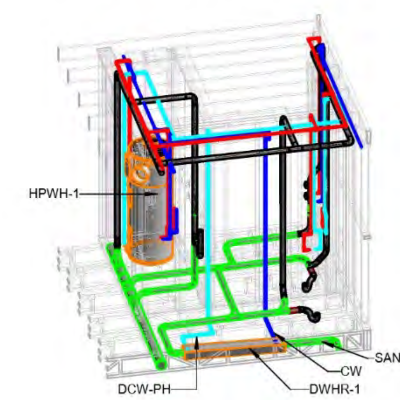
TWO BED - REFERENCE CASE - PLUMBING 3D



TWO BED - MODIFIED CASE - PLUMBING 3D



TWO BED - MODIFIED CASE - DWHR COORDINATION - NO FRAMING



TWO BED - MODIFIED CASE - DWHR COORDINATION

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SEALS AND SIGNATURES

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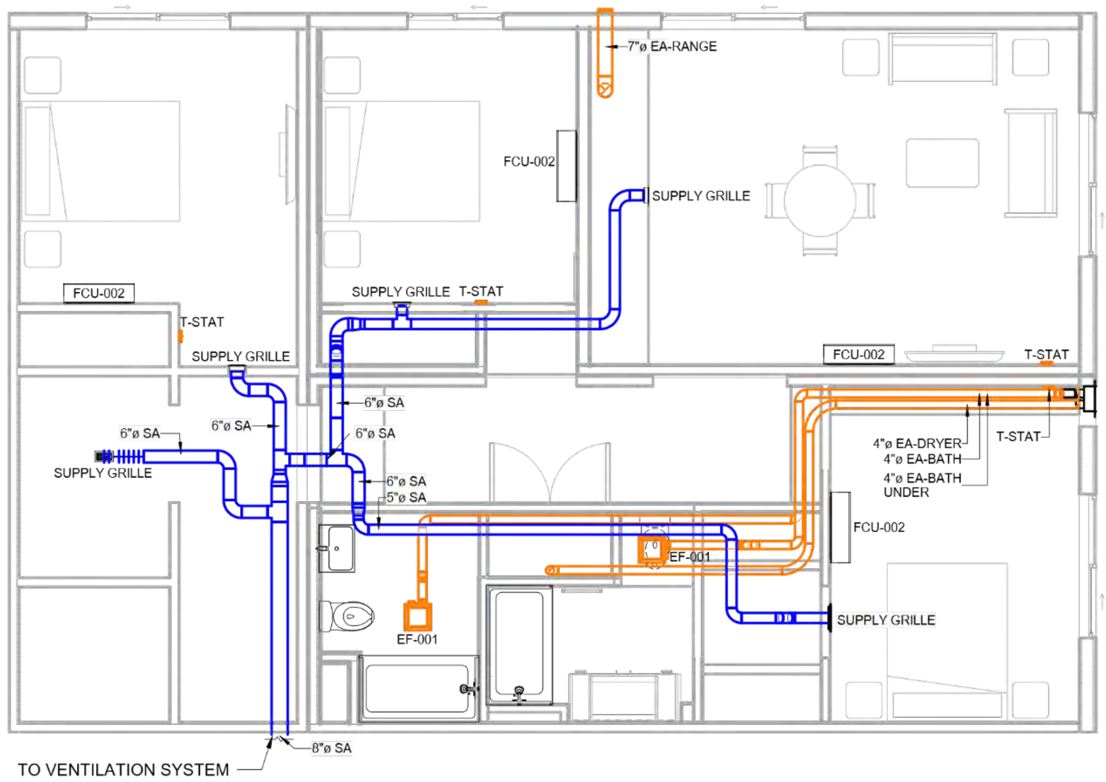
SHEET TITLE
3D VIEWS - TWO BED

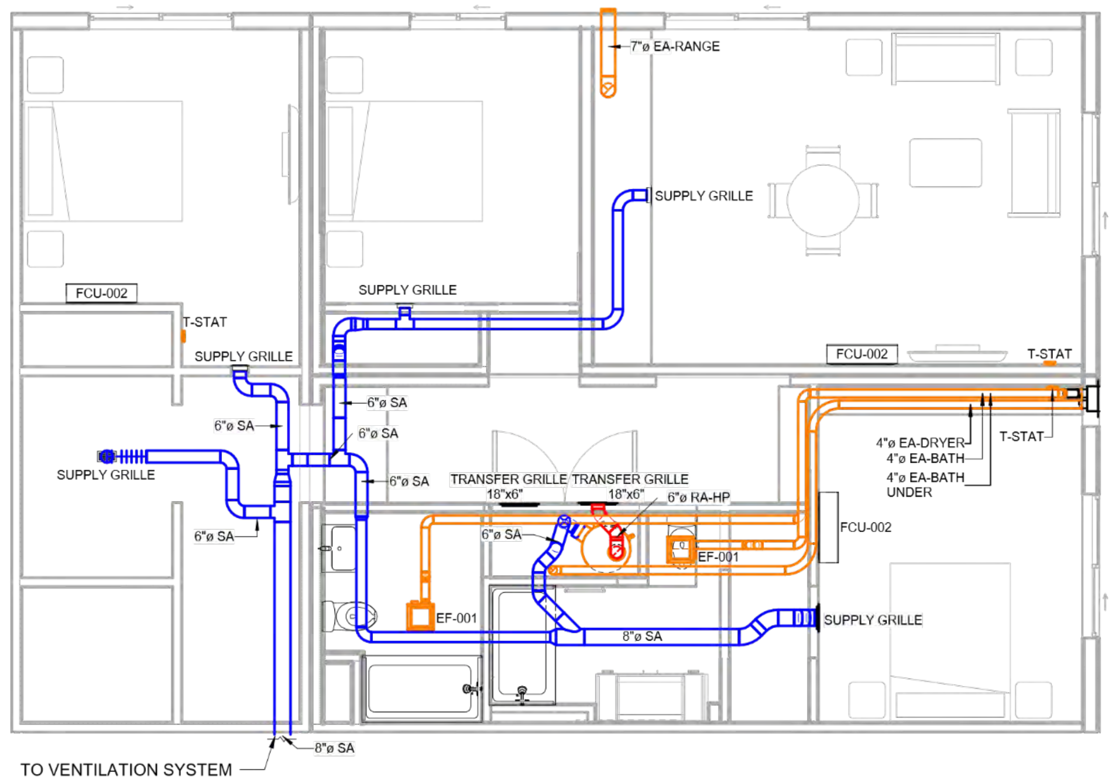
H21687CA
PROJECT NUMBER

MP2.1.7
SHEET NUMBER

Plot Date: 12/15/2022 5:22:56 PM Author



1 THREE BED - REFERENCE CASE - MECHANICAL
SCALE: 1/4" = 1'-0"



2 THREE BED - MODIFIED CASE - MECHANICAL
SCALE: 1/4" = 1'-0"

GENERAL SHEET NOTES

1. REFERENCE TWO BED ROOM 3D VIEWS SHEET FOR THREE BED ROOM 3D VIEWS. TWO BED ROOM AND THREE BED ROOM MECHANICAL AND PLUMBING LAYOUTS ARE SIMILAR.

LEGEND

ABBREVIATION	DESCRIPTION
MECHANICAL	
SA	SUPPLY AIR
RA	RETURN AIR
RA-HP	RETURN AIR TO HEAT PUMP
EA	EXHAUST AIR
EF	EXHAUST FAN
FCU	FAN COIL UNIT
T-STAT	THERMOSTAT
PLUMBING	
CW	DOMESTIC COLD WATER
DCW-PH	PREHEATED DOMESTIC COLD WATER
HW	DOMESTIC HOT WATER
SAN	SANITARY DRAIN
V	SANITARY VENT
MECHANICAL AND PLUMBING EQUIPMENT	
DWHR	DRAIN WATER HEAT RECOVERY UNIT
HPWH	HEAT PUMP WATER HEATER

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SEALS AND SIGNATURES

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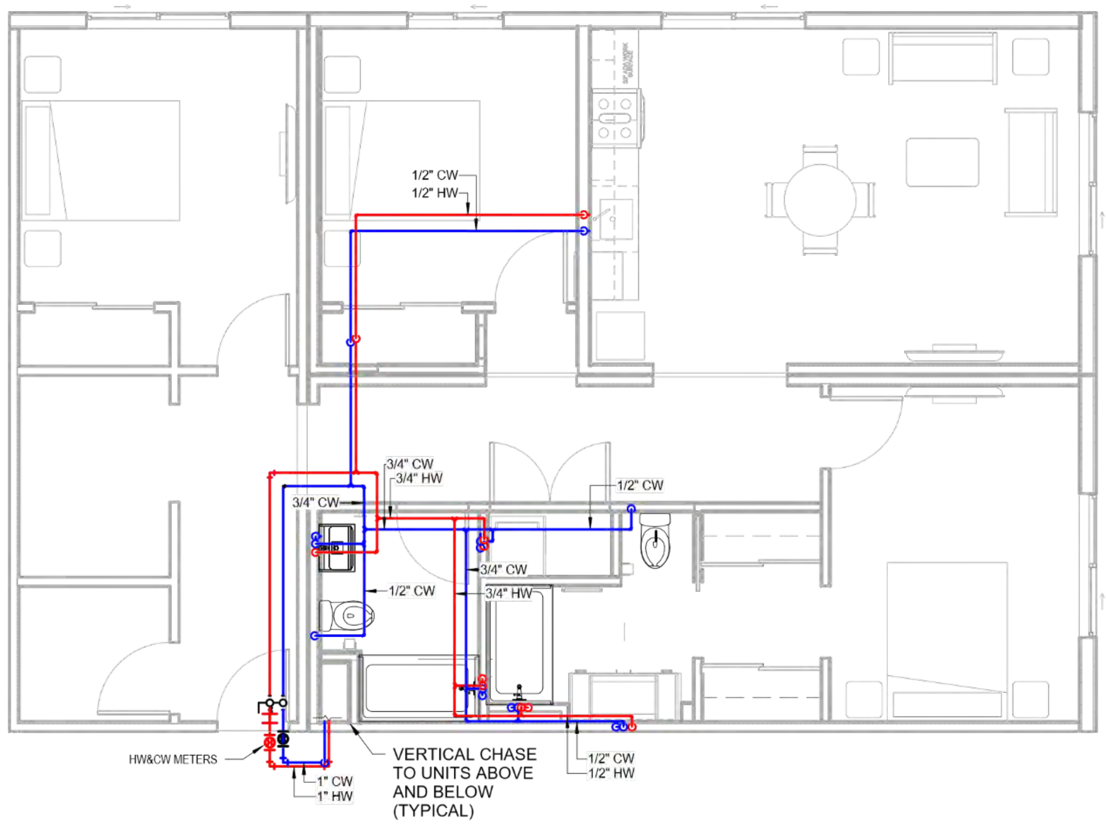
SHEET TITLE
FLOOR PLAN - THREE BED

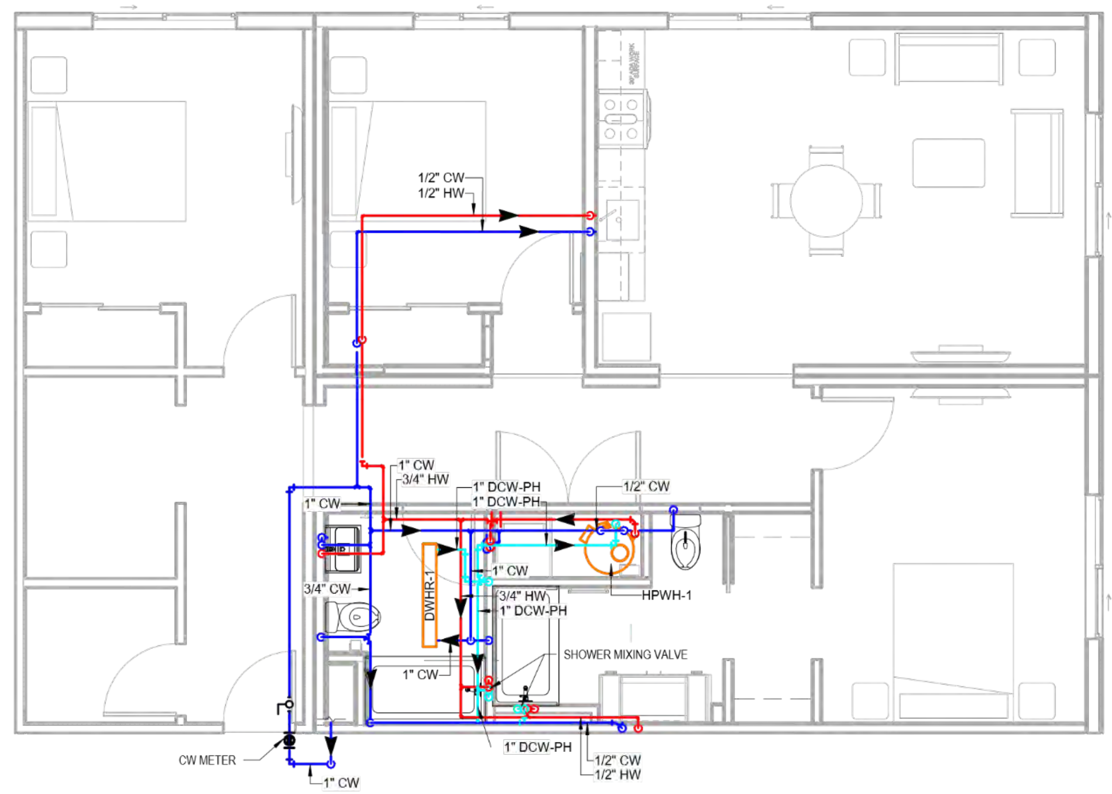
H21687CA
PROJECT NUMBER

MP2.1.8
SHEET NUMBER

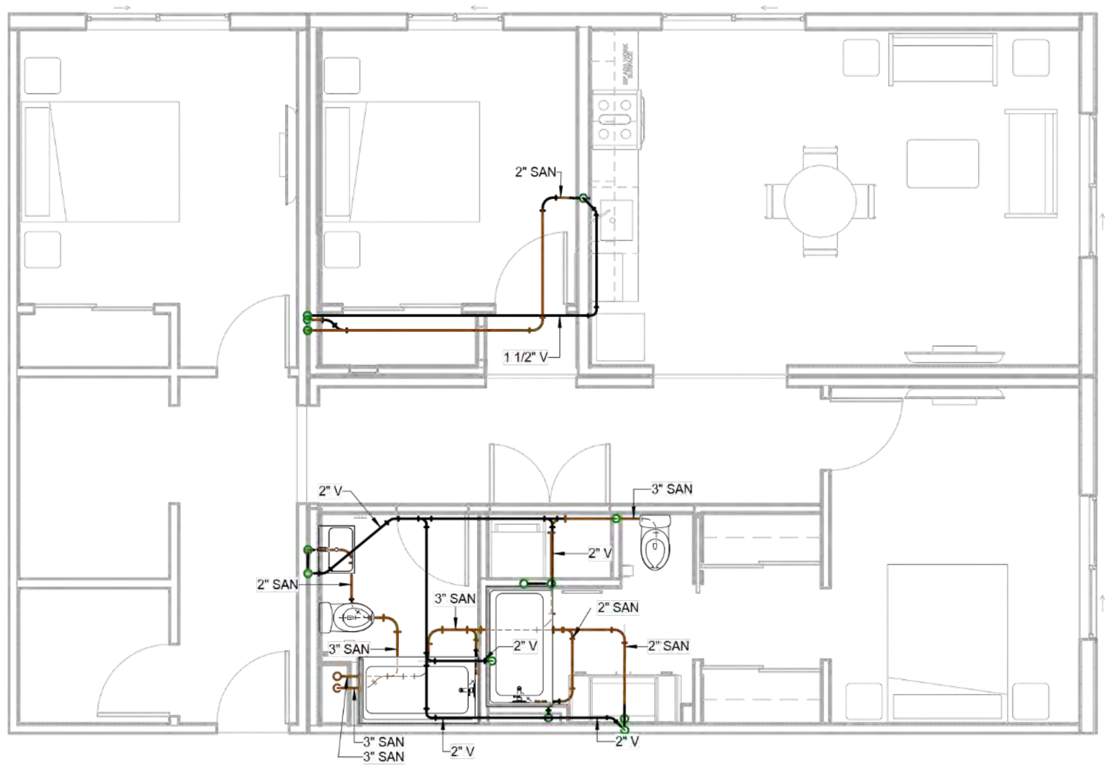
Plot Date: 12/15/2022 5:23:00 PM
Author



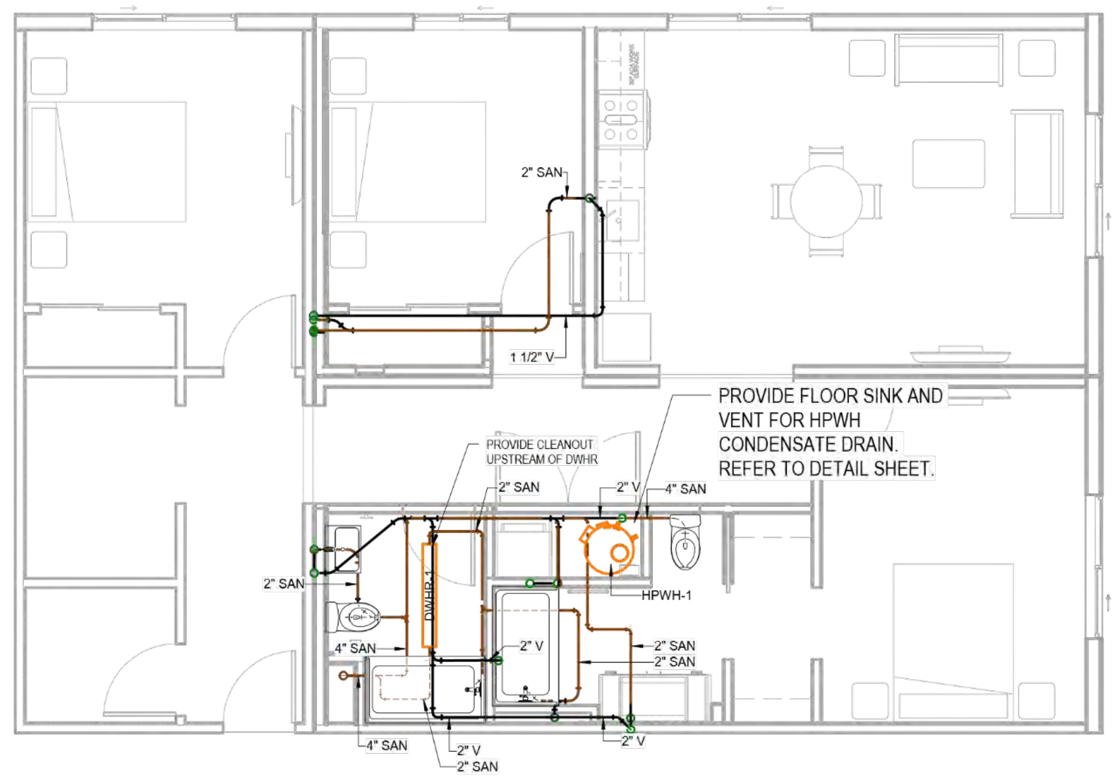
1 THREE BED - REFERENCE CASE - PLUMBING - HW/CW
SCALE: 1/4" = 1'-0"



2 THREE BED - MODIFIED CASE - PLUMBING - HW/CW
SCALE: 1/4" = 1'-0"



3 THREE BED - REFERENCE CASE - PLUMBING - DWV
SCALE: 1/4" = 1'-0"



4 THREE BED - MODIFIED CASE - PLUMBING - DWV
SCALE: 1/4" = 1'-0"

GENERAL SHEET NOTES

1. REFERENCE TWO BED ROOM 3D VIEWS SHEET FOR THREE BED ROOM 3D VIEWS. TWO BED ROOM AND THREE BED ROOM MECHANICAL AND PLUMBING LAYOUTS ARE SIMILAR.

LEGEND

ABBREVIATION	DESCRIPTION
MECHANICAL	
SA	SUPPLY AIR
RA	RETURN AIR
RA-HP	RETURN AIR TO HEAT PUMP
EA	EXHAUST AIR
EF	EXHAUST FAN
FCU	FAN COIL UNIT
T-STAT	THERMOSTAT
PLUMBING	
CW	DOMESTIC COLD WATER
DCW-PH	PREHEATED DOMESTIC COLD WATER
HW	DOMESTIC HOT WATER
SAN	SANITARY DRAIN
V	SANITARY VENT
MECHANICAL AND PLUMBING EQUIPMENT	
DWHR	DRAIN WATER HEAT RECOVERY UNIT
HPWH	HEAT PUMP WATER HEATER

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SEALS AND SIGNATURES

NOT FOR CONSTRUCTION

SHEET TITLE
FLOOR PLAN - THREE BED

H21687CA
PROJECT NUMBER

MP2.1.9
SHEET NUMBER

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HEAT PUMP WATER HEATER

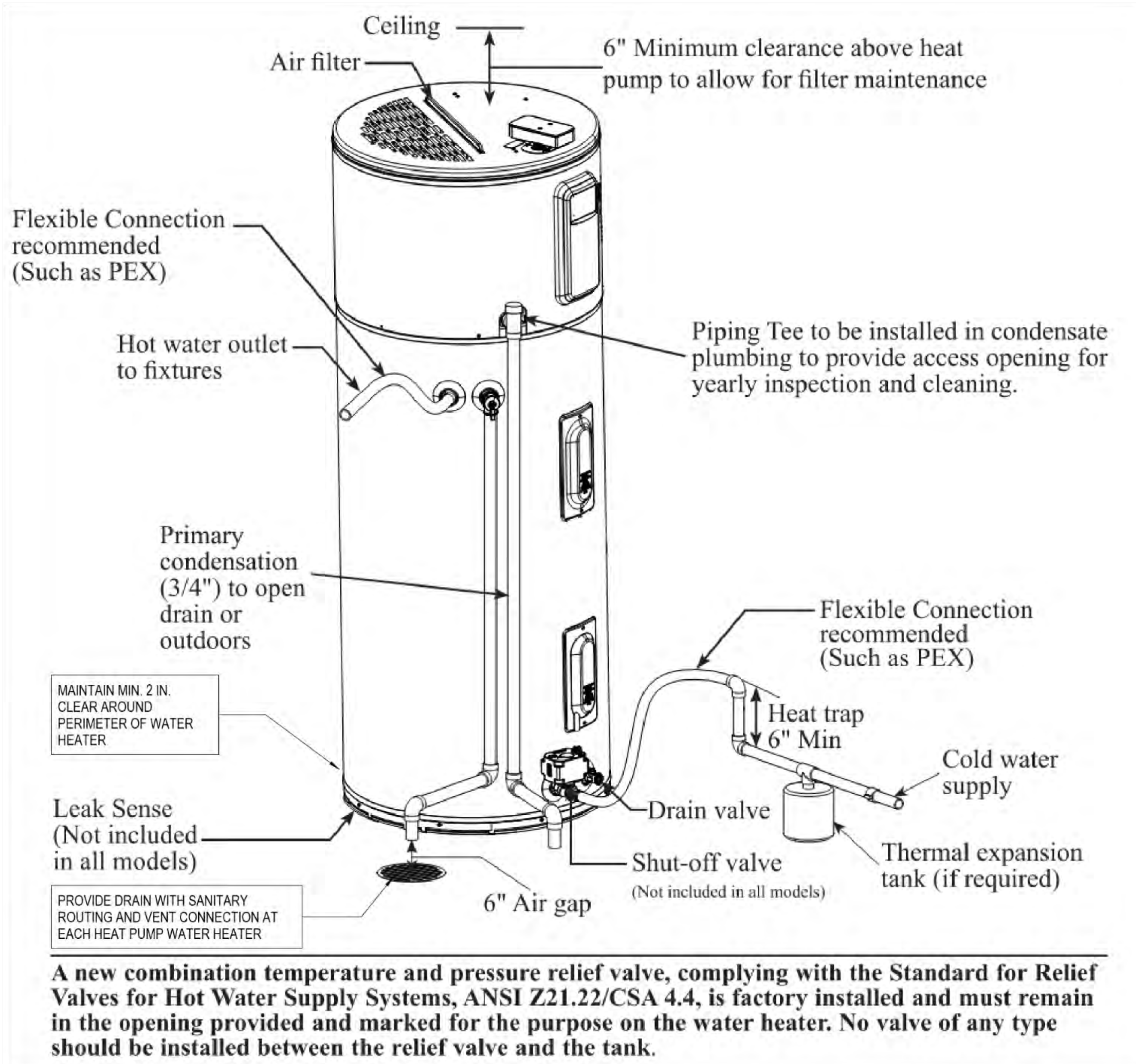
TAG	MANF / MODEL	NOMINAL STORAGE CAPACITY (GAL)	UNIFORM ENERGY FACTOR (UEF)	FIRST HOUR RATING (GALLONS)	COMPRESSOR (BTUH)	SOUND LEVEL (dB)	HEIGHT (IN.)	DIAMETER (IN.)	WEIGHT (LB)	BREAKER SIZE	VOLTAGE / PHASE	TYPE
HPWH-1	RHEEM / PROPH50	50	3.0	55	4,200	55	62	22.25	178	15	120 / 1	120V SHARED CIRCUIT

DRAIN WATER HEAT RECOVERY

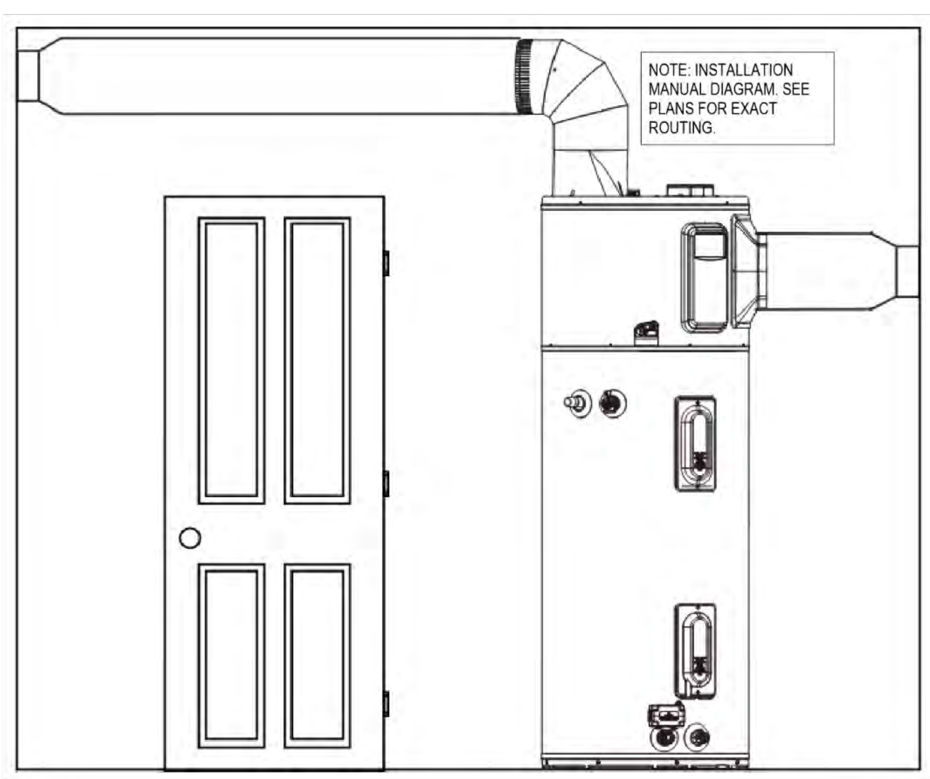
TAG	MANF / MODEL	TYPE	DESIGN SLOPE (DEGREES)	HEAT EXCHANGER EFFECTIVENESS (%)	CONSTRUCTION	SUPPLY WATER CONNECTION	DRAIN WATER CONNECTION	LENGTH (IN.)	WIDTH (IN.)	HEIGHT (IN.)
DWHR-1	ECODRAIN / A1000	HORIZONTAL	2	32	COPPER HEAT EXCHANGER CORE WITH PLASTIC HOUSING	3/4 IN. THREADED	2 IN. ABS	51.4	6.6	4.3

NOTES

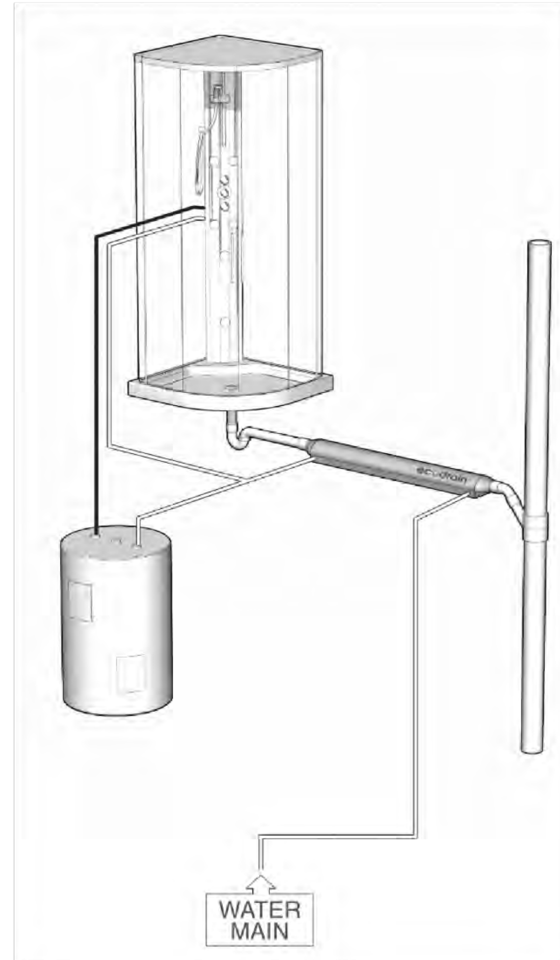
1. HEAT EXCHANGER EFFECTIVENESS ASSUMES EQUAL FLOW AT 1.5 GPM



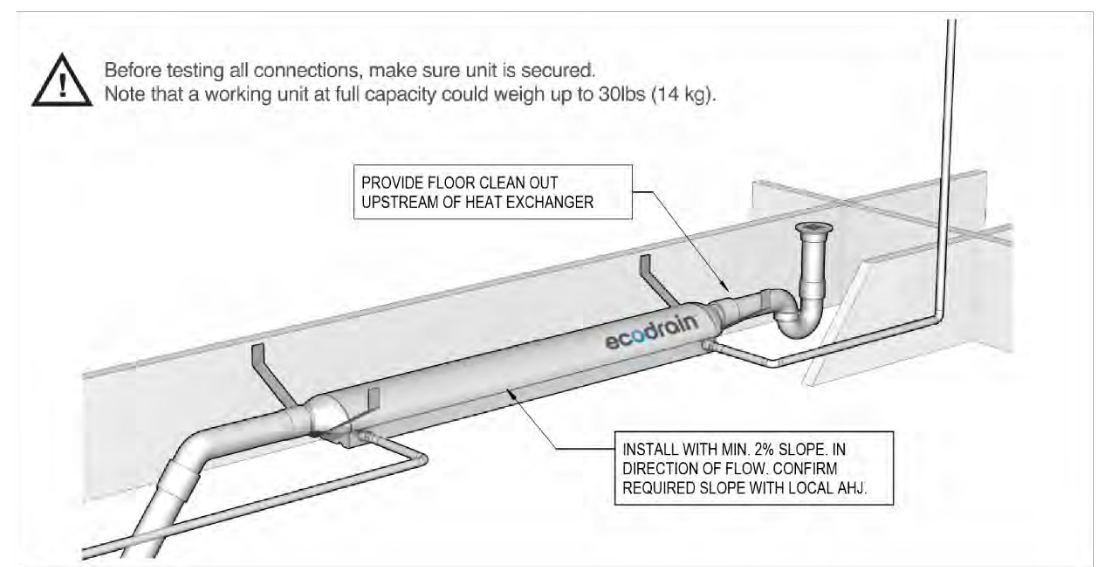
3 HPWH TYPICAL INSTALLATION
SCALE: N.T.S.



4 HPWH - FULLY DUCTED MODIFIED CASE
SCALE: N.T.S.



1 DWHR SHOWER PREHEAT PIPING CONFIGURATION
SCALE: N.T.S.



2 DWHR TYPICAL INSTALLATION
SCALE: N.T.S.

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SHEET TITLE
SCHEDULES AND DETAILS

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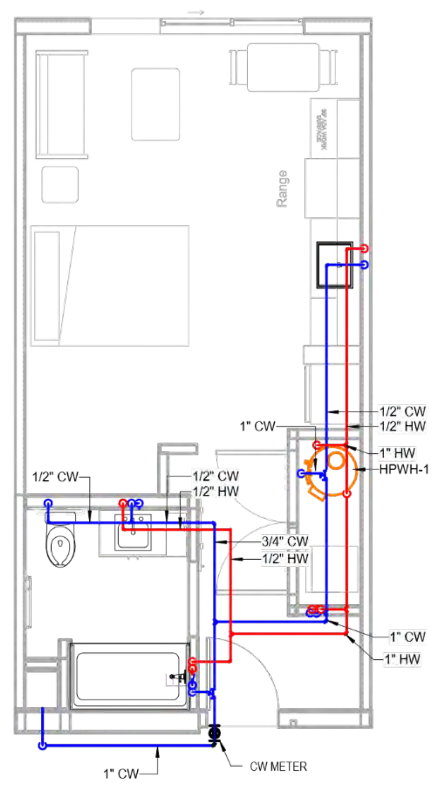
GENERAL SHEET NOTES

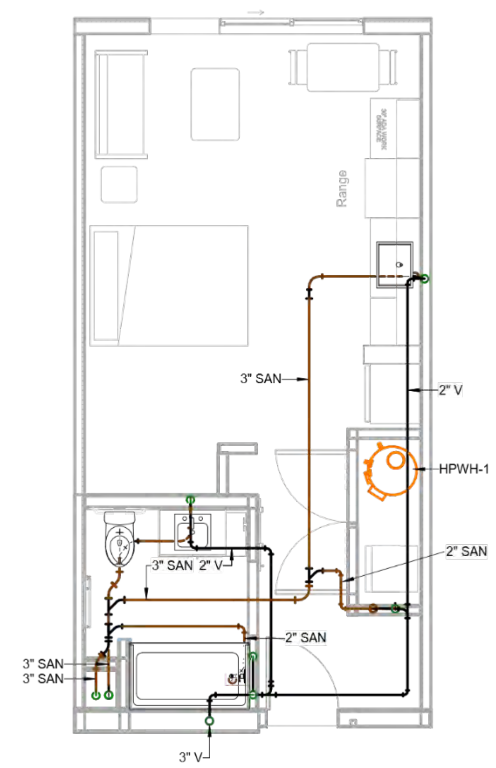
1. ONE BED ROOM ALTERNATE WITHOUT DRAIN WATER HEAT RECOVERY (DWHR) IS SIMILAR TO STUDIO. THREE BED ROOM ALTERNATE WITHOUT DWHR IS SIMILAR TO TWO BED ROOM.

LEGEND

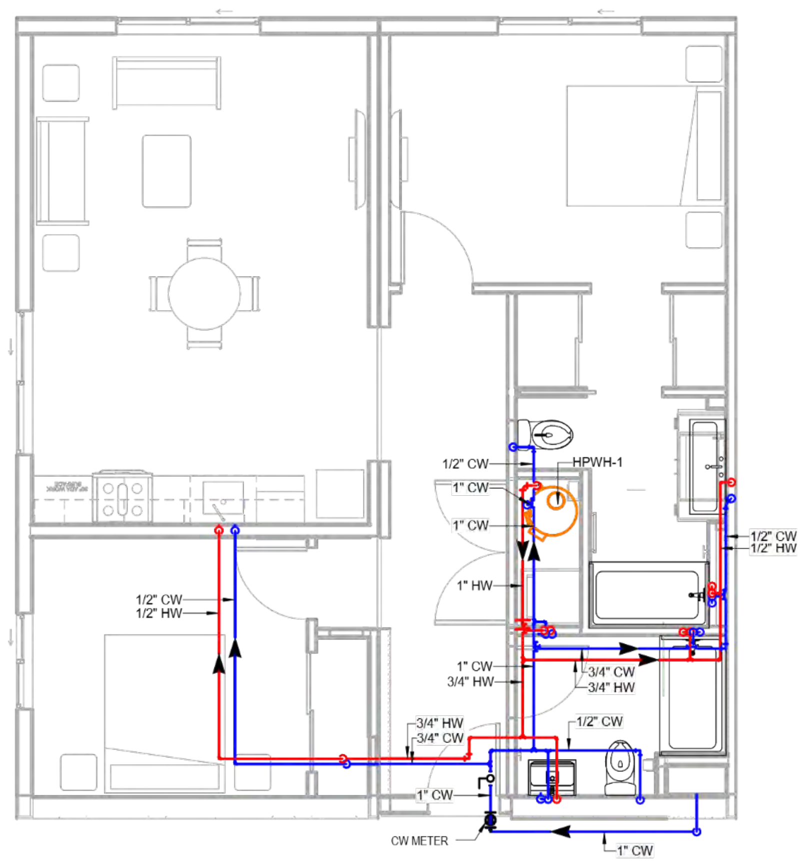
ABBREVIATION	DESCRIPTION
MECHANICAL	
SA	SUPPLY AIR
RA	RETURN AIR
RA-HP	RETURN AIR TO HEAT PUMP
EA	EXHAUST AIR
EF	EXHAUST FAN
FCU	FAN COIL UNIT
T-STAT	THERMOSTAT
PLUMBING	
CW	DOMESTIC COLD WATER
DCW-PH	PREHEATED DOMESTIC COLD WATER
HW	DOMESTIC HOT WATER
SAN	SANITARY DRAIN
V	SANITARY VENT
MECHANICAL AND PLUMBING EQUIPMENT	
DWHR	DRAIN WATER HEAT RECOVERY UNIT
HPWH	HEAT PUMP WATER HEATER



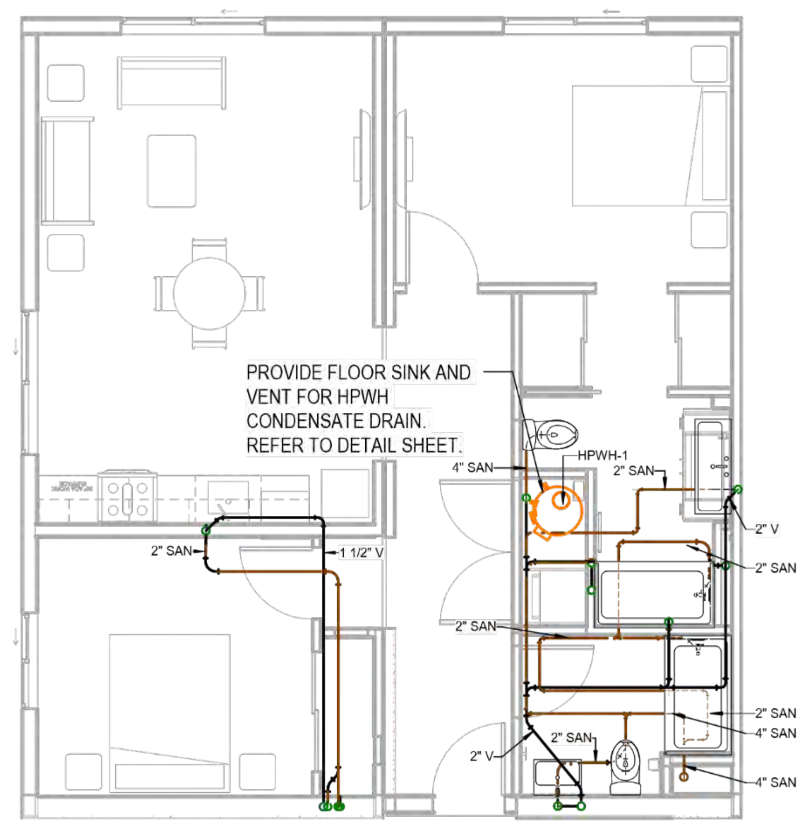
1 STUDIO - MODIFIED CASE NO DWHR - PLUMBING - HW/CW
SCALE: 1/4" = 1'-0"



2 STUDIO - MODIFIED CASE NO DWHR - PLUMBING - DWV
SCALE: 1/4" = 1'-0"



3 TWO BED - MODIFIED CASE NO DWHR - PLUMBING - HW/CW
SCALE: 1/4" = 1'-0"



4 TWO BED - MODIFIED CASE NO DWHR - PLUMBING - DWV
SCALE: 1/4" = 1'-0"

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FLOOR PLAN - ALTERNATES

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