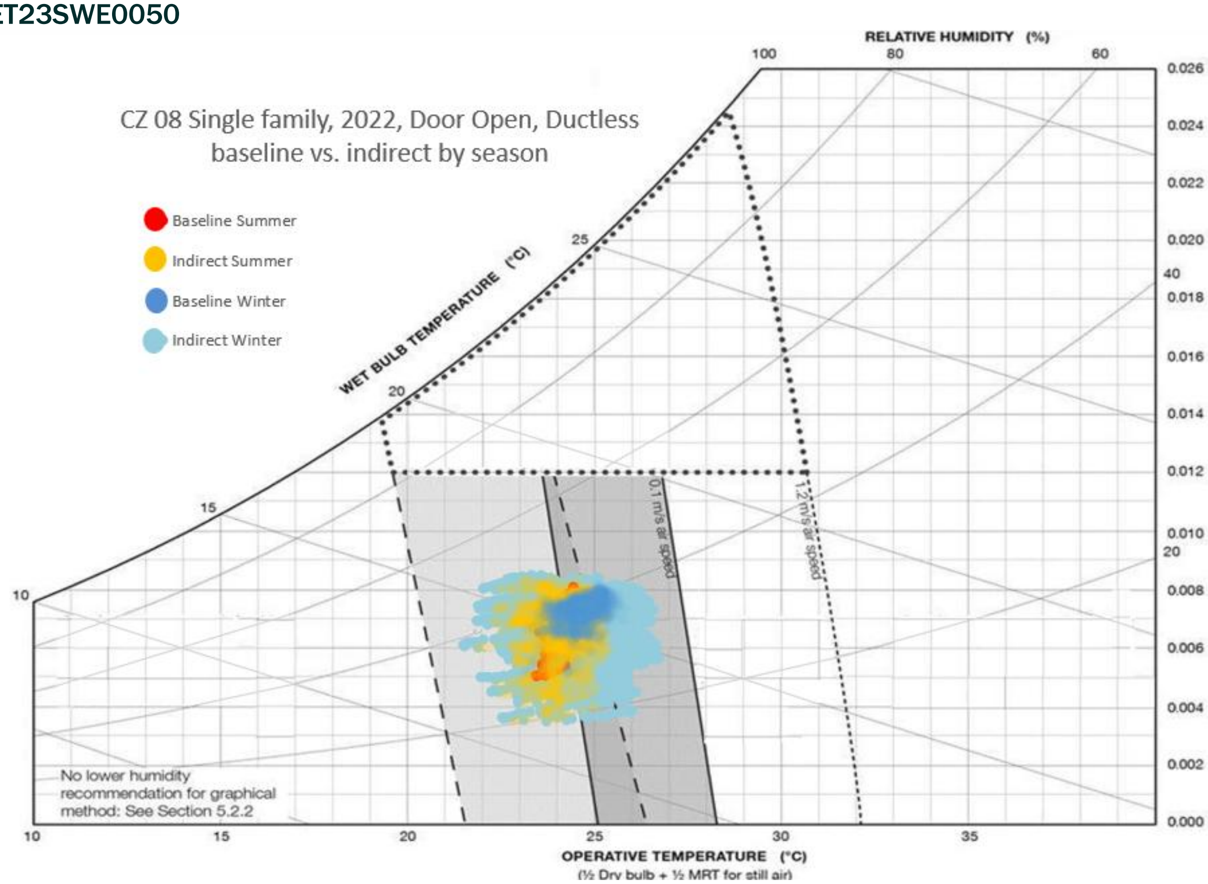
Comfort Impacts of Partial Coverage ASHPs

Final Report

ET23SWE0050



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Disclaimer

Executive Summary

Air source heat pumps (ASHP) are a key technology that Californians are using to fulfill California's climate goals. However, one of the homeowner barriers to installing ASHP systems in existing homes is the initial cost of the equipment. This project explores two different ASHP configurations—*indirect coverage* and *suitable capacity*—to determine if these configurations can offer first-cost savings while still providing occupant comfort. To approach this challenge, the project team used energy simulations on two prototype buildings to model indoor environmental conditions over the course of one year in California climate zones and then used those results to predict thermal comfort. The project team defined configurations for a suitable capacity ASHP system and indirect coverage ASHP system as follows:

Suitable capacity ASHP systems are ASHP systems designed to meet 70 to 90 percent of the home's calculated heating or cooling design load. Reducing the capacity of the ASHP systems allows for smaller equipment and reduces the first costs of ASHP systems.

Indirect coverage ASHP systems are systems in which a home is effectively heated and cooled without direct distribution of conditioned air into every room. Ducted indirect coverage ASHPs reduce installation costs by eliminating the need to place vents and ductwork in every room of the home. Ductless indirect coverage ASHPs reduce installation and upfront costs by not installing an indoor unit in every room.

Both systems were compared against the baseline system configuration, which represents how contractors typically design ASHP systems.

Baseline ASHP systems are ASHP systems designed to meet 100 percent of the heating or cooling design load, with conditioned air directly distributed throughout all rooms in the home.

After reviewing typical California floor plans, the project team developed prototypes for a 2,100-square-foot, single-story, single-family home and a two-bedroom, 1,080-square-foot, multifamily unit to model the different configurations. Manual J and Manual S[1] calculations were completed to determine the home design loads and heat pump sizes needed for the baseline, indirect coverage, and suitable capacity configurations. Additionally, the project team completed energy simulation models to predict space temperatures and humidities, and then used those outputs—along with assumptions for air movement, clothing insulation, and metabolic activity—to model occupant comfort.

We also interviewed eleven contractors to better understand the cost impacts of indirect coverage and suitable capacity systems.

For the **suitable capacity ASHP system configuration**, the project team found an estimated reduction in material first costs for ducted and ductless configurations of between $600 and $1,550, resulting from the decrease in unit capacity. Thermal comfort was also maintained across climate zones.

[1] Manual J is a calculation used to determine the home heating and cooling design loads. Manual S is an HVAC sizing guide.

Therefore, the project team recommends sizing ASHP systems to meet 80 percent of the home heating or cooling design loads in California.

For **indirect coverage ASHP systems**, the project team found an estimated reduction in material and labor first costs for ductless ASHP systems to be between $2,000 and $6,000. For ducted ASHP systems, there may be some material and labor first-cost savings for ducts needing replacement, repair, or additions. There is some impact to occupant thermal comfort in the space not receiving directly conditioned air, but this can be mitigated with clothing adjustments[2] or by installing a transfer fan to mix the air more effectively. A transfer fan is a small fan placed in the wall or ceiling that moves air between the adjoining rooms to balance temperatures.

Both suitable capacity and indirect coverage ASHP systems will reduce first costs compared to a baseline ASHP system. The suitable capacity system is estimated to save less on first costs than the indirect coverage system, while still maintaining occupant comfort. The indirect coverage ASHP system is estimated to reduce first costs more than the suitable capacity system, but occupant comfort will need to be maintained with clothing adjustments or a transfer fan.

The project team recommends additional research to validate the results of this study. Since this study is based on modeled data, these ASHP system configurations should be tested and calibrated in occupied homes. Calibration should include thermal sensation responses across different ASHP configurations, climate zones, and floor plans with a focus on the whole home. Additional research to understand the ongoing energy and maintenance costs of these ASHP system configurations is also needed, since this project only reviewed first cost savings. In addition, first cost savings for combined suitable capacity and indirect coverage systems should be further investigated. Finally, the project team recommends the California code development teams review these findings and consider revising the California Title 24 limits to sizing ASHP system heating capacities.

[2] Clothing adjustments include occupants adding or removing clothing to maintain comfort such as adding a sweater in the winter months or wearing a short sleeve shirt or shorts during the summer months.

Abbreviations and Acronyms

Acronym	Meaning
ACCA	Air Conditioning Contractors of America
ACM	Alternative calculation method
ASHP	Air source heat pump
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
$Btu/h{\cdot}ft^2{\cdot}F$	International British thermal unit per hour per square foot per degree Fahrenheit
CBE	Center for the Built Environment
HP	Heat pump
HVAC	Heating, ventilation, and air conditioning
MF	Multifamily residence
PMV	Predicted mean vote
RASS	California Residential Appliance Saturation Study
SF	Single-family residence
SHGC	Solar Heat Gain Coefficient
W/ft^2	Watt per square foot

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Introduction

Air source heat pumps (ASHPs) are more energy efficient and reduce carbon production compared to traditional natural gas furnace and air conditioning units. However, the initial equipment purchase and installation cost for residential applications remains a barrier for many homeowners. These high upfront costs disproportionally impact low-to-moderate-income customers.

Two ways to mitigate ASHPS' high upfront costs are to reduce either the capacity of the system or the number of directly conditioned rooms within the home. To better understand the impacts on occupant comfort, the project team simulated two ASHP system configurations: **suitable capacity** and **indirect coverage**. These configurations apply to both ducted and ductless ASHP systems. Although the project team primarily focused on retrofit applications, the results could also be applied to new construction.

For the purposes of this study, the project team uses the following definitions:

- **Baseline ASHP systems** are designed to meet 100 percent of the heating or cooling design load, with conditioned air directly distributed into every room in the home.
- **Suitable capacity ASHP systems** are designed to meet 70 to 90 percent of the home's heating or cooling design load rather than 100 percent.
- **Indirect coverage ASHP systems** are systems in which conditioned air is not directly distributed to every space in the home.

This report presents the study methodology, first-cost impacts, and simulated occupant thermal comfort findings of indirect coverage heat pumps and suitable capacity heat pumps in typical California multifamily (MF) and detached single-family (SF) homes. The remainder of this report contains additional details on the background, objectives, methodology, findings, and recommendations.

Background

As proven by evaluations for other utility programs, indirect coverage and suitable capacity ASHP systems can provide sufficient comfort. The project team has performed field evaluations in New York for heat pumps that meet 70 to 90 percent of the Air Conditioning Contractors of America (ACCA) Manual-J-calculated home heating design loads. In these situations, homeowners kept their existing gas heating systems as backup, although some did not use these backup heating systems for several winters. Using only the suitable capacity ASHP systems, these homeowners confirmed that they have remained comfortable in their homes even when outdoor air temperatures are at and below design temperatures. The project team hypothesized that some of the colder California climate zones may experience similar results as the New York field study.

When engineers and contractors size residential heat pumps they may take conservative approaches which result in oversized heat pumps. Although this study does not directly consider oversized heat pumps, understanding the current heat pump sizing practices and the operation limitations of oversized systems further demonstrates the need for right- and down-sized ASHPs. ASHP equipment sized larger than what is required to meet the full design load results in a heat pump that has excess capacity at the design temperature and may be oversized for low-load conditions. There are three reasons a contractor or designer might oversize an ASHP system: incorrect assumptions about existing conditions, a desire for zero complaints and callbacks, and lack of sizing calculations entirely.

1. Simplifying assumptions or incorrect inputs for the home's Manual J design load calculation. When installing heat pumps in existing homes, there is often a lack of information on the home's existing envelope such as air infiltration rates, R-values, or window U-factors.
2. The contractor or design engineer might oversize the HVAC system to avoid customer complaints and callbacks
3. The contractor or designer might inadvertently oversize the HVAC system by replacing the existing system with the same capacity system, without performing home design load calculations to determine an appropriate HVAC system capacity.

To avoid callback risk, typical HVAC installers have historically sized systems to meet potential heating and cooling demands for extreme weather conditions, which avoids customer complaints due to discomfort. However, when heat pumps are oversized for the spaces they condition, the heat pumps run inefficiently because they are incapable of providing the small amount of heating or cooling needed. This situation results in low-load cycling. Most of a heat pump's annual run-hours are in moderate conditions relative to the design temperature, e.g., a location with a design temperature of 16°F has most heating run-hours between 40°F and 60°F.

If the heat pump is oversized and the design load is less than the minimum compressor capacity, the heat pump will cycle because it is providing more heating or cooling than needed. Low-load cycling can occur in all oversized heat pumps, including single-stage and variable- or multi-stage heat pumps. Low-load cycling results in more indoor space temperature variation, inefficient operation, poor dehumidification, and substandard performance. For smaller capacity heat pumps to maintain the correct indoor air temperature, they may operate for more hours annually. However, when they are operating in a more efficient manner, they can save energy and reduce peak demand when compared to a larger system running inefficiently. Additionally, continuous operation provides better dehumidification in the cooling season.

The ACCA Manual J and Manual S are used to determine the size of HVAC equipment needed for a residential space. Manual J is a calculation used to determine the heating and cooling loads for the whole home and different spaces within the home at design conditions, while Manual S is an HVAC sizing guide. The home design loads calculated using Manual J are inputs used in Manual S to determine the correct heat pump size.

California building code requires building design loads to be calculated in accordance with Manual J. While prior to December 31, 2025, there was no limitation on the required heat pump capacity, there were requirements to provide sufficient occupant comfort. Per the California Residential Code, Title 24, Part 2.5 Section R303—and consistent with American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 55 and 2021 International Building Code—interior spaces intended for human occupancy shall be provided with active or passive space heating. Passive space heating systems must be capable of maintaining an indoor temperature of no less than 68°F (20°C) at a point 3 feet (914 mm) above the floor on the design heating day. The 2025 Title 24 updates, which go into effect on January 1, 2026, include a new measure to limit under-sizing ASHP system heating capacity to meet the minimum California Building Code requirements without including supplemental heating capacities. Although there are limits to under-sizing heat pumps, there are still no limitations on oversizing. The new code may be interpreted as excluding suitable capacity ASHP configurations.

Objectives

The goal of this project was to determine if indirect coverage and suitable capacity heat pumps provide: 1) sufficient comfort for residential occupants, and 2) first-cost savings compared to traditional ASHP systems. For this project, the team examined existing residential homes, taking into account the building construction differences across several home vintages. We did not assess new construction or commercial spaces, nor the operating costs of these configurations.

This study evaluated the validity of the following hypothesized outcomes of this project:

- Models showing that successful deployment of ASHPs in suitable capacity and indirect coverage applications is possible without adverse thermal comfort impacts.
- Modeling results describing space temperatures in typical SF and MF residential building types in California climates.
- Cost analysis showing that indirect coverage ASHP systems and suitable capacity ASHP systems can result in first-cost savings, compared to a typical full design load ASHP system.

The project team made recommendations based on the results of this research for situations where indirect and suitable capacity systems can result in first-cost savings and occupant comfort.

Methods and Approach

To determine if indirect and suitable capacity ASHP systems provide sufficient occupant comfort, the project team conducted a detailed analysis using multiple tools. First, the team defined four home scenarios that would benefit from suitable capacity and indirect coverage system configurations. Then, we developed representative homes that could benefit from these ASHP systems before conducting design load calculations and selecting equipment for these homes using ACCA Manual J (Rutkowski 2011) and Manual S (ACCA 2023). The project team then created detailed energy prototype models of the homes with the selected equipment and ran simulations to determine the indoor temperatures in the home throughout the year. Lastly, we used the indoor temperature outputs from the energy model, along with other assumptions, to predict thermal comfort using the Center for the Built Environment (CBE) Thermal Comfort Tool and pythermalcomfort 3.5.1 (Tartarini, et al. 2020).

To determine if there are first-cost savings for suitable capacity and indirect coverage ASHP systems compared to standard heat pump systems, the project team interviewed 11 contractors. In the interviews, we gathered information about ASHP sizing practices in California and collected first-cost estimates for labor and materials.

The approach and methodology for each of these steps is detailed in this section.

Scenarios

The project team reviewed 12 different scenarios covering potential ductwork configurations, ducted vs. ductless heat pump systems, and indirect coverage vs. suitable capacity configurations, all of which are detailed in Table 1. After reviewing these scenarios, the project team determined that there were no major component differences between single-family and multifamily homes, so the same parameters were applied to each. The project team concluded that 7 of the 12 scenarios could benefit from the proposed ASHP system in a real-world application.

Table 1: Home scenarios.

Scenario	Condition of Existing Ductwork	Proposed Duct Configuration	Proposed ASHP System	Likely to benefit from proposed ASHP system?
Scenario A	Usable	Ducted	Indirect coverage	No, first costs will not be reduced if ductwork needs to be removed. This scenario is impractical in a real word setting.
Scenario B	Needs replacement or substantial adaptation	Ducted	Indirect coverage	Yes, first costs may be reduced if fewer ducts are installed in a home. For modeling purposes, the project only modeled Scenario C, which applies to this scenario, as well.
*Scenario C	No ductwork	Ducted	Indirect coverage	Yes, first costs may be reduced by installing fewer ducts in a home.
Scenario D	Usable	Ductless	Indirect coverage	No, will likely install ducted if ducts are usable. This scenario is impractical in a real word setting.
Scenario E	Needs replacement or substantial adaptation	Ductless	Indirect coverage	Yes, it may reduce first costs to replace with a ductless system. For modeling purposes, the project only modeled scenario F, which applies to this scenario as well.

Scenario	Condition of Existing Ductwork	Proposed Duct Configuration	Proposed ASHP System	Likely to benefit from proposed ASHP system?
*Scenario F	No ductwork	Ductless	Indirect coverage	Yes, first costs may be reduced if fewer heads are installed when using a ductless system.
Scenario G	Usable	Ducted	Suitable capacity	Yes, the existing ductwork is not vital for the suitable capacity system.
Scenario H	Needs replacement or substantial adaptation	Ducted	Suitable capacity	No, it is more likely that a ductless system will be installed in this scenario if cost is of concern.
Scenario I	No ductwork	Ducted	Suitable capacity	No, it is more likely that a ductless system will be installed in this scenario if cost is of concern.
Scenario J	Usable	Ductless	Suitable capacity	No, it is more likely that a ducted system will be installed in this scenario.
Scenario K	Needs replacement or substantial adaptation	Ductless	Suitable capacity	Yes, this system could benefit, but for ease of modeling, scenario L will be modeled.
Scenario L	No ductwork	Ductless	Suitable capacity	Yes, a suitable capacity ductless system could reduce first costs.

Note: An asterisk (*) indicates a scenario that the project team modeled in this study.

To limit the modeling iterations, the project team narrowed the seven scenarios down to four. For the remainder of this report, Scenarios C, F, G, and L are referred to as follows:

Scenario 1: Indirect coverage ducted system

As described in Scenario C in Table 1, this is a ducted system that would be installed in a home without ductwork.

Scenario 2: Indirect coverage ductless system

As described in Scenario F in Table 1, this is a ductless system that would be installed in a home without usable ductwork.

Scenario 3: Suitable capacity ducted system

As described in Scenario G in Table 1, this is a ducted system that would be installed in a home with usable ductwork.

Scenario 4: Suitable capacity ductless system

As described in Scenario L in Table 1, this is a ductless system that would be installed in a home without usable ductwork.

The project team compared these four scenarios to two baseline conditions: one for ducted and one for ductless. For the baseline scenarios, we sized the ASHP systems based on typical contractor best practices of fulfilling the full design load for every space in the home.

Define Representative Home Characteristics

The project team identified and created a typical SF and MF home to use in modeling scenarios 1, 2, 3, and 4. The result was a 2,100-square-foot, single-story, single-family home and a two-bedroom, 1,080-square-foot, multifamily unit.

First, the project team collaborated with in-house industry experts to develop a hypothesis. The team hypothesized that to achieve first-cost savings with indirect coverage and suitable capacity ASHP configurations compared to standard ASHP configurations, the baseline ASHP system must be large enough to be reduced to a smaller, market available system and have a configuration with at least two directly conditioned spaces. For both MF and SF homes, any home large enough to directly condition at least two spaces should be evaluated.

Floorplans

SINGLE FAMILY

The project team identified a typical SF detached dwelling unit floor plan used to support the analysis in the 2025 CASE report, Buried Ducts and Roofs with Cathedral Ceilings. This floor plan matched the 2022 alternative calculation method (ACM) prototype and is considered a common California SF home, according to the 2019 RASS data. Figure 1 shows the SF floor plan used by the project team for the Manual J and Manual S simulation with thermal comfort modeling outlined below.

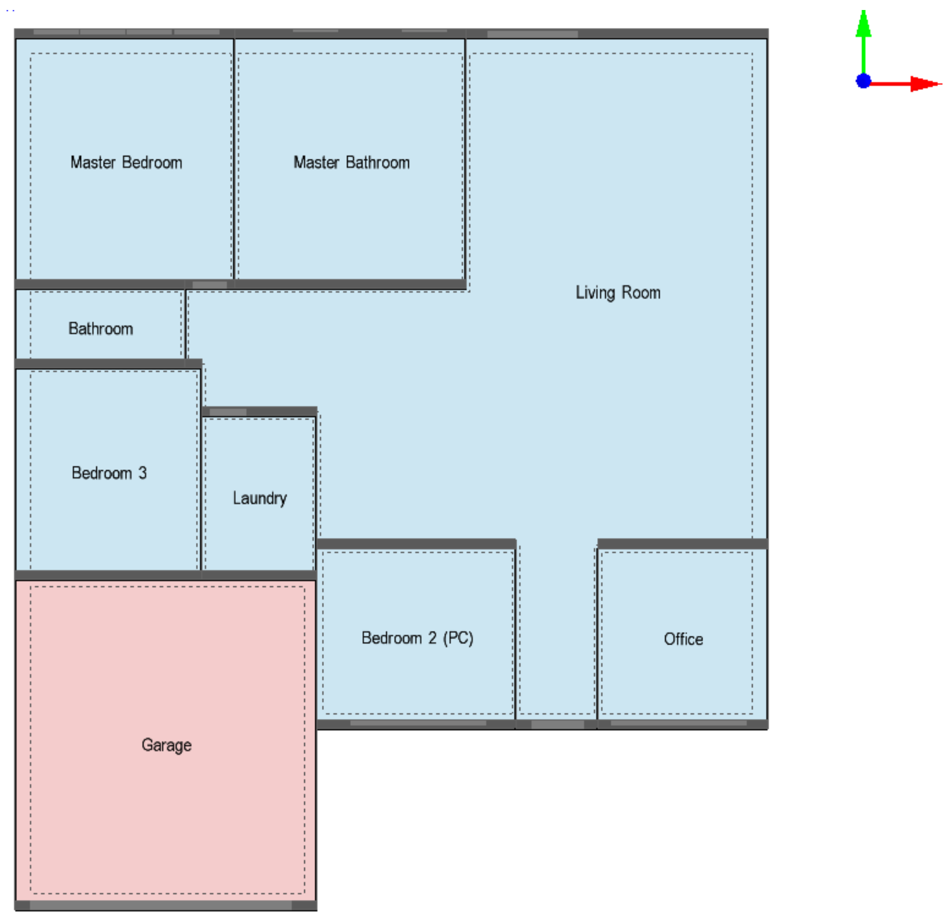


Figure 1: Single-family floor plan.

MULTIFAMILY

After reviewing the 2019 Residential Appliance Saturation Study (RASS) data, the project team confirmed that two-bedroom units are one of the most typical apartment units in California, so we modeled a two-bedroom unit. The project team was unable to identify an existing typical two-bedroom MF dwelling unit floor plan used for California Title 24 development. Therefore, we completed a literature review of California MF floor plans, which included reviewing the 2022 ACM prototypes, 2019 RASS data, and common California MF floor plans.

After reviewing the 2019 RASS data, the project team concluded that most MF units were two-bedroom apartments between 1,001 and 1,250 square feet. This aligns with the 2022 ACM prototypes, which have 1,080-square-foot two-bedroom units. The exterior dimensions of these units are 30 feet by 36 feet, which is what the project team used in the floorplan.

To determine the interior layout of the two-bedroom MF unit, the project team reviewed four California MF floorplans created by other engineering contractors. The goal was to understand the most common configurations of two-bedroom MF dwelling units in California. We reviewed the location—as well as the number of bedrooms, the layout of the kitchen, and the placement of the bathroom(s) - and concluded that the most common configuration for a two-bedroom apartment was as follows:

- One bathroom
- Bedrooms side by side
- Open kitchen
- Bathrooms not connected to bedrooms

The project team created the layout using the information above and had internal engineers review it to confirm its practicality and regularity. Figure 2 shows the floor plan the team is using for this project.

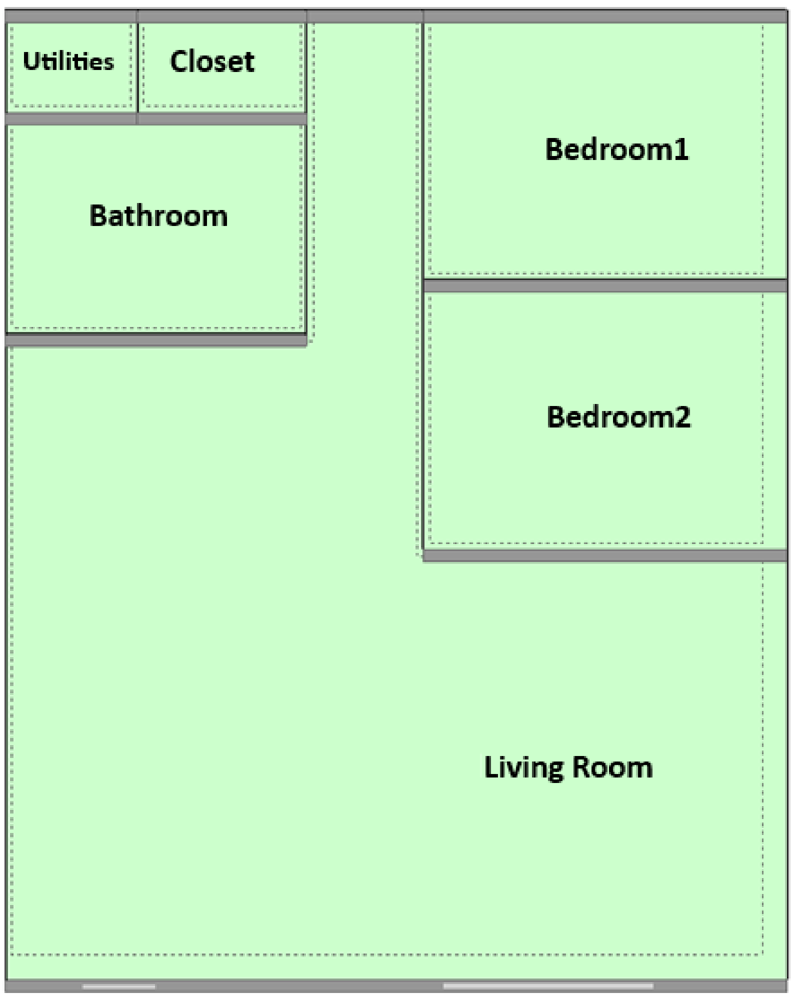


Figure 2: Multifamily floor plan.

Vintages

Due to the various construction characteristics of California homes, the project team defined three different home vintages to represent current California residential building stock. For each SF and MF prototype, three building vintages were used: pre-1978, 1992 to 1998, and 2022. The pre-1978 vintage represents buildings built before the Energy Code existed, the 1992 to 1998 vintage represents the average building stock in the market, and the 2022 vintage represents the characteristics of what newer homes were like as of the writing of this report.

The project team determined building characteristics based on the home's vintages that resulted in the highest impact on building design load, which were the only characteristics considered in the analysis. The construction parameters and assumptions for each vintage are detailed in Table 2 and Table 3. with materials and thermal properties for each vintage from the 2016 and 2022 ACMs, and internal loads adapted from ENERGY STAR ® Simulation Guidelines. The air infiltration rates vary by vintage and incorporate infiltration templates within the modeling software.

Table 2: Single-family construction parameters and assumptions.

Parameter	Pre-1978	1992 - 1998	2022
Roof-ceiling U-factor (Btu/h·ft^2·F)	0.079	0.049	0.026 (CZ: 1, 11-16) and 0.033 (CZ: 2-10)
Wall U-factor (Btu/h·ft^2·F)	0.356	0.102	0.048 (CZ: 1-5, 8-16) and 0.065 (CZ: 6,7)
Window U-factor-wood-frame (Btu/h·ft^2·F)	0.99	0.58	0.3
Window SHGC	0.74	0.65	0.23
Air Infiltration	Poor	Medium	Good
Window-to-wall Ratio	0.2	0.2	0.2
Internal load [lights+plug] (W/ft^2)	1.1	1.1	1.1
People (ft^2/person)	469.5	469.5	469.5

Note: The characteristics of the pre-1978 and 1992 to 1998 vintages came from Table 8-1 in the 2016 ACM: "Default Assumptions for Year Built (Vintage)," and the 2022 vintage came from Table 3-22 in the 2022 ACM: "Standard Design for an Altered Component." The internal load values are adapted from "ENERGY STAR MFNC Simulation Guidelines Version 1, Revision 02."

Table 3: Multifamily construction parameters and assumptions.

Parameter	Pre-1978	1992 - 1998	2022
Roof-ceiling U-factor (Btu/h·ft²·F)	0.079	0.049	0.028 (CZ :1-2, 4, 8-16) and 0.034 (CZ: 3, 5-6) and 0.039 (CZ: 7)
Wall U-factor (Btu/h·ft²·F)	0.356	0.102	0.059 (CZ: 1-5, 8-10, 12-13) and 0.051 (CZ: 11, 14-16) and 0.065 (CZ: 6-7)
Window U-factor Metal-frame (Btu/h·ft²·F)	1.28	0.79	0.34 (CZ: 7-8) and 0.3 for the rest
Window SHGC	0.8	0.7	0.23
Air Infiltration	Poor	Medium	Good
Window-to-wall Ratio	0.3	0.3	0.3
Internal load [lights+plug] (W/ft²)	1.1	1.1	1.1
People (ft²/person)	571.5	571.5	571.5

Note: The characteristics of the pre-1978 and 1992 to 1998 vintages came from Table 8-1 in the 2016 ACM: "Default Assumptions for Year Built (Vintage)," and the 2022 vintage came from Table 3-22 in the 2022 ACM: "Standard Design for an altered Component." The Internal load values are adapted from "ENERGY STAR MFNC Simulation Guidelines Version 1, Revision 02."

Orientation, Adjacency, and Weather

In addition to vintages and layout, the project team considered the various orientations and locations, as well as the configurations within MF buildings, of existing California homes. We parameterized these additional variations in the system sizing, simulation modeling, and thermal comfort assessment model.

ORIENTATION

The project team planned to orient the SF and MF prototypes in different directions to capture the various positions of a home in the real world. We initially limited the orientation of the homes to the four primary cardinal directions: north, south, east, and west. After reviewing the home heating and cooling design loads developed using Manual J calculations, the project team determined there were minimal differences in loads across the four cardinal directions. For the home design load calculations and heat pump sizing, we reduced the number of iterations by using the north orientation only, because it resulted in the largest home heating or cooling design load. For the simulation modeling, the project team simulated all four cardinal directions using EnergyPlus, which accounts for the angle of incidence of solar radiation throughout the year. This angle affects the solar heat gain through the building envelope which influences the indoor air temperature in each space throughout the home.

ADJACENCY

For the multifamily home, the project team considered different adjacencies of the unit within the multifamily building, including the floor (middle or top) and a location within the floor (center or corner). This resulted in four possible MF unit adjacency layouts:

- Corner top unit (three external surfaces, two adiabatic surfaces)
- Center top unit (two external surfaces, three adiabatic surfaces)
- Corner middle unit (two external surfaces, three adiabatic surfaces)
- Center middle unit (one external surface, four adiabatic surfaces)

We did not consider any adjacency variations for SF homes.

WEATHER

The project team considered all 16 California building climate zones defined by the California Energy Commission.

HOME ZONES

For the SF heating and cooling design load calculations, the project team calculated design loads based on the different rooms of the home, which included the master bedroom, master bathroom, great room, bathroom 2, bedroom 3 (which included the laundry room), office, and bedroom 2 (as shown in Figure 1. For the ASHP sizing calculations, some of the loads were combined to create five spaces.

- Space1: Master bedroom and master bathroom
- Space 2: Living room
- Space 3: Bedroom 3, laundry, and bathroom 2
- Space 4: Office
- Space 5: Bedroom 2

The project team modeled the five HVAC zones as described above but modeled the temperatures for each room in the home as shown in the floorplan in Figure 1.

For the MF home, we calculated the heating and cooling design loads for the living room, bedroom 1, bedroom 2, and bathroom, which included the closet and utility room as shown in Figure 2. For the ASHP sizing calculations, the four spaces followed the load calculations as described below:

- Space 1: Bedroom 1
- Space 2: Bedroom 2
- Space 3: Bathroom, utility room, and closet
- Space 4: Living room

The project team modeled the four spaces as described above but modeled the temperatures for each room in the home as shown in the floorplan in Figure 2. This was used to determine occupant comfort in each room of the home.

System Sizing

To replicate how contractors size HVAC units in the field, the project team used Manual J and Manual S to size the heat pump configurations for each design load calculation iteration. The parameters considered and the variations in the sizing calculations are described in Table 4.

Table 4: Description of parameters used in heat pump sizing.

Parameter	Number of Variations	Description of Variations
Building type	2	SF MF
Climate Zone	16	California Building Climate Zones
Orientation	1	Only using North
MF Adjacency (No adjacency for SF)	4	Center units Corner units Middle floor units Top floor units
Vintage	3	Pre-1978, 1992-1998, 2022
Configuration	3	Baseline Indirect Coverage Suitable Capacity
Ducting	2	Ductless Ducted

LOAD CALCULATION (MANUAL J)

The project team conducted detailed Manual J room-by-room design loads for each building type (2), climate zone (16), MF adjacency (4), and vintage (3) listed in Table 4. Additionally, we calculated peak heating and peak cooling design loads for each climate zone. This resulted in 96 SF and 384 MF home design load iterations.

HP SIZING (MANUAL S)

To determine heat pump sizing, the project team used the peak heating and cooling design loads from the Manual J calculations to complete the Manual S calculations. Three different HP sizing scenarios were calculated: baseline, which was sized using industry standard practice; suitable capacity ASHP system; and indirect coverage system.

For the suitable capacity ASHP system, the project team selected equipment with a capacity between 70 and 90 percent of the design load, targeting 80 percent of the design load. For SF, there were 24 ductless ASHP iterations where the heat pump could not be appropriately sized because the suitable capacity configuration resulted in an outdoor unit capacity to combined indoor unit capacity that was greater than the manufacturer specified maximum allowed ratio. Therefore, the number of spaces with individually devoted indoor units had to be reduced from 5 to 4 to allow for appropriate sizing of the heat pump system. This created a new configuration that combines both the suitable capacity and indirect coverage configurations.

For SF indirect coverage system, the team removed an indoor head unit from one of the bedrooms and redistributed its capacity to the other indoor head units, thus reducing the number of directly conditioned spaces by one. For MF indirect coverage, the team reduced the indoor head units to one head, located in the main room. Reducing the number of heads allowed the ASHP system to be sized appropriately for the whole home's heating and cooling loads while avoiding selecting an indoor unit that was severely oversized for the small loads of the bedroom.

With the parameters described in Table 4, the project team used Manual S to size heat pumps for 288 SF iterations and 1,152 MF iterations. For every scenario, the project team used recommended manufacturer ratios to ensure the indoor unit capacities could be supported by the outdoor unit capacity. When the indoor unit capacities needed to meet a home's design load were not supported by the exterior unit capacity, the indoor unit capacities were reduced.

The project team selected ductless multi-split and mini-split heat pump equipment based on the baseline, indirect coverage, and suitable capacity system configurations.

- **A ductless multi-split system configuration** includes one outdoor unit with multiple indoor supply units.
- **A ductless mini-split system configuration** (also called a "one-to-one") includes one outdoor unit for every one indoor unit.

We selected multi-split systems for all full coverage ductless configurations; however, multi-split systems are typically 1.5 tons or larger and thus oversized for many of the MF iterations. For this reason, all the equipment selected for MF indirect coverage were mini-split systems, with one supply unit in the living room and one outdoor unit. SF used multi-split systems for all ductless configurations.

The capacities and efficiencies for the selected systems represent residential heat pumps manufactured by a widely available HVAC brand that is frequently installed throughout California and the United States. The compressors for baseline and indirect coverage systems were sized to the respective heating and cooling design loads calculated for each prototype. Indoor ductless heads were selected based on the zonal heating and cooling design loads they were responsible for.

Thermal Comfort Assessment

Simulation Modeling

The project team modeled the baseline, indirect coverage, and suitable capacity configurations within EnergyPlus. To better understand the conditions where the indirect coverage and suitable capacity systems would provide acceptable thermal comfort to occupants, we completed parametric runs using the parameters and variations described in Table 5. The outputs of indoor mean air temperature, mean radiant temperature, and relative humidity generated by the simulation model were used to evaluate occupant thermal comfort.

The project team used DesignBuilder to develop the SF and MF prototypes using typical California floor plans (as shown in Figure 1 and Figure 2) and building characteristics (as described in Table 2Table 2 and). Table 3). The MF building model consisted of six thermal areas, three of which were directly conditioned in the baseline and suitable capacity configuration. The SF building model included nine thermal areas, five of which were directly conditioned in the baseline and suitable capacity configuration.

Additional inputs for simulation modeling included the ASHP system sizing from Manual J and Manual S, building envelope characteristics developed based on the applicable energy code for each vintage and climate zone, and internal loads. The team aligned residential internal load assumptions for occupancy, lighting, plug loads, and schedules with California Building Energy Code Compliance, ENERGY STAR guidelines, and DesignBuilder defined templates. The Construction Parameters and Assumptions in Table 2 and Table 3 provide detailed descriptions of these modeling inputs.

After the SF and MF prototypes were built in DesignBuilder, the project team used ModelKit to complete parametric runs using the parameters described in Table 5. To automate the simulation of 2,304 SF iterations and 9,216 MF iterations, the project team exported the IDF file from DesignBuilder, parameterized it using ModelKit, and passed the iterations to EnergyPlus.

Table 5: Description of parameters used to generate simulation models.

Parameter	Number of Variations	Description of Variations
Building type	2	SF, MF
Climate Zone	16	California Building Climate Zones
Orientation	4	North, South, East, West
MF Adjacency (No Adjacency for SF)	4	Center units, Corner units, Middle floor units, Top floor units
Vintage	3	Pre-1978, 1992-1998, 2022
Configuration	3	Baseline, Indirect Coverage, Suitable Capacity
Ducting	2	Ductless, Ducted

Parameter	Number of Variations	Description of Variations
Air Flow[3]	2	Door Open, Door Closed

EnergyPlus generated hourly outputs of mean air temperature, mean radiant temperature, and relative humidity for each directly and indirectly conditioned space in the home based on a typical year, or 8,760 hours. By assuming each space had well-mixed air, the model simplified each one to a single uniform datapoint. To model the well-mixed air, the project team modeled the infiltration of outdoor air and airflow between spaces using an air-flow network linking each one through openings and cracks in the constructions. We acknowledge this limitation to the modeling, since in reality, the temperature may vary slightly throughout each space. The model also calculated conductive heat transfer between interior spaces, and between interior spaces and the exterior environment. Exterior insulation and window thermal properties matched the building vintage as per the values in Table 2 and Table 3 and the models represented interior partition surfaces as wood-stud structures without insulation. The zonal energy modeling approach was chosen over Computational Fluid Dynamics which would have accounted for temperature gradients within a space but would have had its own set of limitations such as difficulty modeling changing temperatures over time, heat pump components, and interactive internal gains. The zonal airflow approach we used does account for the interaction between different infiltration sources within the building.

Thermal Comfort Modeling

The project team used two tools for predicting thermal comfort for each ASHP configuration. For exploratory analysis and spot-checking, we used the CBE Thermal Comfort Tool for ASHRAE-55 (Tartarini, et al. 2020). The CBE tool incorporates several different methods for thermal comfort evaluation, from minute-by-minute heat-flow models to algorithmic fits to empirical data. For parametric analysis and bulk processing, the project team used “pythermalcomfort,” a python library for calculating thermal comfort predictive indices directly (Tartarini, et al. 2020).

Heat flow models use elements representing body components, such as skin, core, arms, and legs. Heat flow within body components is modeled, along with convective, conductive, and radiative heat transfer with the environment. These models run until a steady-state skin temperature is reached, when all input variables are held constant. Skin temperature is a reliable predictor of thermal sensation. This type of modeling is very similar to building performance models, but instead of modeling a building, the tool models the human body.

Empirical models use human survey data and concurrent physical measurements to establish a statistical relationship between a set of environmental variables and “votes” on thermal comfort scales. These are usually 7-point Likert scales (Likert 1932) of the form “-3 (cold) to “0” (neutral) to +3 (hot).” To date, many hundreds of thousands of thermal comfort votes have been collected over hundreds of studies, providing the statistical reliability derived from large sample sizes.

[3] Air flow from room to room resulting from the door being open or closed was not a parameter that was used in the equipment sizing calculations (Manual S). This is a passive airflow value that is not taken into consideration when sizing HVAC equipment.

Both the CBE Thermal Comfort Tool and pythermalcomfort.py output a set of indices to predict the thermal comfort vote of an average person—with specific clothing insulation and metabolic activity—in a space. Figure 3 shows a psychrometric chart with the summer and winter comfort zones for indoor environments shown by the red and blue shaded area respectively (ASHRAE 2023) (ISO 2005); the difference between summer and winter is due to expected clothing insulation with changes in season. A psychrometric chart is the graphical representation of the thermodynamic properties of moist air at a constant pressure and helps to analyze cooling, heating, humidification, and dehumidification in the home. The psychrometric chart is used widely to design HVAC systems.

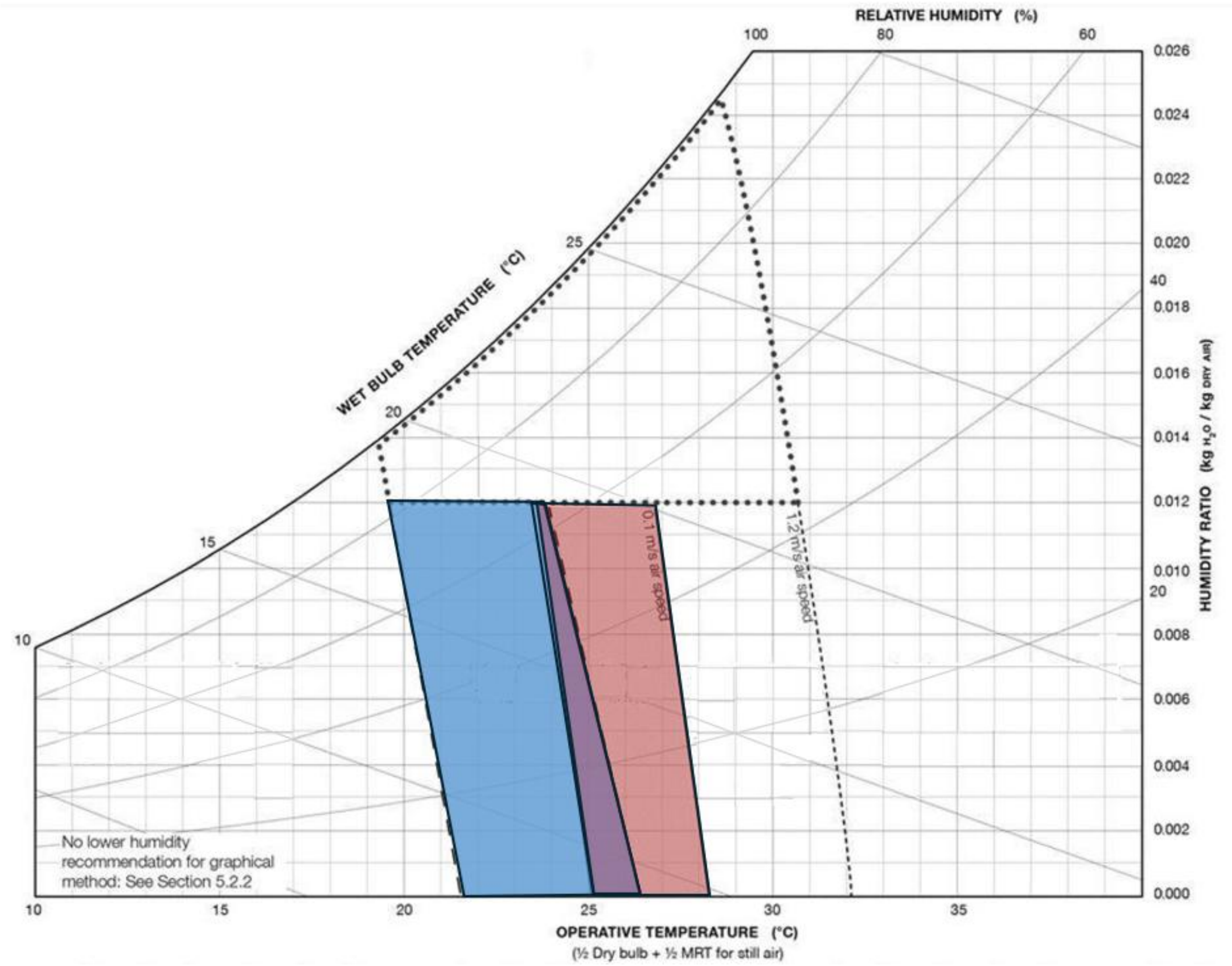


Figure 3: Psychrometric chart with thermal comfort zones.

Source: (ASHRAE 2023) (ISO 2005)

For this report, we present thermal comfort results using the predicted mean vote (PMV) index (Fanger 1970). PMV represents the predicted vote on a seven-point scale, as shown in Figure 4.

Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
-3	-2	-1	0	+1	+2	+3

Figure 4: PMV Scale

For the purposes of this study, the project team analyzed the comfort of one occupant standing in the center of each room in our models. There are six inputs needed to model comfort using the CBE Thermal Comfort Tool, detailed in Table 6.

Table 6: Thermal comfort model inputs and sources

Input	Source
Air Temperature	Simulation Model output
Relative Humidity	Simulation Model output
Air Velocity	Assume a well-mixed volume at the still air perception threshold (0.15 m/s)
Clothing insulation (clo)	Assume based on ASHRAE standard 55 Informative Appendix G daily value (1 clo)
Metabolic Rate	Assume standing sedentary person (1.2 met)
Mean Radiant Temperature	Computed

The project team reviewed hourly occupant temperatures over the course of one year under typical weather conditions for the climate zone to determine if the indices fall within the comfort range for the average person. These results were compared across the baseline, indirect coverage, and suitable capacity ASHP configurations and iterations developed in the simulation modeling.

System Cost Assessment

The following section outlines the approach and methods for conducting the system cost assessment, which was primarily HVAC contractor interviews. The following subsections detail the recruitment, data collection, and analysis process.

HVAC Contractor Interviews

The objectives of the HVAC contractor interviews were to: 1) understand how contractors in California typically size ASHP systems, and 2) obtain first-cost pricing information related to each of the ASHP configurations.

RECRUITMENT LIST

The project team used past recruitment efforts, as well as the TECH Clean California database, to compile a list of contractors who had installed ASHP systems in California. To recruit contractors for the interviews, we first emailed contacts with available email addresses and followed up with phone calls, when possible, and reminder emails. Each interview length was 45 minutes and the project team provided an incentive for each completed interview.

To ensure the sample reflected a range of market conditions, the recruitment team screened contractors based on the type of projects they were familiar with, including home type, ASHP ducting, and California building climate zone, as shown in Table 7.

Table 7: Contractor sample targets and actual.

Contractor Projects		Target	Actual
Home Type	SF Projects	5	6
	MF Projects	5	5
Heat Pump Ducting	Ducted	5	6
	Ductless	5	5
California Building Climate Zone	CZ 1 - 10	5	5
	CZ 11 - 16	5	6
	Total Interviews	10	11

Of the 11 contractors we interviewed, about half were located within the heating-dominated California building climate zones (Climate Zones 11 through 16). Six of the contractors had ductless heat pump experience and primarily served single-family homes, while five had ducted heat pump experience and primarily served multifamily homes, as shown in

Table 8 below. Nearly all contractors reported familiarity with both ducted and ductless heat pump replacements, while experience with single-family versus multifamily installations was roughly equal.

Table 8: Summary of contractors interviewed.

Home Type	HVAC system type	Climate Zone	Count of Contractors
Single Family	Ducted	3, 12, 13	3
	Ductless	2, 10, 13	3
Multifamily	Ducted	9, 11, 12	3
	Ductless	7, 11	2

DATA COLLECTION

The project team's primary questions centered on understanding how contractors determine the appropriate sizing for heat pump systems and the key factors and considerations influencing those sizing decisions. The complete interview guide is available in Appendix B.

For the pricing component, the project team asked about the overall and component price differences between the baseline ASHP configuration and the indirect coverage and suitable capacity system configurations. This information helped us better understand first-cost variations and identify key cost drivers. Additionally, the qualitative data provided insights into how contractors make sizing decisions beyond standard heating and cooling design load calculations, including subjective and judgment-based factors that influence system design choices.

ANALYSIS

Following the completion of interviews, the project team conducted both financial and qualitative analyses to better understand contractor practices and pricing dynamics. For the financial data, the project team analyzed contractor estimates by separating them into baseline and intervention scenarios for comparison. The team found that reported material and labor costs varied widely across contractors, which limited confidence in cross-contractor cost comparisons. However, because each contractor's pricing information was internally consistent, the team was able to conduct a more reliable and directly comparable analysis of the difference in costs between baseline and intervention scenarios across the estimates given by the contractors. This approach provided insight into the relative impact of system sizing and configuration on installed costs, while reducing distortion from absolute cost differences driven by factors such as business scale, regional labor rates, and contractor-specific pricing structures.

For the qualitative data, the project team organized responses around the research objectives and identified key themes. The team then assessed the prevalence of each theme by counting the number of contractors who referenced it, which provided a systematic measure of how common specific perspectives and practices were across the sample. In addition to frequency counts, the team reviewed the context in which themes were raised to better understand differences in emphasis and relevance to contractor decision-making processes. This method balanced breadth (showing how widely a theme was shared) with depth (illustrating the circumstances under which particular practices or barriers were most salient).

Findings

Suitable Capacity Configuration

The suitable capacity system configuration is based on sizing the heat pump for 70 to 90 percent of the home heating or cooling design load, which the project team found will provide some first-cost savings to occupants while maintaining occupant thermal comfort.

System Sizing

The contractors the project team spoke with used a mix of information to determine the appropriate size of an ASHP system for a home, including customer preferences, home orientation, condition of existing ductwork, Manual J design load calculations, and Title 24 setpoints. Three contractors mentioned that they would not select a heat pump with a capacity smaller than what is recommended for the home's calculated thermal load, but the remaining eight contractors discussed various reasons for selecting a smaller capacity heat pump including the following:

- Home envelope is very efficient, or in the process of becoming more efficient (n = 3 contractors)
- Desire to dehumidify the home (n = 2 contractors)

Another contractor talked about accounting for existing ductwork and its ability to handle a larger system, the potential to install a variable speed compressor to meet the heating and cooling load, and the electrical capacity of the home.

To align with contractor best practices, the project team also accounted for home orientation, Manual J home design loads, and Title 24 setpoints to determine the appropriate ASHP capacity for each iteration. However, after completing the Manual J home design load calculations for the SF and MF prototype homes, we found that some adjustments to the MF ASHP system sizing were needed for the suitable capacity system configuration. Due to the low home design loads in the MF prototype, 91 percent of the 384 MF suitable capacity iterations required a 1.5-ton ASHP unit, which is the smallest available on the market for the baseline configuration. Because there are no smaller ASHPs available on the market, the project team was unable to test the suitable capacity configuration for these iterations. However, for 9 percent of the iterations, the project team was able to downsize the ASHP capacity by 0.5 tons. For ductless units, this occurred under the following conditions:

- Corner mid, and upper MF units built before 1978 in Climate Zones 8 through 14 and Climate Zone 16

For ducted units, this occurred for units under the following conditions:

- Corner mid, and upper units in Climate Zone 15 for units built between 1992 and 1998
- Corner mid, and upper units in Climate Zones 10 through 15 for units built pre-1978
- Center middle, and upper units in Climate Zone 15 built before 1978

For the SF prototype, the home design loads were large enough that reducing the home loads to 80 percent resulted in a smaller capacity system. For 68 percent of the SF suitable capacity iterations, the project team reduced the ASHP system capacity by between 0.5 tons and 3 tons for ducted ASHPs and between 0.5 and 1.5 for ductless systems. For the remaining 32 percent of the 96 SF suitable capacity iterations, we also reduced the number of spaces receiving directly conditioned air by removing the supply in bedroom 2, due to the maximum number of indoor heads allowed for a given exterior unit capacity. This occurred in ductless ASHPs in Climate Zones 1 through 15 for homes built between 1992 and 1998, and in all climate zones for homes built in 2022. These combination systems are not investigated in this report.

First Cost

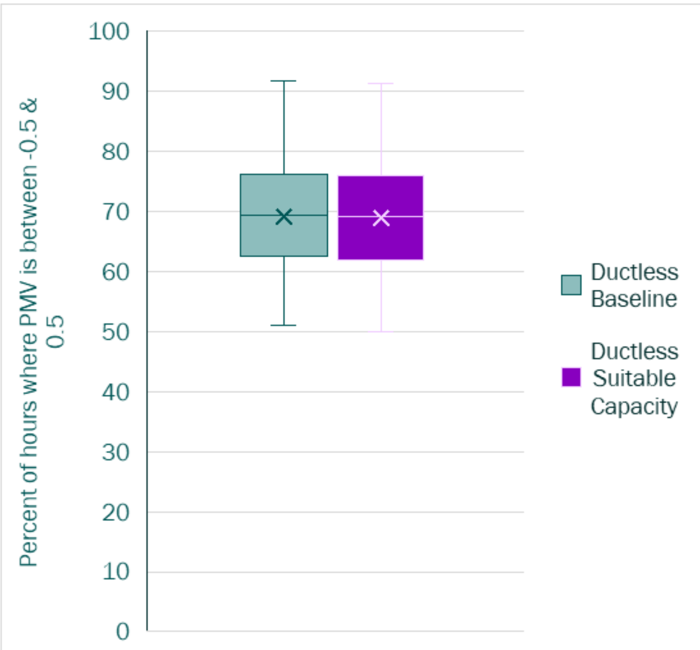
The cost of an ASHP varies throughout California based on factors such as equipment size, labor rates, ducting needs, electrical work, and location. The estimated installed cost for a central ducted heat pump in 2025 ranges from $12,000 to $18,000 but can be as low as $3,000 and as high as $44,000 (Goebes, Battisti and Davis 2025). The six contractors interviewed by the project team regarding suitable capacity ASHP system configurations noted that most of the cost savings would be in material costs from purchasing a smaller capacity ASHP system. They estimated a reduction in material costs between $600 to $1,550, which would account for the reduction in ASHP capacity. There would be no labor cost savings because the same number of labor hours would be needed to install a smaller capacity system compared to a typically sized system. Therefore, the cost reductions are dependent on the reduction of ASHP capacity available for the home. The more a heat pump system can be reduced in capacity, the more affordable the system will be. In the interviews, four contractors emphasized that while selecting a suitable capacity ASHP system can reduce equipment costs, the impact on the total project is limited since labor, ductwork, and electrical work (if needed) will generally remain the same. This means that the opportunities for cost reductions from smaller capacity ASHP systems are also limited.

Thermal Comfort

This study is based on modeled data. The inputs for the modeled home prototypes are based on California Building Energy Code Compliance software residential data that is calibrated from metered energy consumption and published research on building usage. The thermal comfort modeling is based on actual occupant thermal comfort results from different thermal environments. After completing the thermal comfort modeling, the project team found that there was not a significant difference in occupant thermal comfort between the baseline ASHP configuration and the suitable capacity configuration. These results were consistent across building type, orientation, vintage, ducting for both SF and MF homes, and adjacency for MF homes. As expected, the thermal comfort models showed more occupant discomfort when the doors were closed, thus limiting air flow, and for older vintage homes with leakier building envelopes. However, this reduction in occupant thermal comfort was consistent across the baseline and suitable capacity heat pump system configurations, so the project team concluded that the suitable capacity system results in no difference in occupant thermal comfort compared to the baseline.

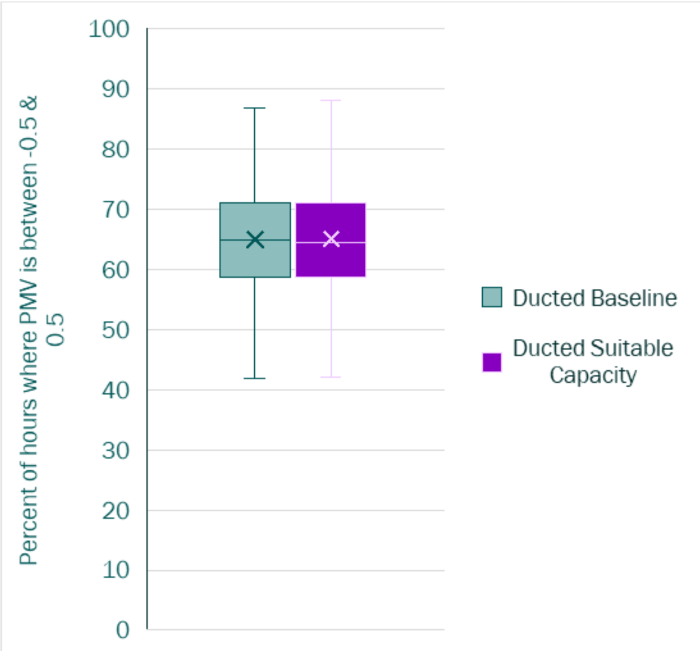
MULTIFAMILY

To compare across MF home prototype iterations, the project team calculated the percentage of hours throughout the year that is within the predicted mean vote (PMV) of -0.5 to 0.5. This range assumes 80 percent of occupants are comfortable, with 10 percent wanting their bodies to feel warmer or cooler and 10 percent wanting less local discomfort, such as cold feed or hands, no drafts, etc. The higher the percentage of hours within the range of -0.5 to 0.5, the more hours of the year occupants feel thermally comfortable. The project team compared the baseline and suitable capacity ASHP configurations across the MF modeling iterations and found similar trends across iterations. The distribution of the percent of annual hours where PMV was between -0.5 and 0.5 for all the baseline and suitable capacity iterations in the MF prototype is shown in Figure 5 and Figure 6. There was very little difference in occupant comfort between the baseline and suitable capacity ASHP configurations.



Note: This figure shows the percentage of annual hours with the PMV between -0.5 and 0.5 in a MF unit living room. (n = 128 iterations each for ductless baseline and suitable capacity)

Figure 5: MF living room, ductless suitable capacity ASHP configuration.



Note: This figure shows the percentage of annual hours with the PMV between -0.5 and 0.5 in a MF unit living room. (n = 128 iterations each for ductless baseline and suitable capacity)

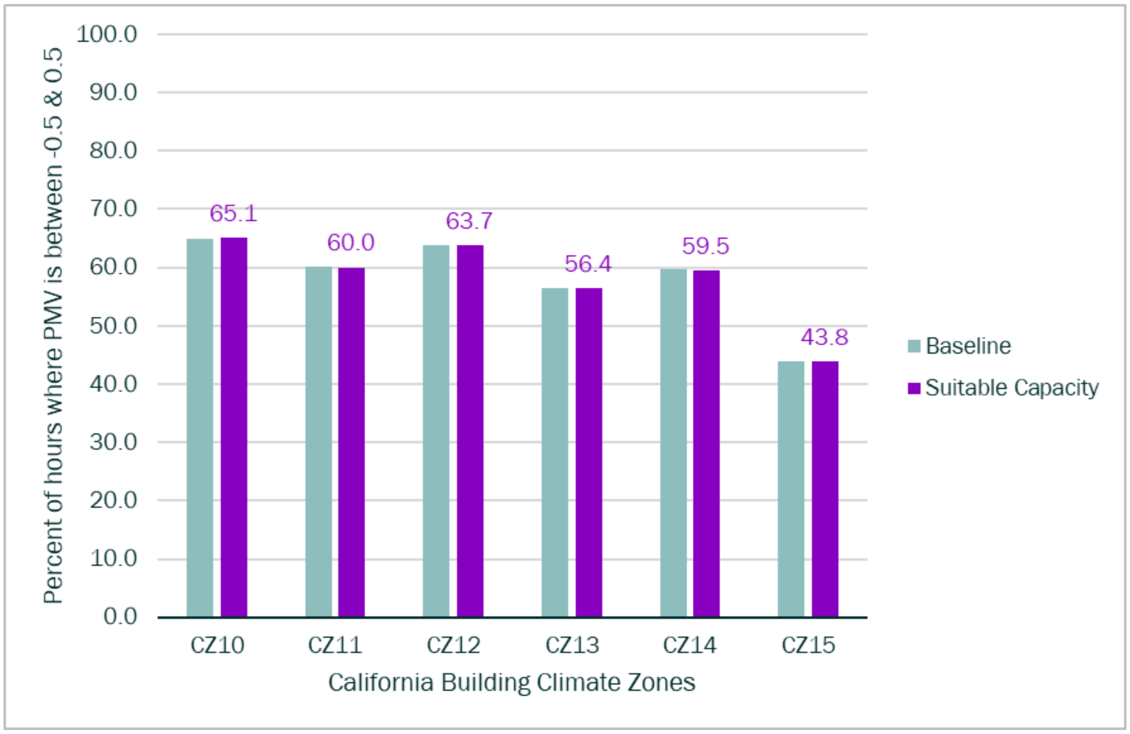
Figure 6: MF living room, ducted suitable capacity ASHP configuration.

For the purposes of this report, the project team selected a representative MF iteration for the suitable capacity configuration to further explain the trends. The iteration we selected was the pre-1978 MF north-facing upper corner unit. For this MF iteration, the suitable capacity configuration was only possible for ductless systems in Climate Zones 8 through 16, and for ducted systems in Climate Zones 10 through 16. For the other climate zones, the baseline system used the smallest ASHP available on the market, so the system size could not be reduced. For the iteration and climate zones shown in Figure 7Figure 7, the project team reduced the ASHP system capacity by 0.5 tons from the baseline to the suitable capacity configuration. The figure shows occupant comfort in the living room, which is the largest space in the MF unit.

For this iteration, the annual hours in the targeted PMV is between 44 and 70 percent, depending on the climate zone. The occupant comfort in the suitable capacity configuration closely follows the baseline configuration, which means that occupant comfort is not affected by the reduced capacity ASHP. This same trend is also followed by the ducted system in Figure 8. There is no significant difference between the suitable capacity and baseline configurations for ducted ASHP systems.

Note: This figure shows the percentage of annual hours with the PMV between -0.5 and 0.5 for a MF north-facing upper corner unit living room with the door open.

Figure 7: Pre-1978 MF unit with ductless suitable capacity ASHP configuration.

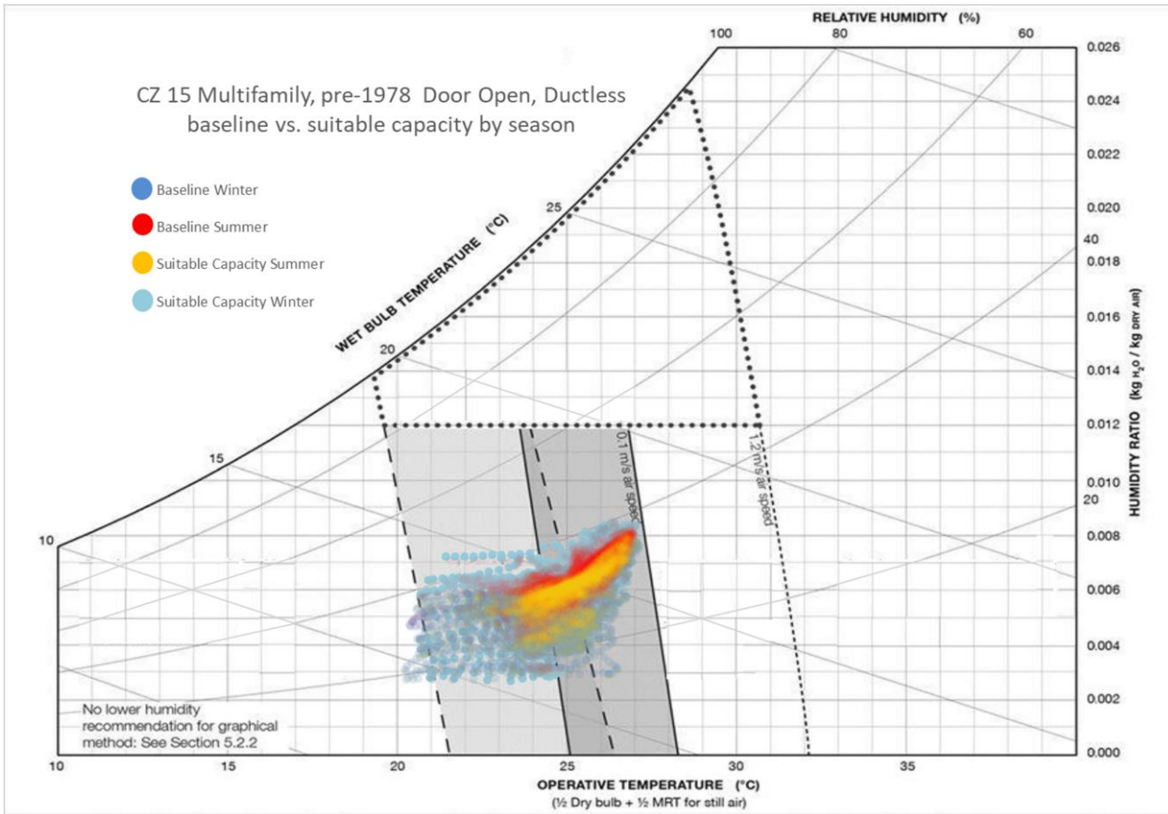


Note: This figure shows the percentage of annual hours with the PMV between -0.5 and 0.5 in a MF north-facing upper corner unit living room with the door open.

Figure 8: Pre-1978 MF unit with a ducted suitable capacity ASHP configuration.

The project team also modeled passive air flow through the space with two air flow assumptions, door opened or closed. Again, there was no difference in thermal comfort in the living room between the doors in apartment being opened or closed, nor was there a difference in the orientation of the MF unit. The suitable capacity ASHP was able to provide occupant thermal comfort across all orientations. For additional graphs, see Appendix ASuitable Capacity Configuration Supplemental Figures.

Figure 9 shows space temperatures at each hour of the year for the living room of the north-facing upper corner MF unit, located in Climate Zone 15 and built pre-1978, with the door open and a ductless ASHP system, for both the baseline and suitable capacity systems, on a psychrometric chart. Climate Zone 15 was selected because it has the overall lowest number of annual hours where the PMV was between -0.5 and 0.5. The space temperatures in both the baseline and suitable capacity systems are within the summer and winter comfort zones for almost all hours of the year. Therefore, occupant thermal comfort is maintained with the suitable capacity system.



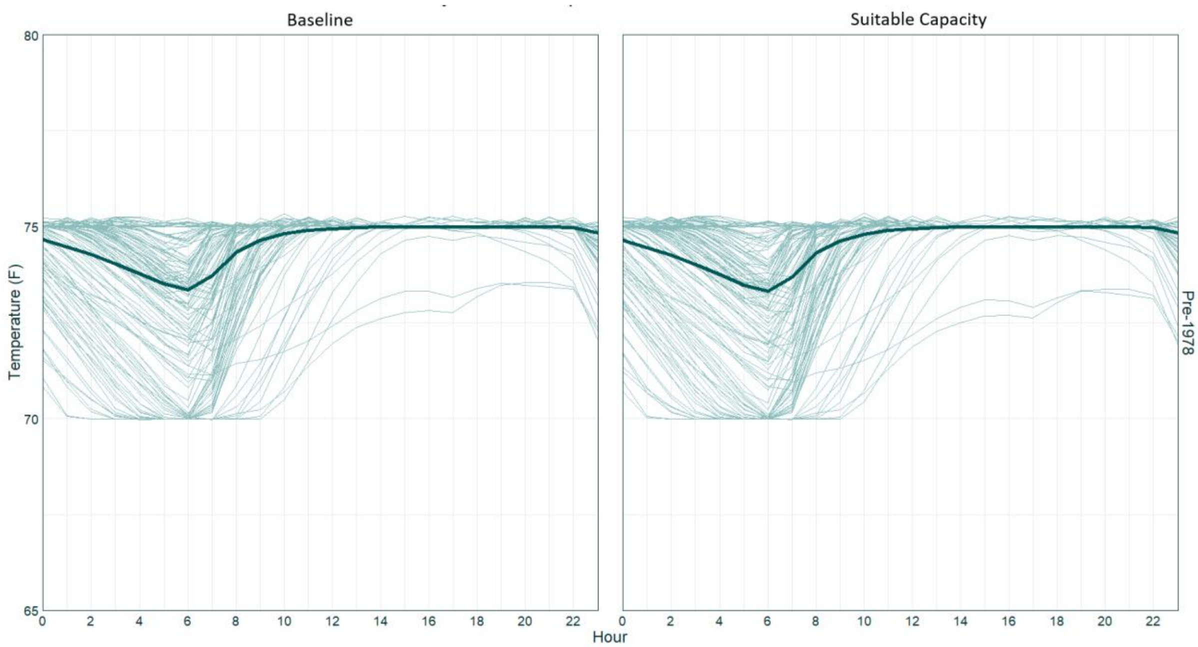
Note: For both the baseline and suitable capacity configuration, this shows the living room of a MF north-facing upper corner unit with the door open.

Figure 9: Psychrometric chart of a pre-1978 MF unit with a ductless suitable capacity ASHP configuration, compared to a baseline configuration in Climate Zone 15.

The project team used an additional simplified method to further demonstrate that occupant thermal comfort is maintained in the suitable capacity ASHP system configuration. Reaching this finding required the team to analyze the data by plotting the ambient air temperature for the baseline ASHP configuration and the suitable capacity system. Figure 10 plots the daily ambient air temperature during the winter months (September 21 through March 20), and Figure 11

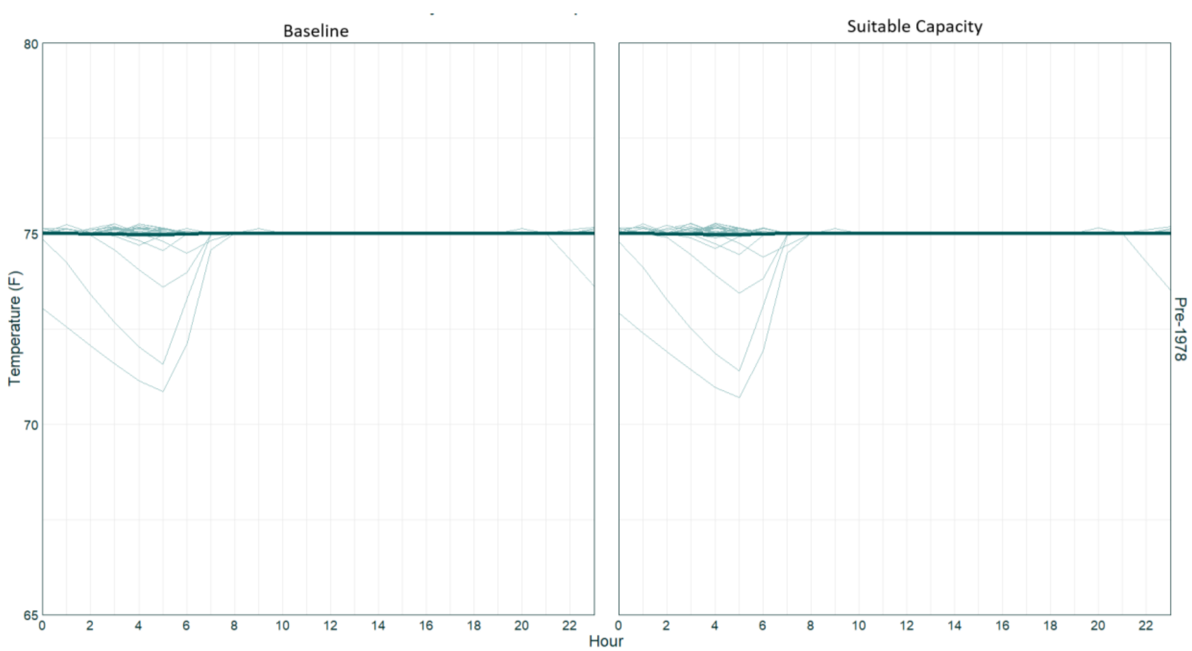
Note: This pre-1978 MF unit living room is in a north-facing upper corner unit with the door open.

Figure 11plots the daily ambient air temperatures during the summer months (March 21 through September 20). Each light green line represents a day in the year, and the dark green line is the average across the season. For the same upper corner MF unit built pre-1978 with the door open and a ductless suitable capacity ASHP system, the ambient air temperature in the space is maintained between 70°F and 75°F. There is no significant difference in ambient air temperature in the living room between the baseline and suitable capacity configuration.



Note: This pre-1978 MF unit living room is in a north-facing upper corner unit with the door open.

Figure 10: Ambient air temperature during the winter months in a MF unit with a ductless suitable capacity ASHP configuration compared to a baseline configuration in Climate Zone 15.



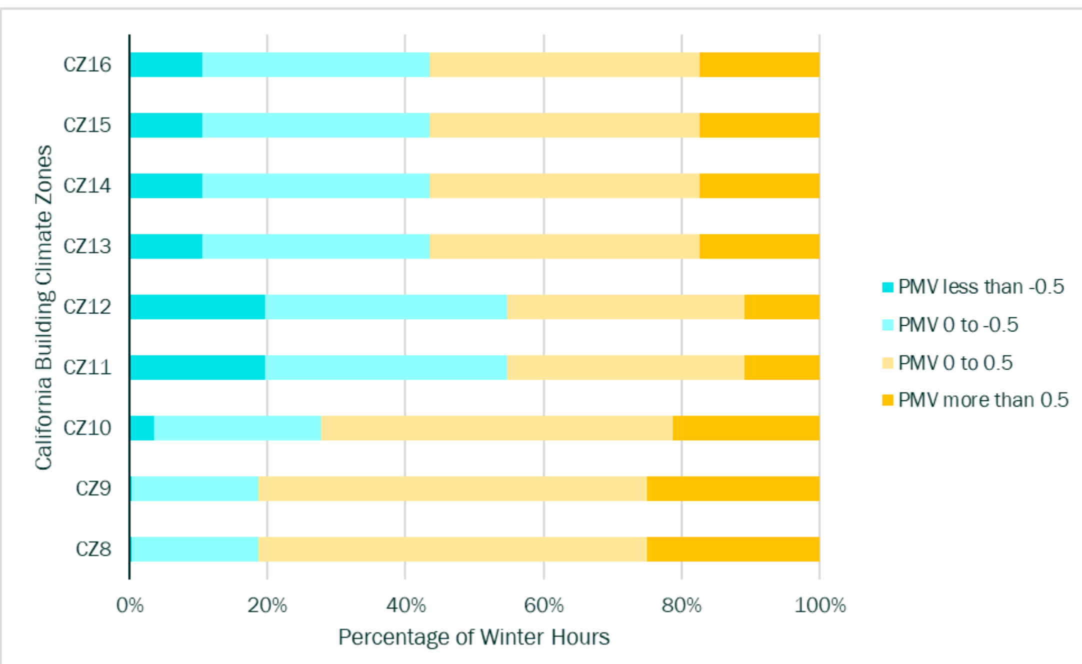
Note: This pre-1978 MF unit living room is in a north-facing upper corner unit with the door open.

Figure 11: Ambient air temperature during the summer months in a MF with a ductless suitable capacity ASHP configuration, compared to a baseline configuration in Climate Zone 15.

Although there is little difference in thermal comfort between the suitable capacity configuration and the baseline configuration, the overall percentage of hours within the -0.5 to 0.5 PMV range is low, less than 80 percent. This is a result of the mean radiant temperature input in the thermal comfort model, which accounts for the radiant temperature of the surfaces within the space, such as the windows and walls. The unit vintage is pre-1978, so the envelope is leakier than a newer build and occupants are more affected by the exterior temperatures.

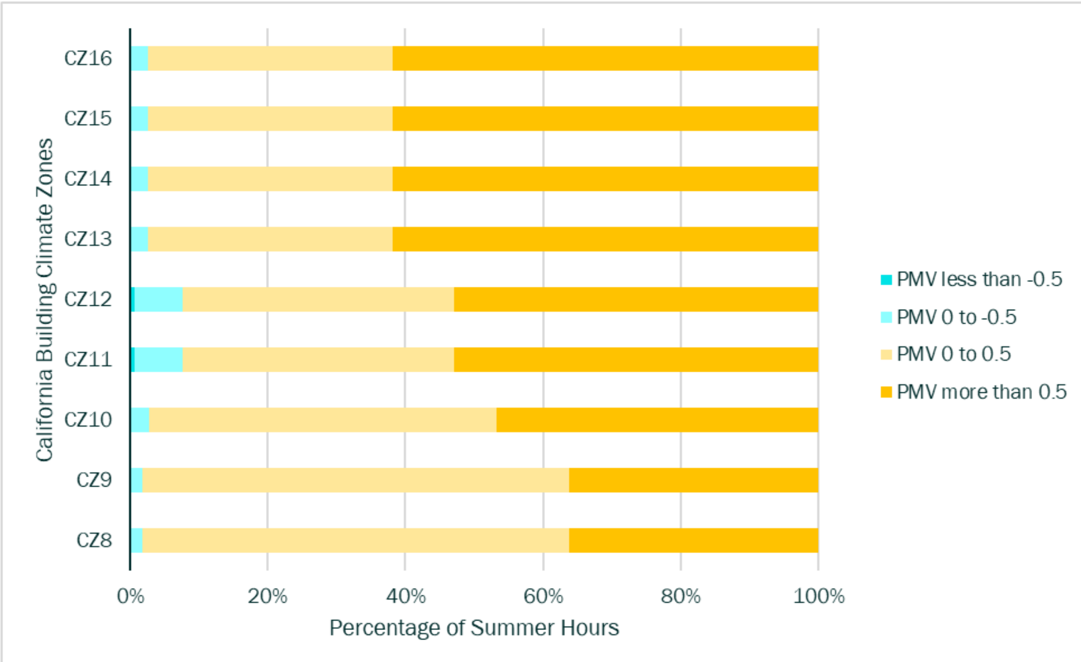
Occupants typically feel warm during the summer months when the exterior temperatures are higher, and cool during the winter months when the exterior temperatures are colder. Figure 12 shows the percentage of hours during the winter months (September 21 through March 20) and Figure 13 shows the percentage of hours during the summer months (March 21 through September 20), when the PMV is less than or greater than 0.

When the PMV is less than 0, occupants feel slightly cool (0 to -0.5 PMV) or cool (less than -0.5 PMV), as represented by the blue bars. When the PMV is greater than 0, occupants feel slightly warm (0 to 0.5 PMV) or warm (greater than 0.5 PMV), as represented by the orange bars. The light orange and light blue bars represent slight discomfort, since the PMV is still within the -0.5 and 0.5 comfort range. The hours occupants feel cool increases in the winter months and decreases in the summer months; as expected, occupants are typically warm during the hottest hours of the day in the late afternoon and early evening hours, and cool during the coldest hours of the day in the early morning hours.



Note: This figure shows the percentage of annual hours where PMV is less than 0 or more than 0 in a MF north-facing upper corner unit living room with the door open.

Figure 12: Pre-1978 MF unit living room with a ductless ASHP during the winter months.

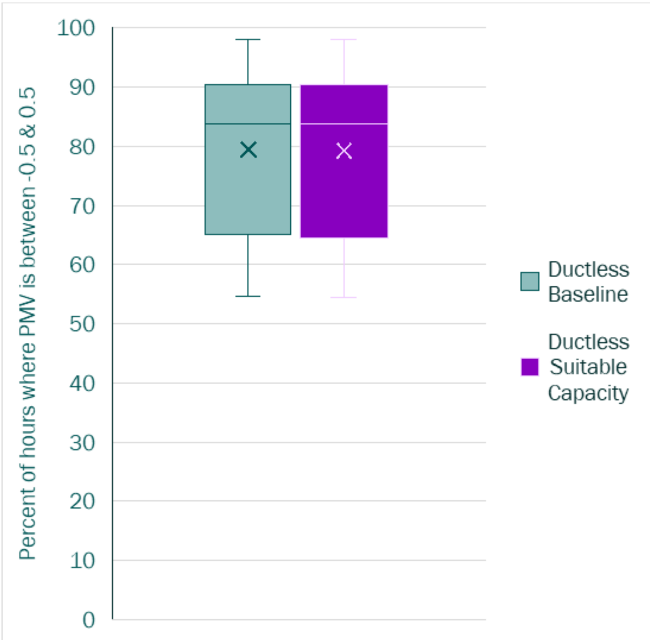


Note: This figure shows the percentage of annual hours where PMV is less than 0 or more than 0 in a MF north-facing upper corner unit living room with the door open.

Figure 13: Pre-1978 MF unit living room with a ductless ASHP during the summer months.

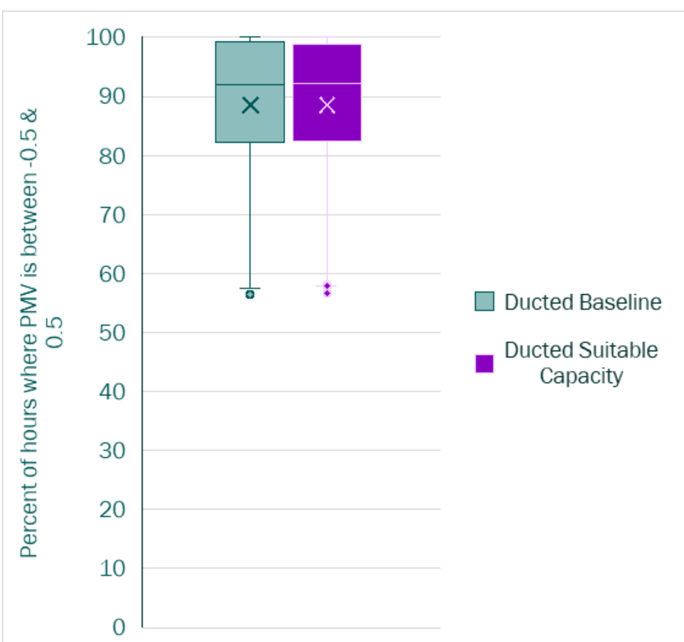
SINGLE-FAMILY

To review the SF building iterations, the project team again calculated the percentage of hours throughout the year within the PMV range of -0.5 to 0.5. We compared the baseline and suitable capacity ASHP configurations and found similar trends across iterations. Figure 14 and Figure 15Figure 15 show the percentage of annual hours where the PMV is within the -0.5 to 0.5 comfort range for ductless and ducted systems respectively. Similar to the MF prototype, there is very little difference in occupant thermal comfort between the baseline and suitable capacity ASHP configurations. Note that there are overall less iterations in the ductless distribution in Figure 14 (136 iterations) compared to the ducted distribution in Figure 15 (384 iterations) because only suitable capacity configurations were evaluated and not combination configurations.



Note: This figure shows the percentage of annual hours with the PMV between -0.5 and 0.5 in a SF unit living room. (n = 136 iterations each for ductless baseline and suitable capacity)

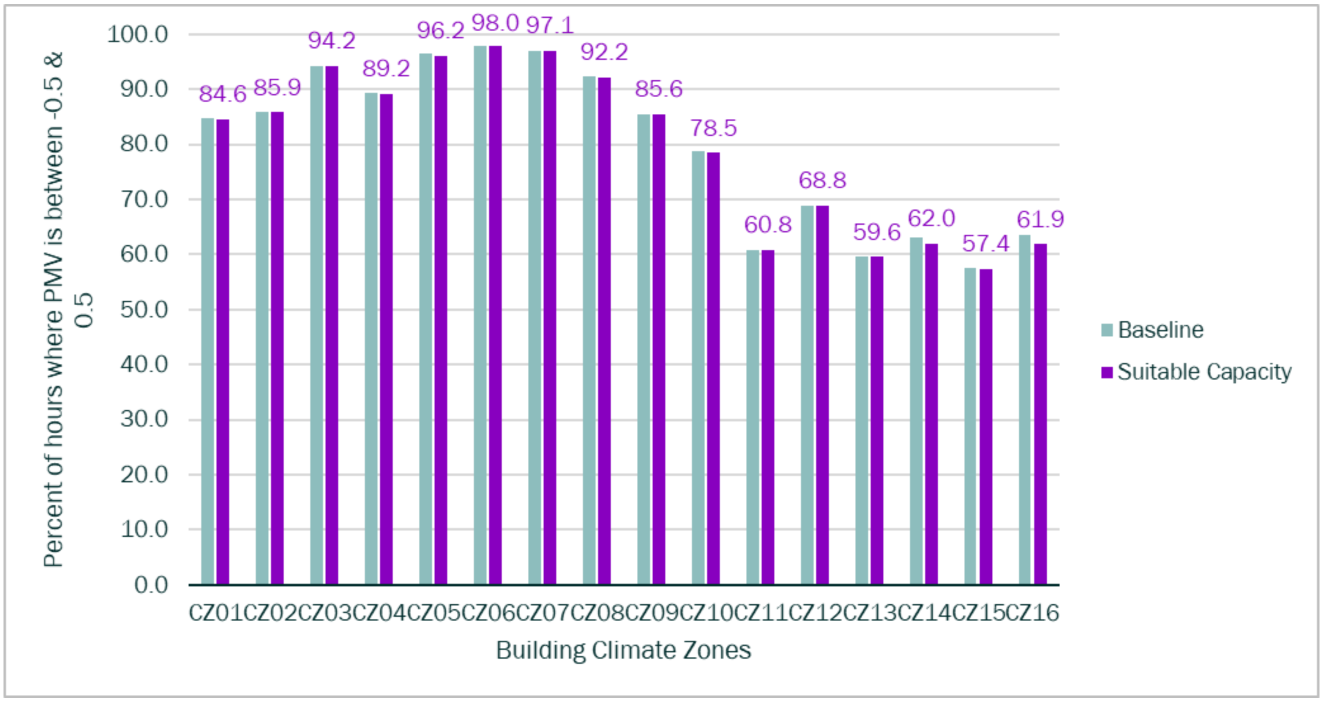
Figure 14: SF living room, ductless suitable capacity ASHP configuration.



Note: This figure shows the percentage of annual hours with the PMV between -0.5 and 0.5 in a SF unit living room. (n = 384 iterations each for ducted baseline and suitable capacity)

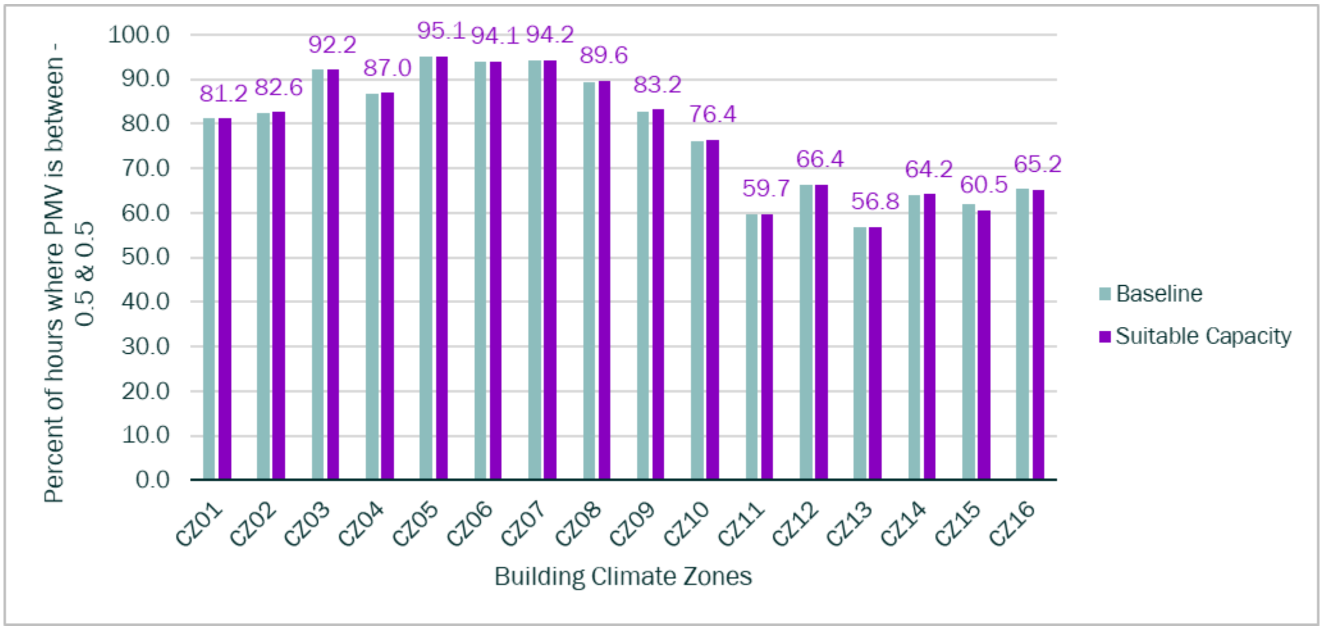
Figure 15: SF living room, ducted suitable capacity ASHP configuration.

To demonstrate the suitable capacity configuration trends, the project team selected a representative iteration: the north-facing SF living room with the doors open. Figure 16 and Figure 17 show the percent of hours where PMV is between -0.5 and 0.5 in this SF iteration for ductless and ducted systems, respectively. For these iterations, the project team reduced the suitable capacity system capacity from between 0.5 to 1.5 tons from the baseline system capacity. Similar to the MF home, the occupant comfort in the suitable capacity configuration closely follows the baseline configuration, meaning that occupant comfort is not affected by the reduced capacity ASHP.



Note: This figure shows the percentage of annual hours with the PMV between -0.5 and 0.5 for a SF north-facing living room with the door open.

Figure 16: Pre-1978 SF home with a ductless suitable capacity ASHP configuration.

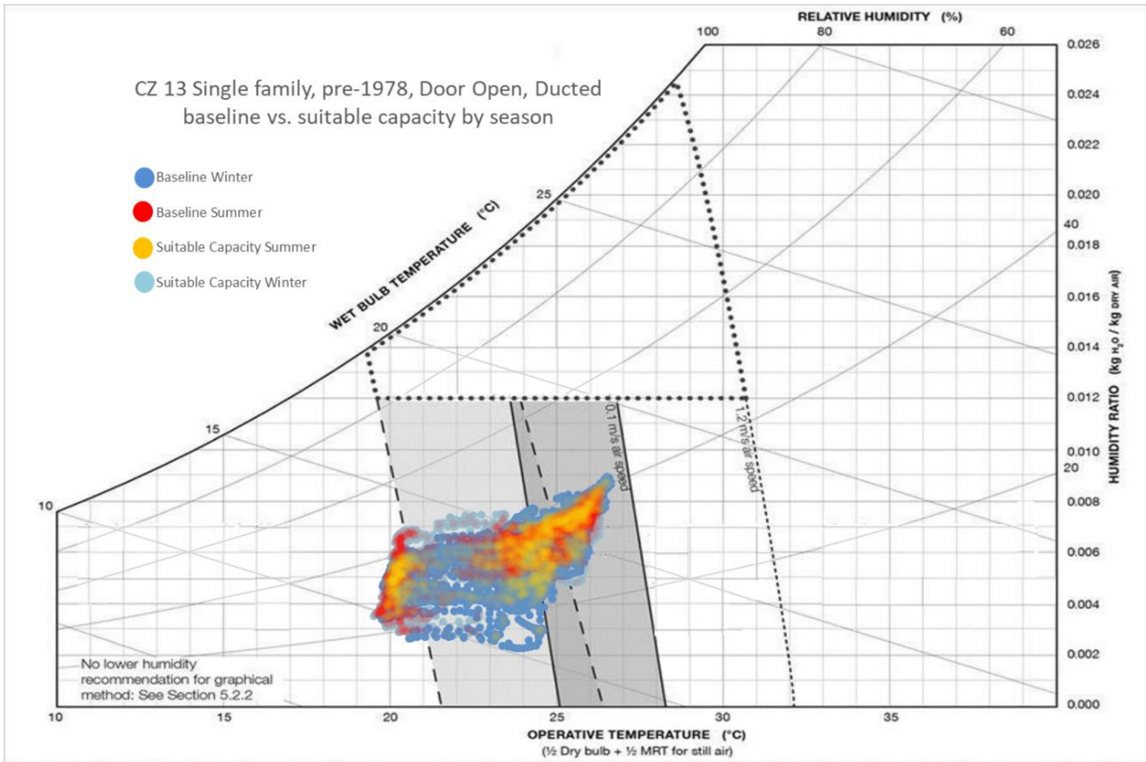


Note: This figure shows the percentage of annual hours with the PMV between -0.5 and 0.5 for a SF north-facing living room with the door open.

Figure 17: Pre-1978 SF with a ducted suitable capacity ASHP configuration

The project team reviewed and compared the iterations with the door open versus door closed, as well as iterations across vintages and orientation, and found no significant difference in occupant thermal comfort between the baseline and suitable capacity ASHP configurations. For supplemental figures, see Appendix A.

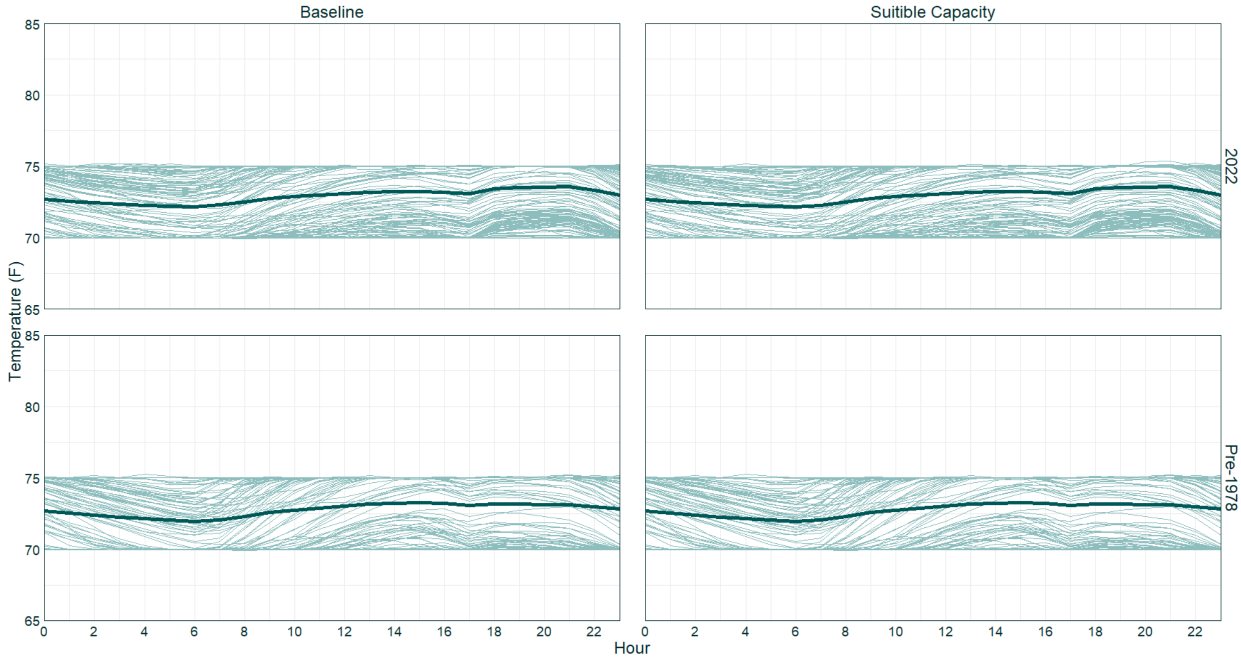
Figure 18 shows the space temperatures at each hour of the year for the living room of the SF north-facing home located in Climate Zone 13, built pre-1978, with the door open and a ducted ASHP system, for both the baseline and suitable capacity systems, on a psychrometric chart. Climate Zone 13 was selected because it has the overall lowest number of annual hours where the PMV is between -0.5 and 0.5. The space temperatures in both the baseline and suitable capacity systems stay within the summer and winter comfort zones for the majority of the hours in the year. They do fall out of the comfort zone for some hours in the year, but this occurs equally for both the baseline and suitable capacity systems. This is most likely a result of the pre-1978 home vintage with an overall poor envelope and not the suitable capacity ASHP configuration. Therefore, we can conclude that the suitable capacity ASHP configuration maintains the same level of occupant comfort as the baseline ASHP system configuration.



Note: For both the baseline and suitable capacity configuration, this shows the living room of a SF north-facing home with the door open.

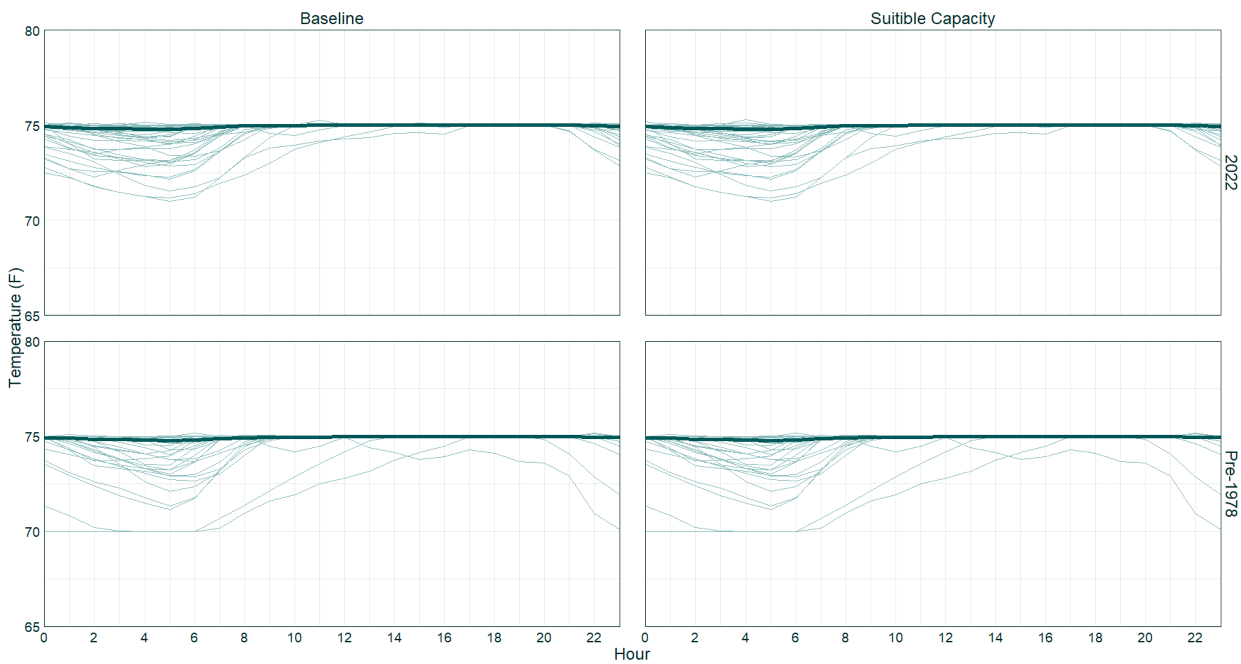
Figure 18: Psychrometric chart of a pre-1978 SF home with a ducted suitable capacity ASHP configuration compared to a baseline configuration in Climate Zone 13.

The project team used an additional simplified method to further demonstrate that the suitable capacity system configuration can maintain ambient air temperature and therefore occupant comfort as well as the baseline configuration. Reaching this finding required the team to review the ambient air temperature in the living room between the suitable capacity and baseline configurations. Figure 19 plots the living room daily ambient air temperature during the winter months (September 21 through March 20) and Figure 20 plots the daily ambient air temperatures during the summer months (March 21 through September 20). Each light green line represents a day in the year, and the dark green line is the average across the season. For the SF north-facing home in Climate Zone 13 with the door open and a ducted ASHP system, the ambient air temperature in the space is maintained between 70°F and 75°F for the baseline, and suitable capacity configurations in the 2022 and pre-1978 vintage homes. The pre-1978 vintage home represents a home with a leakier envelope, compared to a newer home built in 2022. There is no significant difference in ambient air temperature in the living room between the baseline and suitable capacity configuration. Additionally, the suitable capacity configuration can maintain the 70°F to 75°F ambient air temperature in both the leakier pre-1978 home and the tighter 2022 home.



Note: This SF home living room is in a north-facing home with the door open.

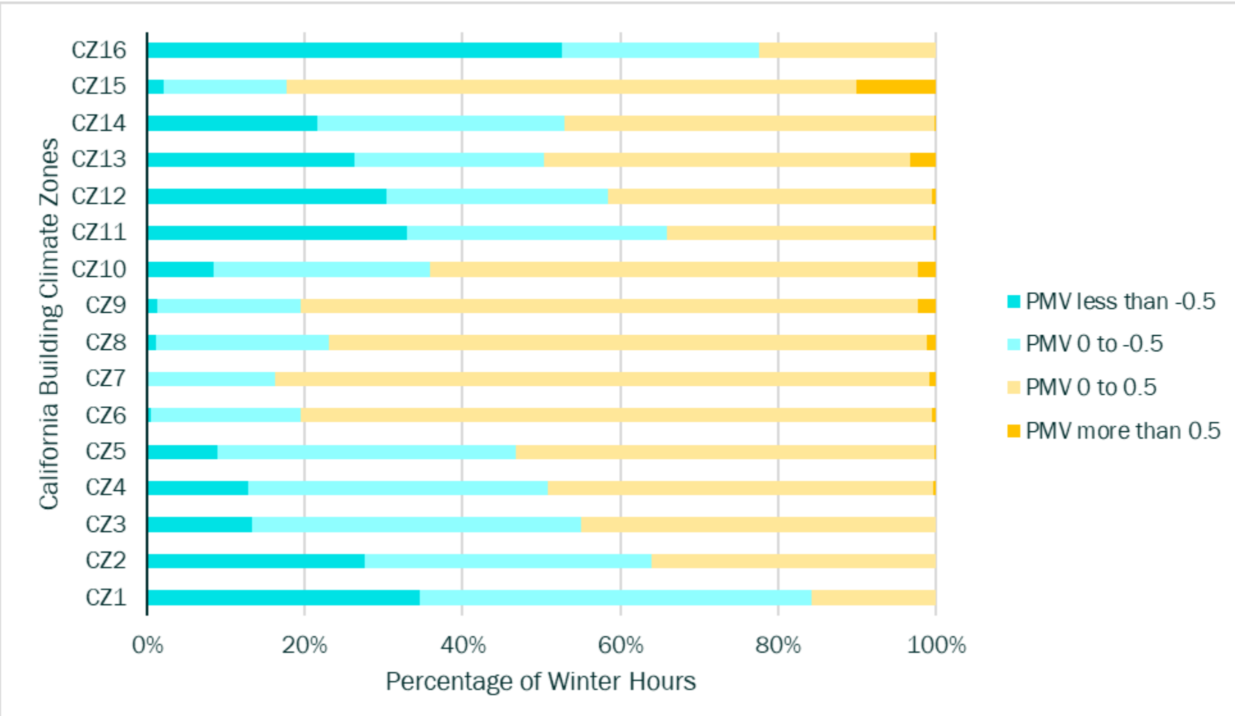
Figure 19: Ambient air temperature during the winter months in a SF home with a ducted suitable capacity ASHP configuration compared to a baseline configuration in Climate Zone 13.



Note: This SF home living room is in a north-facing home with the door open.

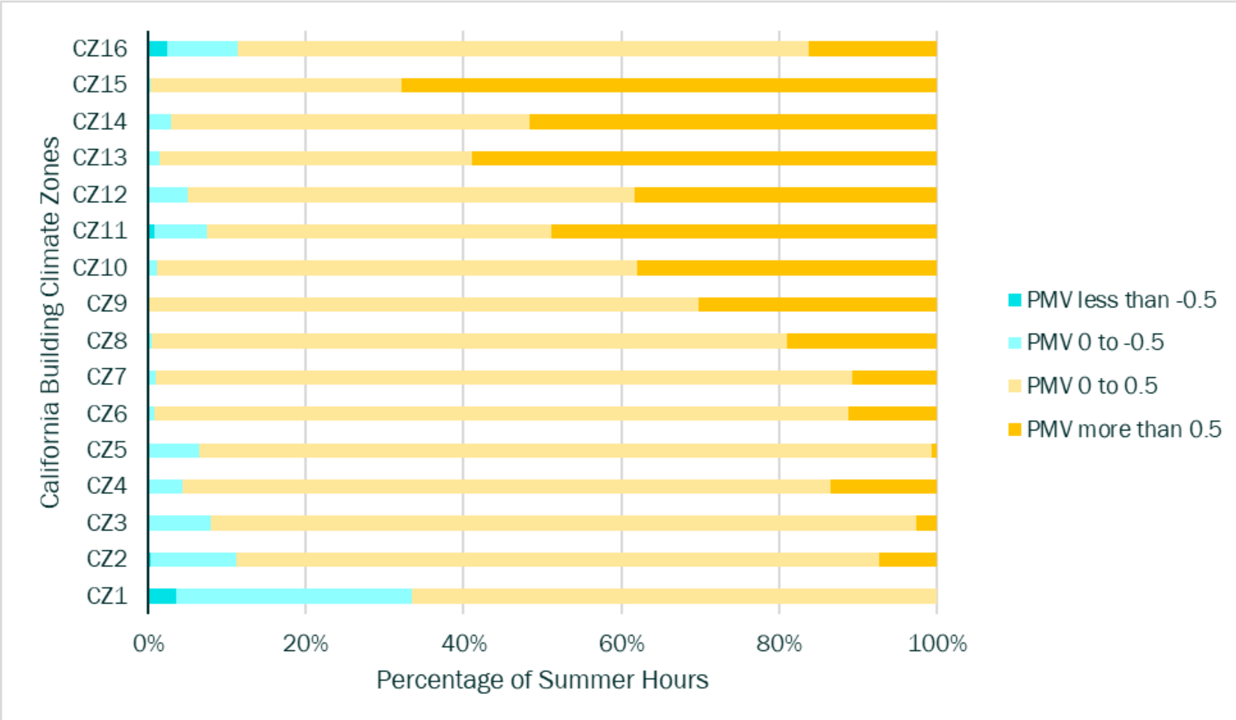
Figure 20: Ambient air temperature during the summer months in a SF home with ducted suitable capacity ASHP configuration, compared to a baseline configuration in Climate Zone 13.

In a pre-1978 SF home with a ducted suitable capacity ASHP configuration, occupants typically feel warm during the summer months when the exterior temperatures are higher and cool during the winter months when the exterior temperatures are colder. Figure 21 shows the percentage of hours during the winter months (September 21 through March 20) and Figure 22 shows the percentage of hours during the summer months (March 21 through September 20) when the PMV is less than or greater than 0. When the PMV is less than 0, occupants feel slightly cool (0 to -0.5 PMV) or cool (less than -0.5 PMV), as represented by the blue bars. When the PMV is greater than 0, occupants feel slightly warm (0 to 0.5 PMV) or warm (greater than 0.5 PMV), as represented by the orange bars. The light orange and light blue bars represent slight discomfort, since the PMV is still within the -0.5 and 0.5 comfort range. As expected, occupants are typically warm during the hottest hours of the day in the late afternoon and early evening hours, and cool during the coldest hours of the day in the early morning hours.



Note: This figure shows the percentage of annual hours where PMV is less than 0 or more than 0 in a SF north-facing living room with the door open.

Figure 21: Pre-1978 SF living room with a ducted ASHP during the winter months.



Note: This figure shows the percentage of annual hours where PMV is less than 0 or more than 0 in a SF north-facing living room with the door open.

Figure 22: Pre-1978 SF living room with a ducted ASHP during the summer months.

Indirect Coverage Configuration

The indirect system configuration is based on removing one supply unit from one space in the home. The project team found that the indirect coverage heat pump configuration provided some first-cost savings to occupants but also resulted in slight occupant thermal discomfort which can be mitigated by adjusting clothing levels or installing a transfer fan.

System Sizing

Similar to the suitable capacity configuration, after completing the Manual J heating and cooling home design load calculations for the MF and SF prototype homes, the project team found that some adjustments to ASHP system sizing were needed for the indirect coverage system configuration. As noted in the sizing methodology section, the directly conditioned spaces were reduced from three to one in the MF indirect coverage configuration. Approximately 44 percent of the 384 MF iterations required the outdoor cooling rated capacity to be reduced by 1,000 Btu; this was due to the different ASHP models available on the market and had no effect on first cost or occupant thermal comfort. Additionally, 2 percent of the 384 MF iterations resulted in a reduced capacity ASHP to properly condition the space, and 1 percent of the 384 MF iterations required an increase in capacity to properly condition the space. These cases are summarized in Appendix C but were not evaluated by the project team.

Similarly for SF, 17 percent of the 96 indirect coverage SF iterations required a reduced capacity heat pump from the baseline to properly condition the space and 4 percent of the 96 indirect coverage iterations required an increased capacity from the baseline configuration; these iterations are listed in Appendix C, but were not evaluated by the project team.

First Cost

The five contractors interviewed by the project team regarding indirect coverage ASHP system configurations noted that the first cost reductions would come from both labor and materials. They estimated a total reduction in costs between $2,000 and $6,000. For ductless systems, savings come from installing fewer heads than what might otherwise have been installed, at approximately $1,000 per head. The reduction in labor costs varied from contractor to contractor and ranged from $0 to $3,000.

In retrofit applications, there are no anticipated savings for ducted indirect coverage ASHPs because the ductwork is already installed. However, if the ductwork needs to be repaired, replaced, or added to, then there could be some first-cost savings. Careful evaluation of the ductwork should be considered to determine if the existing ductwork is appropriately sized for the indirect system configuration. Of the contractors the project team interviewed, two mentioned that complete ductwork replacement occurs roughly half of the time, and an additional three mentioned needing the full replacement around 10 to 15 percent of the time. Homes in need of ductwork replacement would be good candidates for the indirect coverage system configuration, as there may be cost savings with less ductwork to install. However, if supplemental ductwork is needed to ensure the system can handle capacity, this may add additional cost.

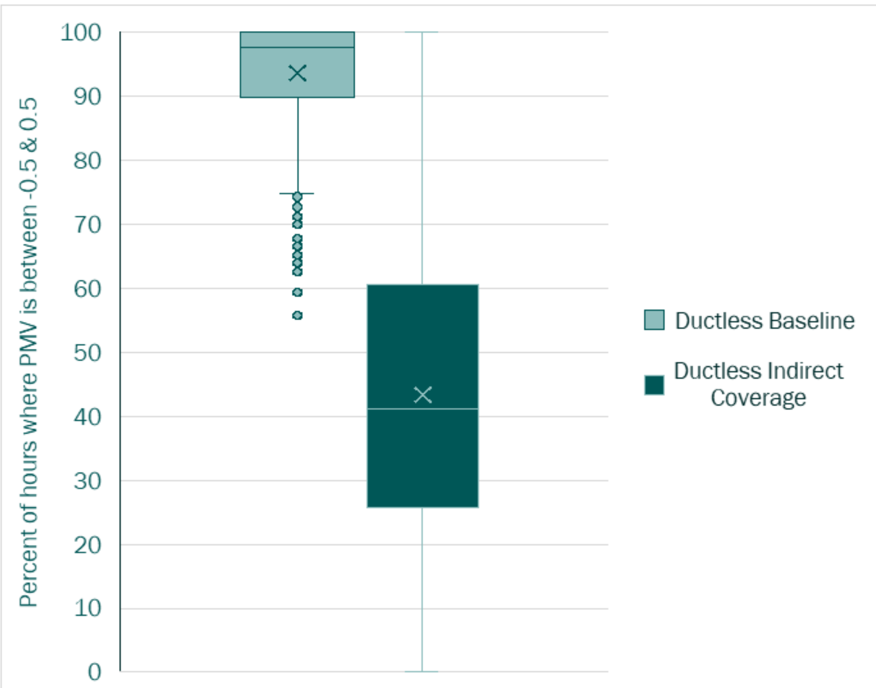
One of the contractors also noted that while indirect coverage can reduce upfront costs, it is often constrained by comfort expectations. They emphasized that using fewer heads requires careful design to ensure airflow and distribution still meet household needs, particularly in bedrooms or other high-use living spaces—which adds another layer of complexity that contractors may be inclined to avoid by simply using the standard number of heads normally required.

Thermal Comfort

After completing the thermal comfort modeling, the project team found that for the California building climate zones experiencing very high and low temperatures—Climate Zones 13, 14, 15, and 16—the indirect coverage system configuration produced conditions that did fall within the ASHRAE 55 comfort zones year-round. This could be mitigated with clothing adjustments or installing transfer fans. However, for homes located in the more moderate climate zones—Climate Zones 1, 3, and 5—the indirect coverage system configuration resulted in very little difference in occupant comfort compared to the baseline system configuration. The thermal comfort models also showed more occupant discomfort when the doors were closed, thus limiting air flow, and for older vintage homes with leakier building envelopes. These configurations may benefit from the use of a transfer fan to maintain occupant thermal comfort in spaces not receiving directly conditioned air. Therefore, the indirect coverage system configuration can be recommended for homes in moderate climate zones that have tight envelopes, while applications in other climate zones should be evaluated on a case-by-case basis.

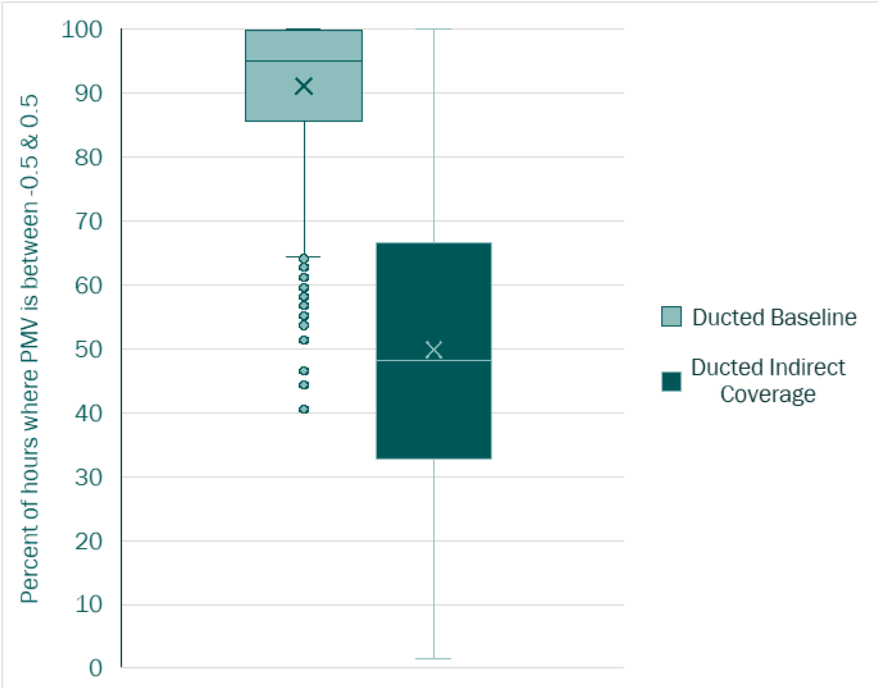
MULTIFAMILY

To compare across MF home prototype iterations, the project team again calculated the percentage of hours throughout the year that were within the predicted mean vote (PMV) of -0.5 to 0.5. The project team compared the baseline and indirect coverage ASHP configurations across the MF modeling iterations and found similar trends across iterations. The distribution of the percent of annual hours where PMV is between -0.5 and 0.5 for all the baseline and indirect coverage iterations in the MF prototype is shown in Figure 23 for ductless systems and Figure 24 for ducted systems. For the indirect system configuration, the annual percentage of hours within the comfort zone has a wider range and a lower mean compared with the baseline system. However, the data underlying the mean are less than one scale value on the 7-point PMV Likert scale (Thermal Comfort Modeling)—well within the comfort zone outside boundaries—which suggests any discomfort can be mitigated with minor clothing adjustments.



Note: This figure shows the percentage of annual hours with the PMV between -0.5 and 0.5 in a MF unit bedroom 2. (n = 1,448 iterations each for ductless baseline and indirect coverage)

Figure 23: MF bedroom 2, ductless indirect coverage ASHP configuration.

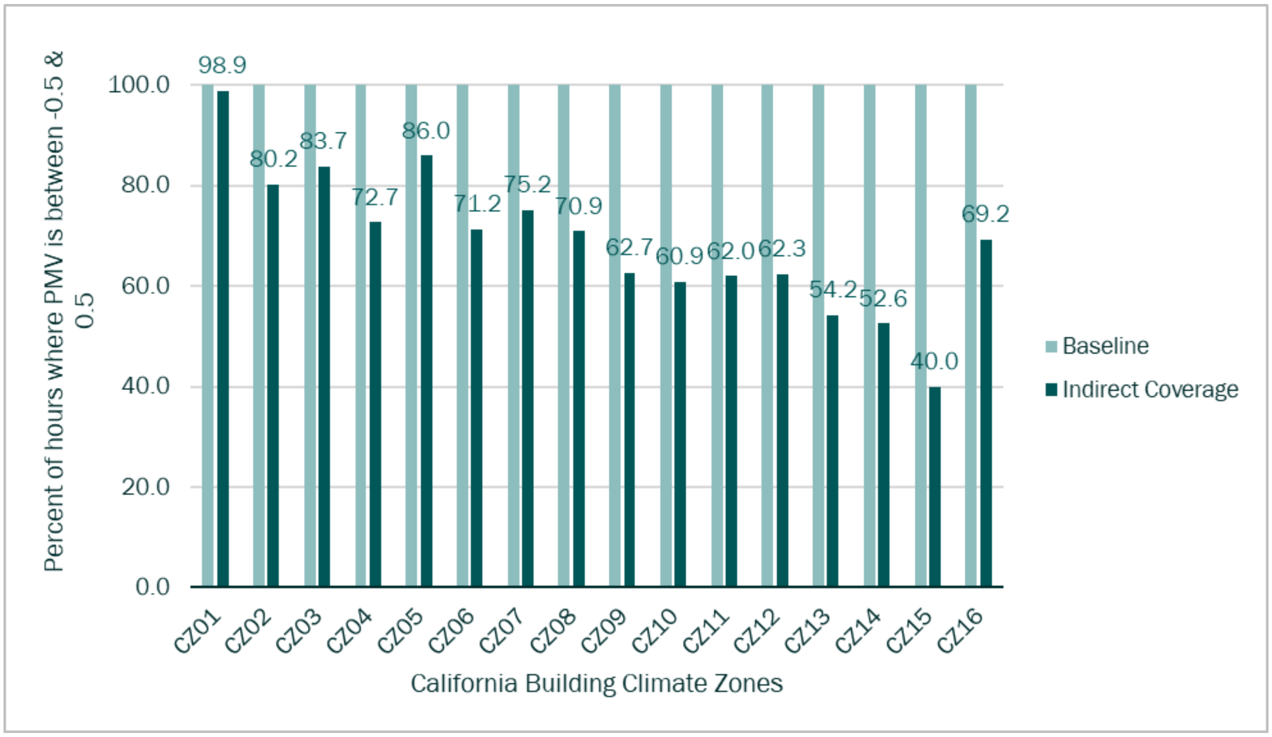


Note: This figure shows the percentage of annual hours with the PMV between -0.5 and 0.5 in a MF unit bedroom 2. (n = 1,536 iterations each for ducted baseline and indirect coverage)

Figure 24: MF bedroom 2, ducted indirect coverage ASHP configuration.

For the purposes of this report, the project team selected a representative MF iteration for the indirect coverage configuration to explain these trends. The iteration we selected was the 2022 MF north-facing middle-center unit with a ductless indirect coverage ASHP configuration. Figure 25 shows the percentage of hours where the PMV is between -0.5 and 0.5 for bedroom 2, which is not receiving directly conditioned air. There is a significant difference in occupant thermal comfort in the baseline configuration compared to the indirect coverage configuration, with significantly less thermal occupant comfort occurring in Climate Zones 13, 14, and 15. Climate Zone 15 experiences some of the hottest temperatures in California; it also had the least occupant thermal comfort for the indirect system configuration of all the California climate zones. However, this discomfort would likely be mitigated with occupant clothing adjustments.

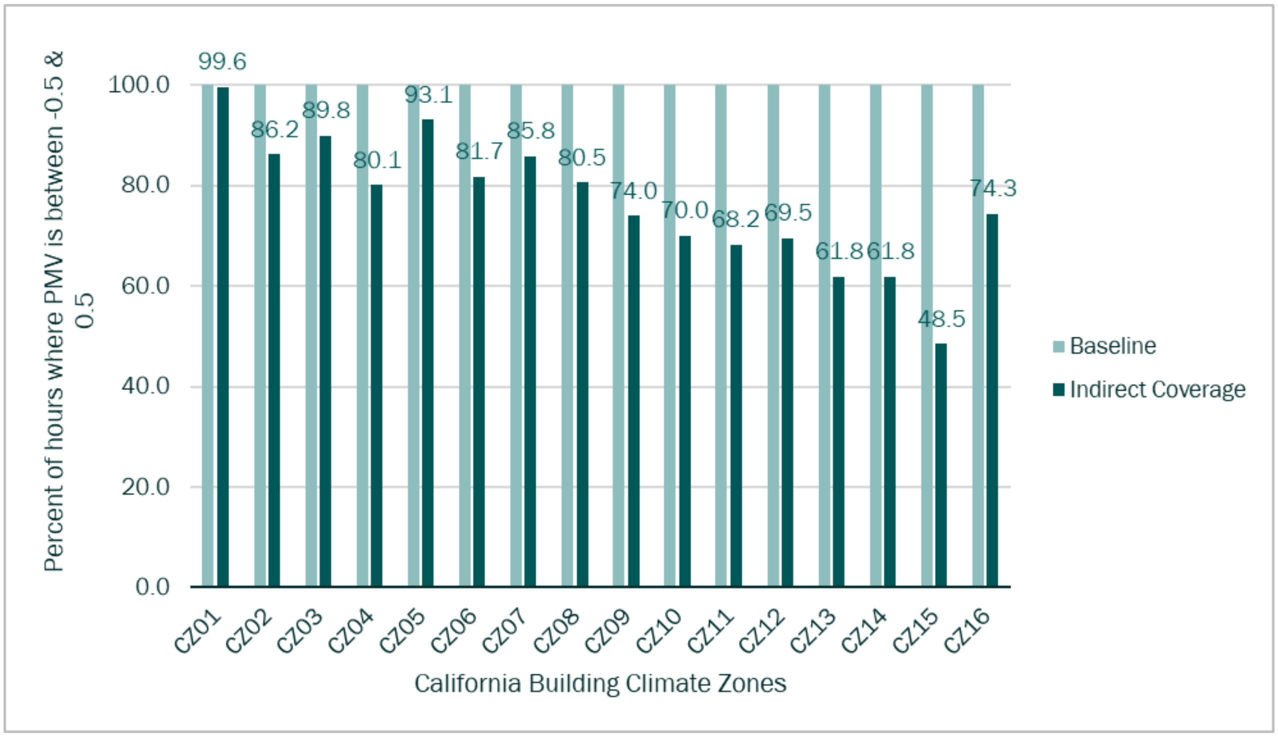
Homes located in Climate Zone 1 experienced the highest level of occupant thermal comfort, which more closely matched the baseline. The slightly cooler outside air temperatures in Climate Zone 1, between 32°F and 85°F, combined with the middle-center unit having warmer indoor air temperatures in general due to the position of the unit within the building, created the perfect case for the indirect coverage ASHP configuration. For the 2022 MF north-facing middle-center unit bedroom 2 with door open, the thermal occupant comfort would be met with the indirect coverage ASHP configuration.



Note: This figure shows the percentage of annual hours with the PMV between -0.5 and 0.5 for a MF north-facing upper corner unit bedroom 2 with the door open.

Figure 25: 2022 MF unit with a ductless indirect coverage ASHP configuration.

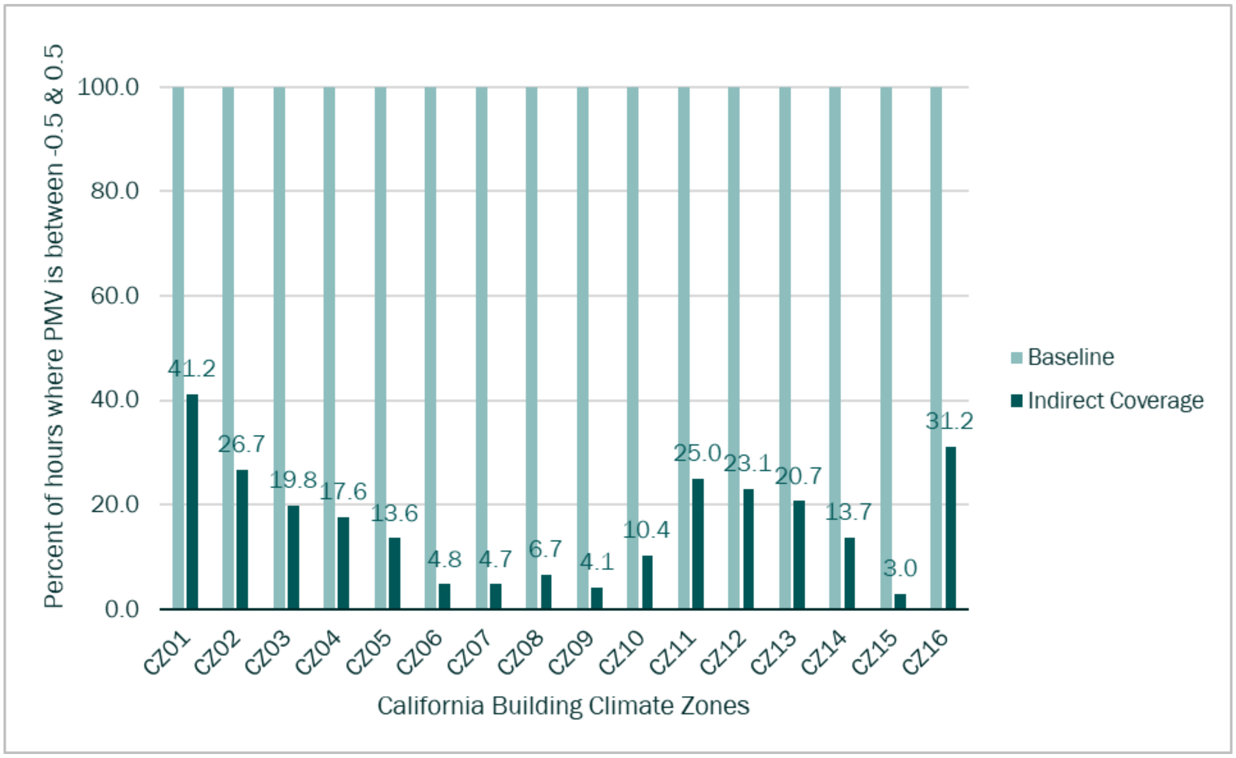
Figure 26 shows the percent of hours where the PMV is between -0.5 and 0.5 in the same MF north-facing middle-center unit, but with a ducted indirect coverage ASHP configuration. The occupant thermal comfort is slightly higher overall for the ducted ASHP system than the ductless system, with a range between 48 and 100 percent compared to the ductless range of 40 to 99 percent. However, a ductless system is estimated to save more first costs over a ducted system—hence the focus on the ductless indirect coverage configuration.



Note: This figure shows the percentage of annual hours with the PMV between -0.5 and 0.5 for a MF north-facing upper corner unit bedroom 2 with the door open.

Figure 26: 2022 MF unit with a ducted indirect coverage ASHP configuration.

In Figure 27, the same MF middle center unit is shown with the door closed. The occupant thermal comfort significantly decreases with the door closed to a range of 3 to 41 percent of annual hours between -0.5 and 0.5 PMV compared to the door open, which has a range of 40 to 99 percent in Figure 26. This finding supports the conclusion that a transfer fan can be an effective option for maintaining occupant comfort when designing an indirect coverage ASHP system configuration.

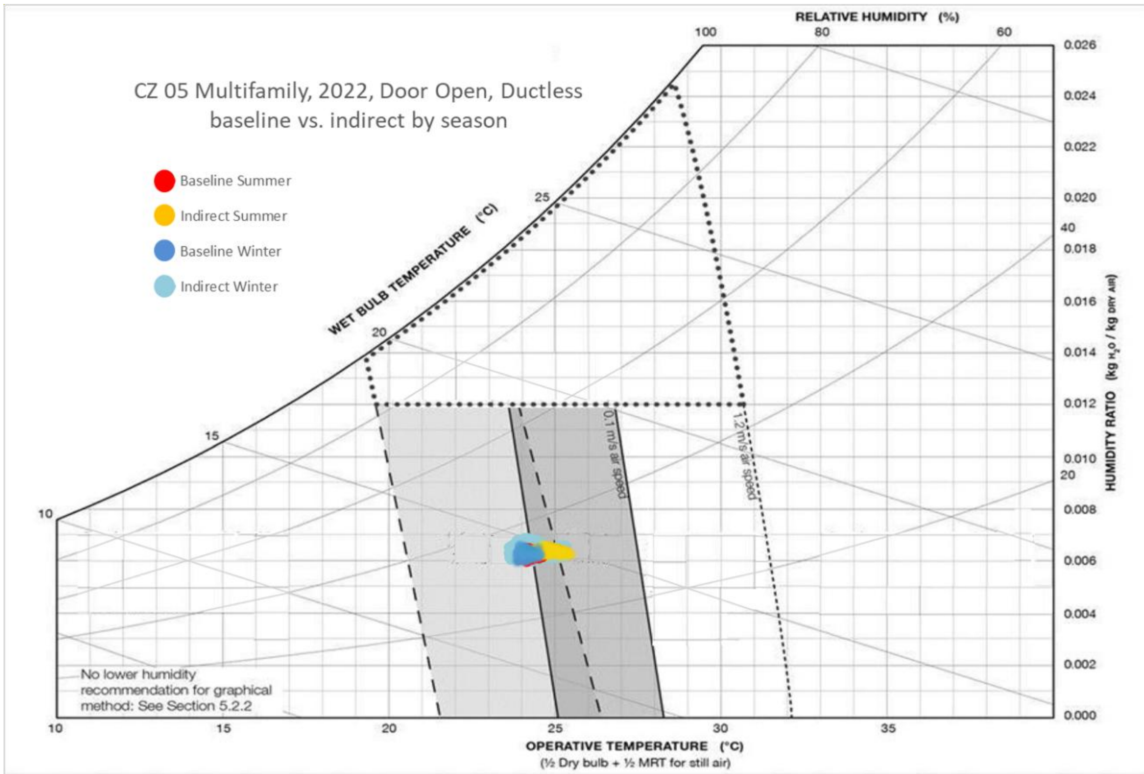


Note: This figure shows the percentage of annual hours with the PMV between -0.5 and 0.5 for a MF north-facing upper corner unit bedroom 2 with a ducted ASHP.

Figure 27: 2022 MF unit with a ducted indirect coverage ASHP configuration and the door closed.

Although not as significant as the door open versus door closed, the vintage and orientation of the unit also affect the occupant thermal comfort in the indirectly conditioned room. The tighter unit envelope in the 2022 vintage unit is better able to maintain occupant thermal comfort in bedroom 2 compared to the pre-1978 unit. Additionally, the orientation of the building also plays a role in occupant thermal comfort for the indirect coverage system configuration. When the indirectly conditioned room, bedroom 2, is in an orientation that is less affected by the exterior environment—e.g., west orientation—the room is better able to maintain occupant thermal comfort. For more information and additional figures, see Suitable Capacity Configuration Supplemental Figures.

For the indirect coverage system configuration, the space not receiving directly conditioned air should be carefully evaluated including the orientation of the room, home vintage, and susceptibility to exterior environmental conditions. Figure 28 shows the space temperatures at each hour of the year for bedroom 2 of the MF north-facing middle-center unit in Climate Zone 5, built in 2022, with the door open and a ductless ASHP system, for both the baseline and indirect coverage configurations, on a psychrometric chart. Climate Zone 5 was selected because it shows promising results for maintaining thermal occupant comfort. The results support that conclusion, the space temperatures in both the baseline and indirect coverage systems are within the summer and winter comfort zones for the whole year. Therefore, occupant thermal comfort is maintained with the indirect coverage ASHP system configuration in this MF unit.

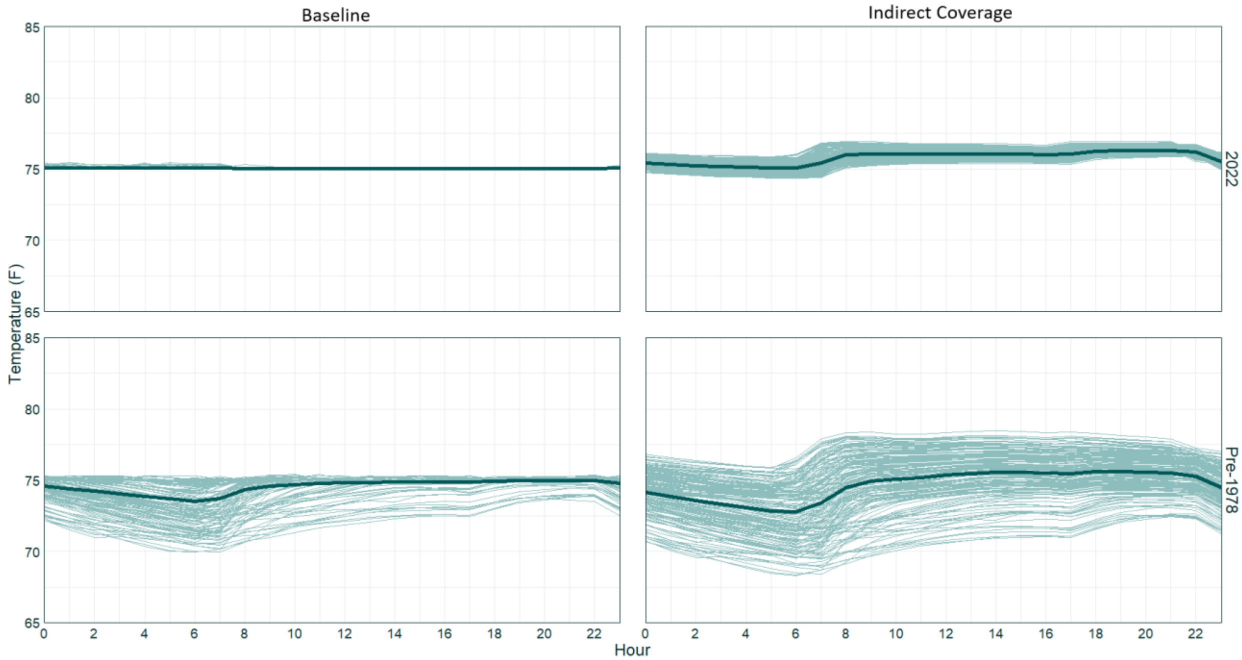


Note: For both the baseline and indirect coverage configuration, this shows the bedroom 2 of a MF north-facing middle-center unit with the door open.

Figure 28: Psychrometric chart of a 2022 MF with a ductless indirect coverage ASHP configuration compared to a baseline configuration in Climate Zone 5.

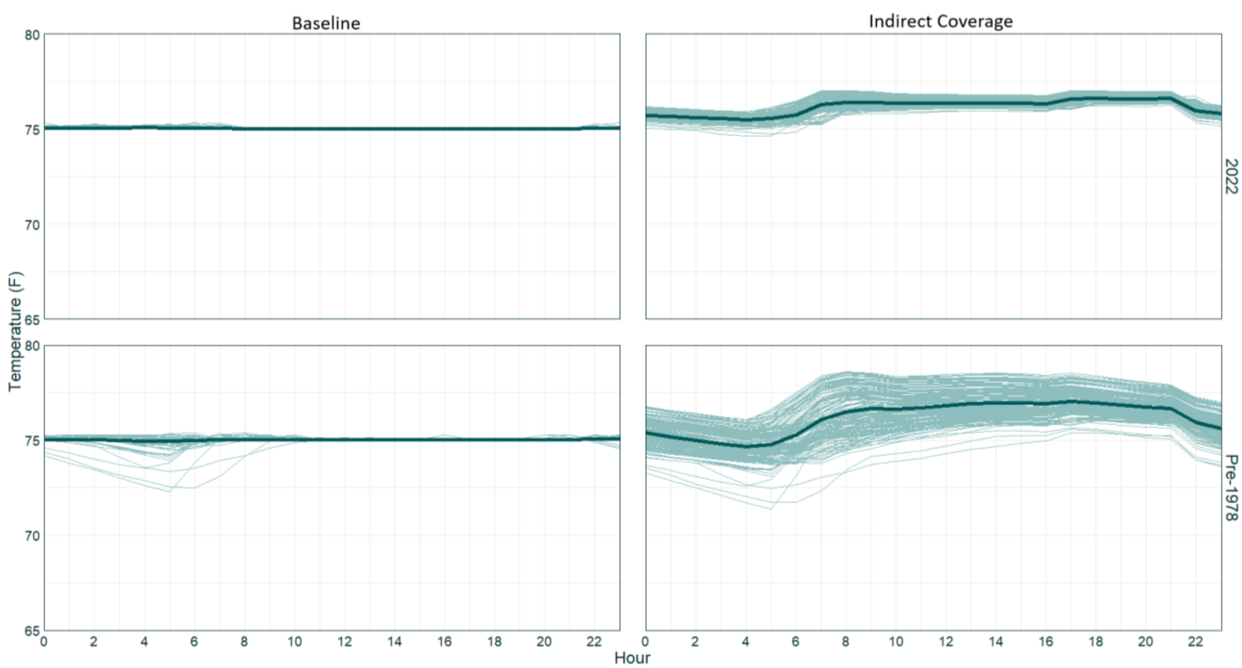
Another simplified way to look at the data is to plot the ambient air temperature for the baseline ASHP configuration and the indirect coverage system. For a representative case, the project team kept the same MF middle center unit facing north with the door open and a ductless system, and also chose the moderate Climate Zone 5, where the percentage of annual hours between -0.5 and 0.5 PMV was higher than some of the other climate zones. Figure 29 shows the ambient air temperature in bedroom 2 for the winter months (September 21 through March 20) and Figure 30 shows the ambient air temperature in bedroom 2 during the summer months (March 21 through September 20). Each light green line represents a day in the year, and the dark green line is the average for the season. The overall temperature range does not vary greatly. This is due to the position of the MF unit in the middle-center of the building, which was modeled with five adiabatic surfaces, a larger thermal mass heat storage, and a higher window-to wall ratio.

The home built in 2022 with the tighter envelope has a more controlled ambient temperature range than the home built pre-1978. However, the indirect coverage configuration cannot maintain the temperature in bedroom 2 between 70°F and 75°F like the suitable capacity configurations. The temperature range does not fall too far above 75°F or below 70°F, but this could cause thermal discomfort for some occupants but would likely be mitigated with clothing adjustments.



Note: This MF unit bedroom 2 is in a north-facing middle-center unit with the door open.

Figure 29: Ambient air temperature during the winter months in a MF unit with ductless indirect coverage ASHP configuration compared to a baseline configuration in Climate Zone 5.

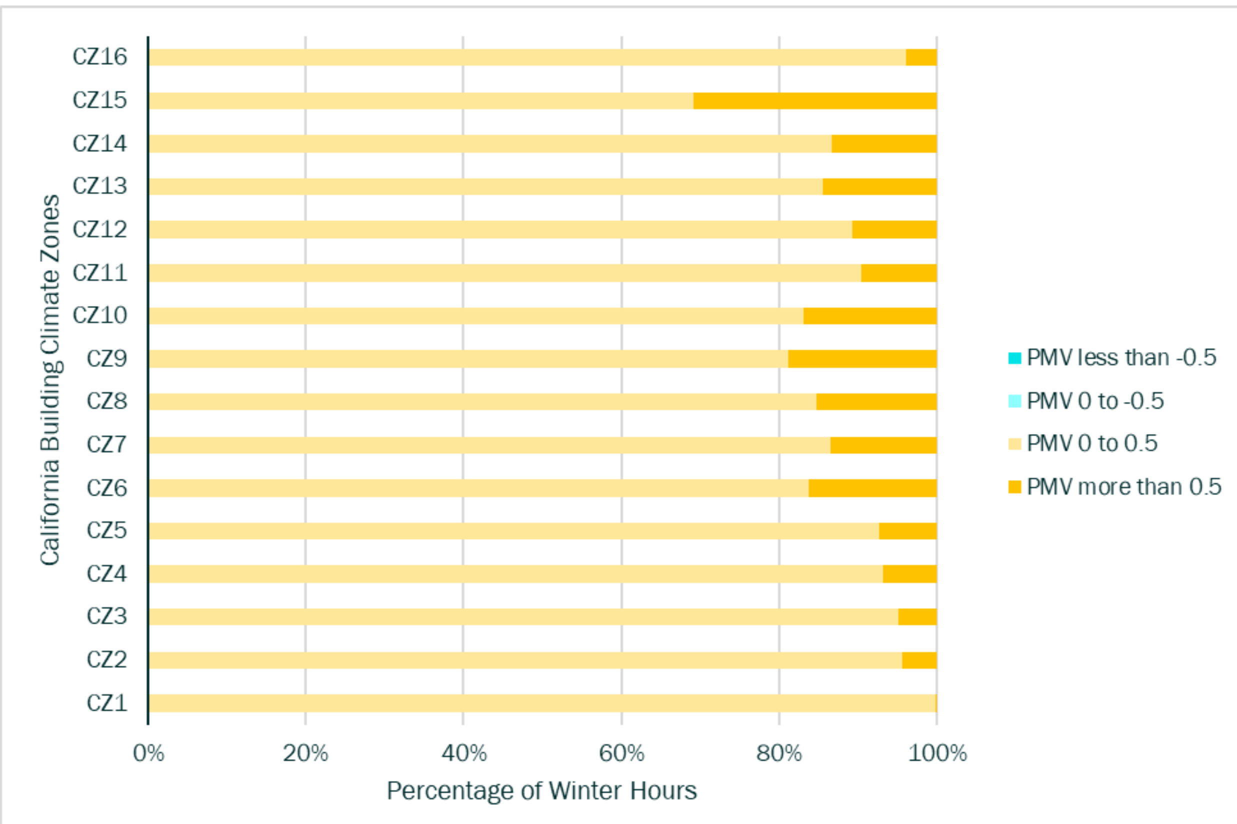


Note: This MF unit bedroom 2 is in a north-facing middle-center unit with the door open.

Figure 30: Ambient air temperature during the summer months in a MF unit ductless indirect coverage ASHP configuration compared to a baseline configuration in Climate Zone 5.

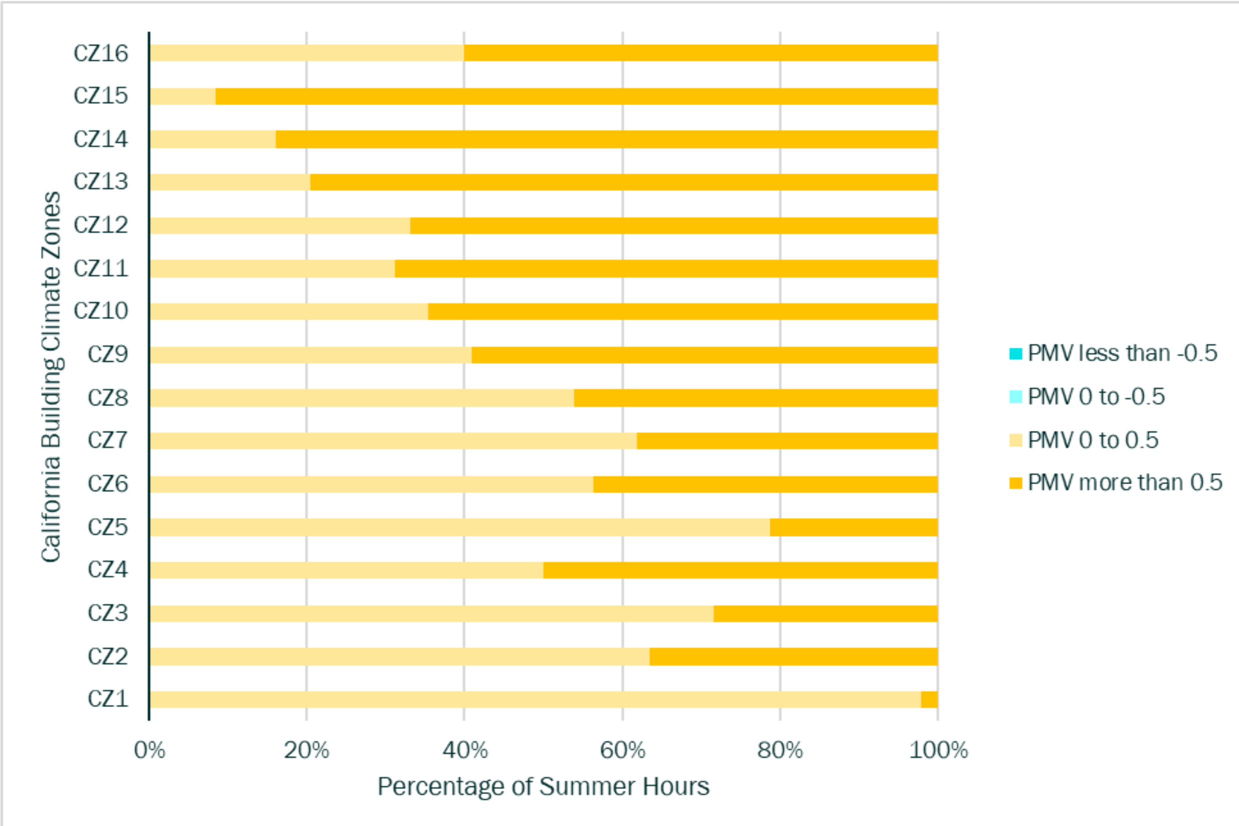
In the same 2022 north-facing MF middle-center unit with a ductless indirect coverage ASHP and the door open, occupants typically feel slightly warm throughout the year. Figure 31 shows the percentage of hours during the winter months (September 21 through March 20) and Figure 32 shows the percentage of hours during the summer months (March 21 through September 20) when the PMV is less than or greater than 0. When the PMV is greater than 0, occupants feel slightly warm (0 to 0.5 PMV) or warm (greater than 0.5 PMV), as represented by the orange bars. The light orange bars represent slight discomfort, since the PMV is still within the -0.5 and 0.5 comfort range.

There are little to no hours when occupants feel slightly cool (0 to -0.5 PMV) or cool (Less than -0.5 PMV) in this configuration. This is likely due to the adjacency of the middle center MF unit compared to other units in the building, resulting in a larger thermal mass for heat storage and the unit typically running warm overall. Bedroom 2 is typically warm for occupants throughout the day, but the hottest time of the day is midmorning, with the temperatures slowly decreasing until the evening and nighttime hours.



Note: This figure shows the percentage of annual hours where PMV is less than 0 or more than 0 in the bedroom 2 of a MF north-facing middle-center unit with the door open.

Figure 31: 2022 MF unit bedroom 2 with a ductless indirect coverage ASHP during the winter months.

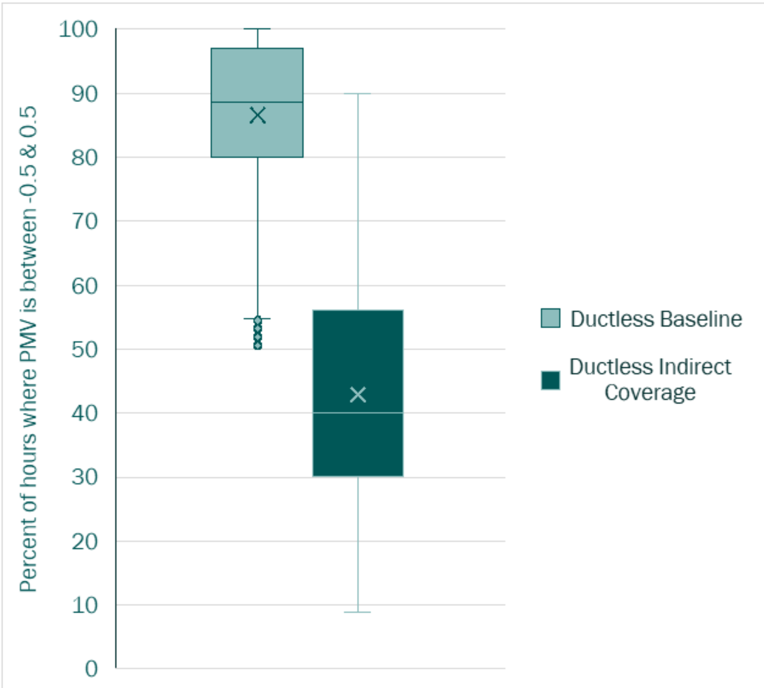


Note: This figure shows the percentage of annual hours where PMV is less than 0 or more than 0 in the bedroom 2 of a MF north-facing middle-center unit with the door open.

Figure 32: 2022 MF unit bedroom with ductless indirect coverage ASHP during the summer months.

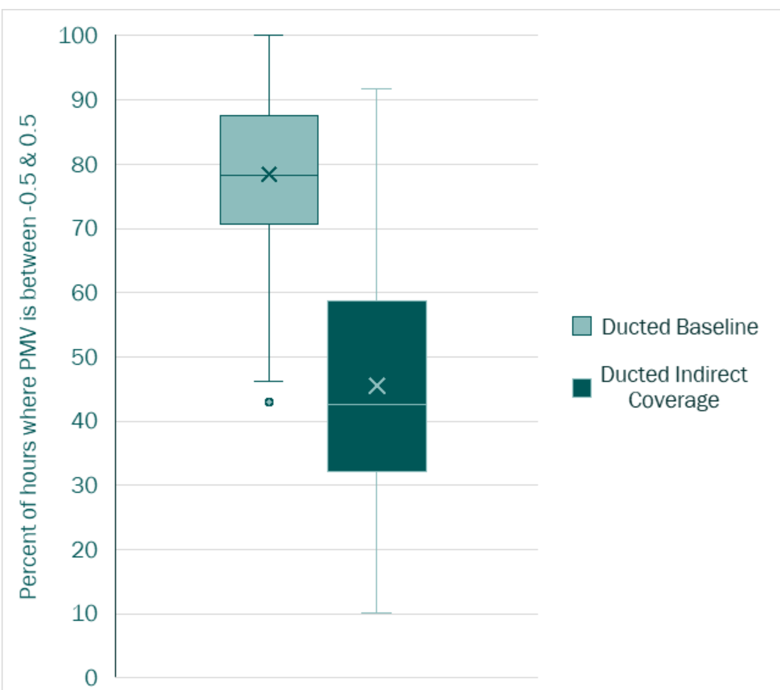
SINGLE-FAMILY

The project team found similar results for the SF prototype home. The distribution of the percentage of annual hours where the PMV was between -0.5 and 0.5 in the SF baseline and indirect coverage configurations is shown in Figure 33 for ductless and Figure 34 for ducted ASHP systems. As in the MF analysis, the annual percentage of hours within the comfort zone has a wider range and a lower mean in the indirect system configuration compared with the baseline system. However, the data underlying the mean are less than one scale value on the 7-point PMV Likert scale (Thermal Comfort Modeling)—well within the comfort zone outside boundaries—which suggests any discomfort can be mitigated with minor clothing adjustments.



Note: This figure shows the percentage of annual hours with the PMV between -0.5 and 0.5 in a SF unit bedroom 2. (n = 304 iterations each for ductless baseline and indirect coverage)

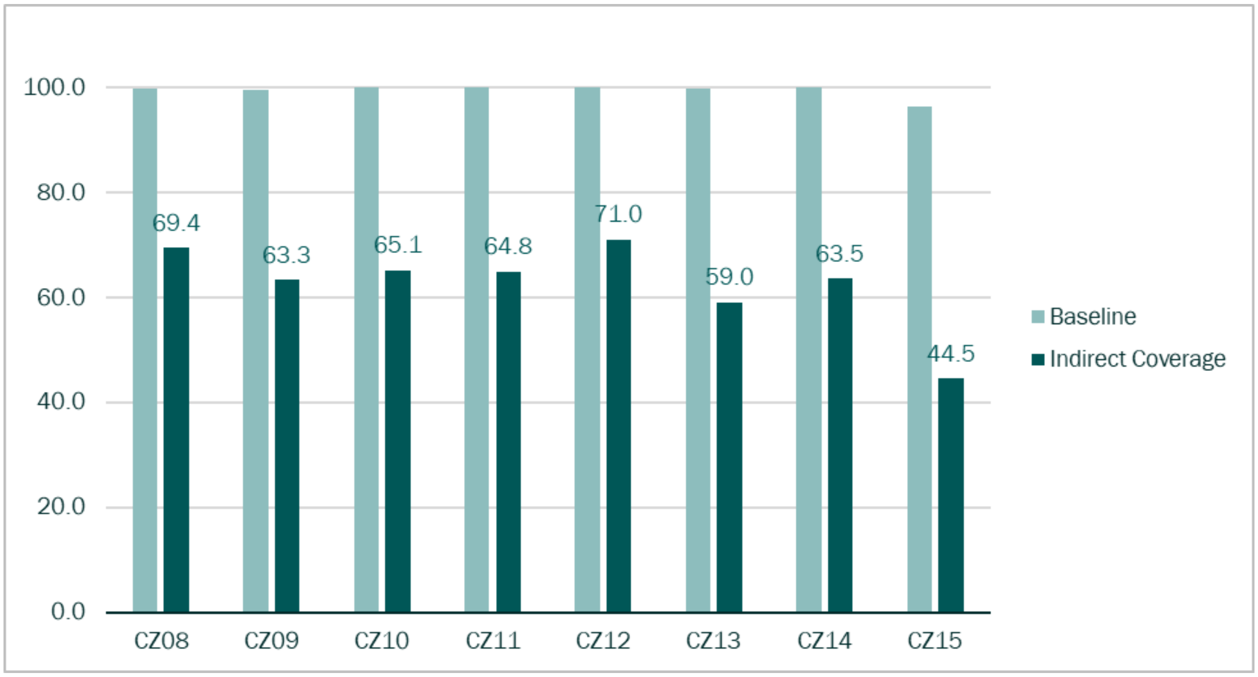
Figure 33: SF bedroom 2, ductless indirect coverage ASHP configuration.



Note: This figure shows the percentage of annual hours with the PMV between -0.5 and 0.5 in a SF unit bedroom 2. (n = 312 iterations each for ducted baseline and indirect coverage)

Figure 34: SF bedroom 2, ducted indirect coverage ASHP configuration.

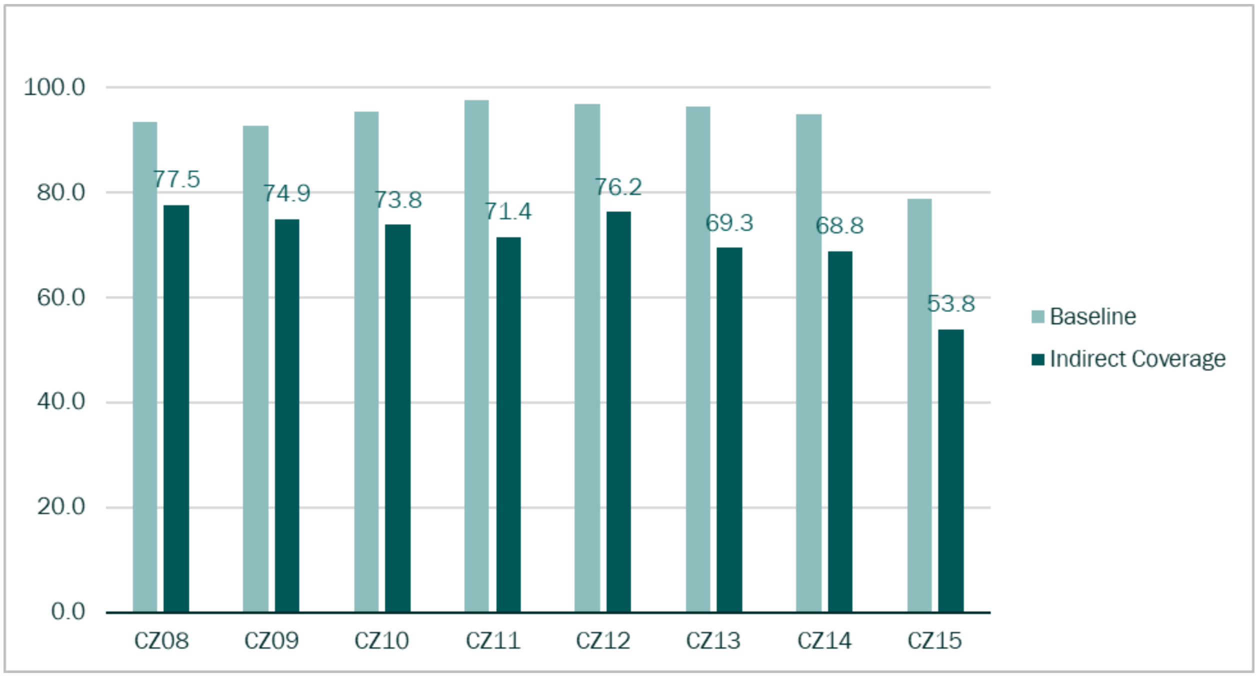
To demonstrate these trends in this report, the project team selected the iteration of the SF north-facing home built in 2022 with a ductless ASHP installed and the doors open. Figure 35 depicts the percentage of hours where the PMV is between -0.5 and 0.5 for this iteration. Only Climate Zones 8 through 15 are shown, since the remaining climate zones were combination cases where the ASHP system was resized in addition to having a room without directly conditioned air. As with the MF indirect coverage configuration, the SF indirect coverage configuration does not maintain a similar thermal occupant comfort as the baseline configuration, but this can be mitigated with clothing adjustments or a transfer fan.



Note: This figure shows the percentage of annual hours with the PMV between -0.5 and 0.5 in bedroom 2 of a SF north-facing home with the door open.

Figure 35: 2022 SF home with a ductless indirect coverage ASHP configuration.

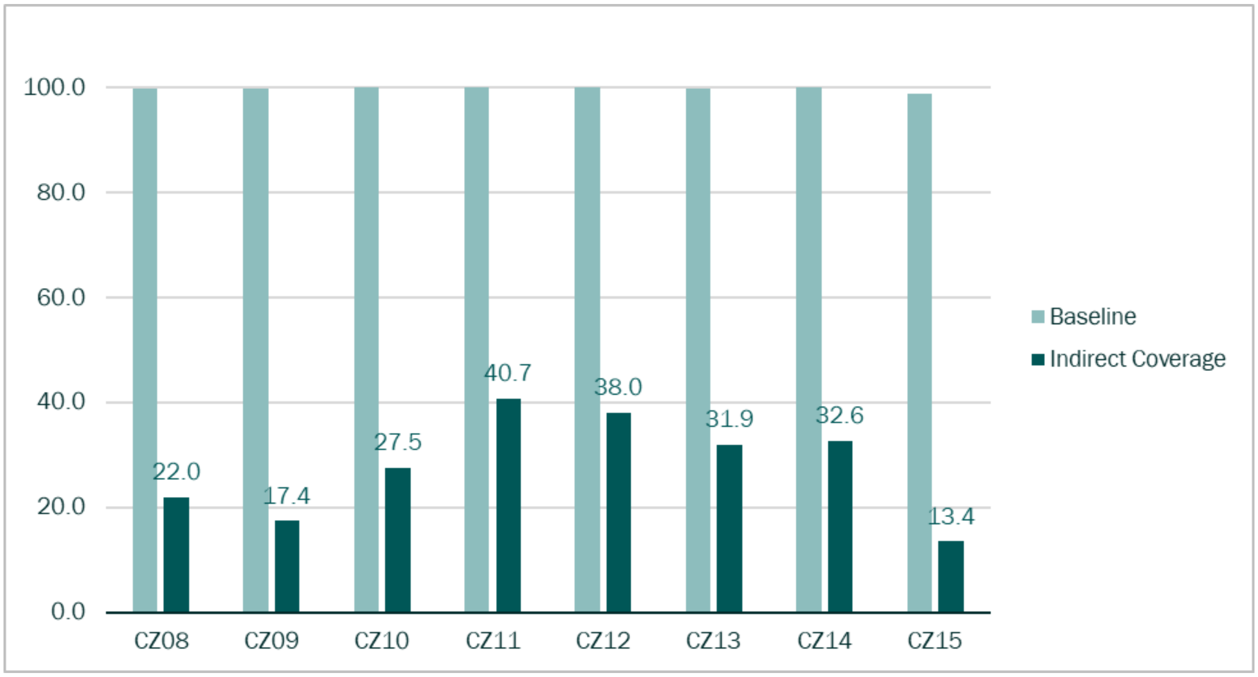
The same SF north-facing home built in 2022 with the door open, but with a ducted indirect coverage ASHP configuration, is shown in Figure 36. The ducted ASHP system can maintain a little higher occupant thermal comfort with between 54 and 77 percent of annual hours within the -0.5 and 0.5 PMV range. Comparatively, the ductless system has between 44 and 69 percent of annual hours within the same PMV range; however, the ductless systems are estimated to save more first costs than ducted systems, so that is what the project team focused on in this report.



Note: This figure shows the percentage of annual hours with the PMV between -0.5 and 0.5 in bedroom 2 of a SF north-facing home with the door open.

Figure 36: 2022 SF home with a ducted indirect coverage ASHP configuration.

Figure 37 depicts bedroom 2 in the same SF north-facing home built in 2022, with a ductless system installed, but the doors are closed. Similar to MF, there is a significant drop in occupant thermal comfort in the room without directly conditioned air. The annual percentage of PMV within the -0.5 to 0.5 range drops from 44 to 69 percent in the door open iteration to between 13 and 41 percent in the door closed iteration. This again points to the need for a transfer fan to help maintain occupant thermal comfort in the room without directly conditioned air.

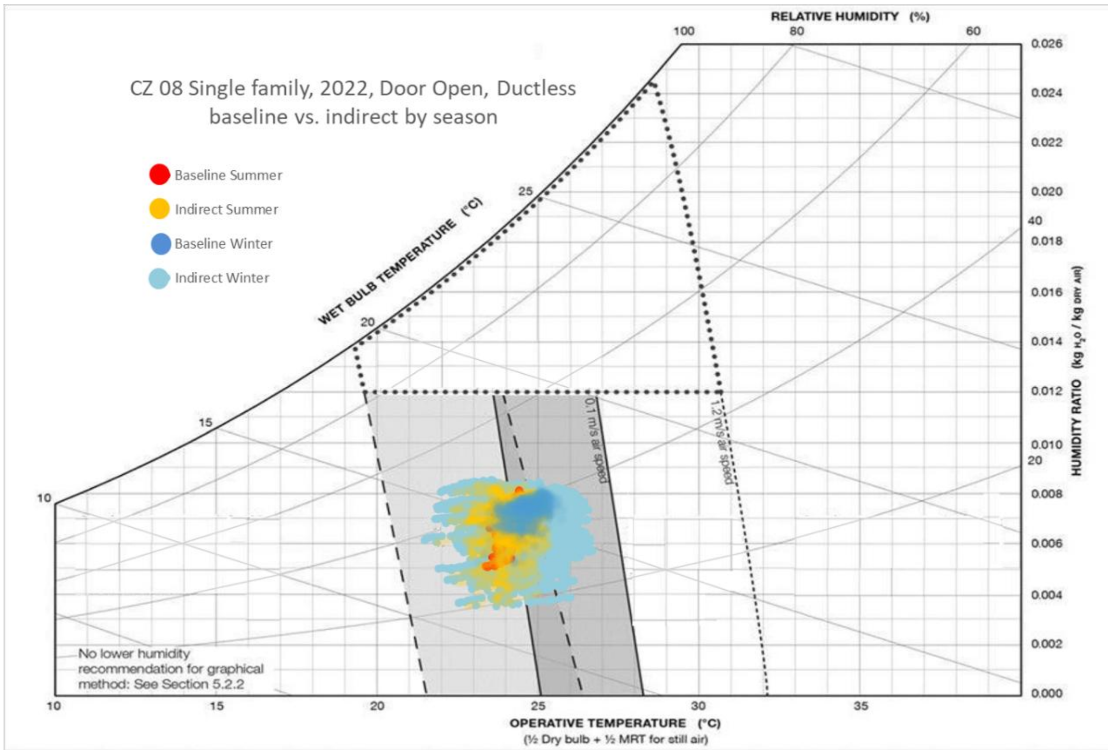


Note: This figure shows the percentage of annual hours with the PMV between -0.5 and 0.5 in bedroom 2 of a SF north-facing home.

Figure 37: 2022 SF home with door closed and a ductless indirect coverage ASHP configuration.

Similar to MF, the occupant thermal comfort in the indirectly conditioned bedroom 2 is susceptible to the exterior environmental conditions of the home. The vintage and orientation of the home influences the occupant thermal comfort; the 2022 home with the tighter envelope provided higher levels of occupant thermal comfort than the pre-1978 home with the leakier envelope. Additionally, occupant thermal comfort is higher for homes where the indirectly conditioned room, bedroom 2, faces a direction that is less affected by the exterior environment, such as south. When designing an ASHP system with the indirect coverage configuration, the space not receiving directly conditioned air should be carefully evaluated—including the home vintage, orientation of the room, susceptibility to exterior environmental conditions, and occupant willingness to make clothing adjustments.

Figure 38 shows the space temperatures at each hour of the year for bedroom 2 of the SF north-facing home in Climate Zone 8, built in 2022, with the door open and a ductless ASHP system, for both the baseline and indirect coverage systems on a psychrometric chart. Climate Zone 8 was selected because it shows promising results for maintaining thermal occupant comfort. The psychrometric chart confirms this hypothesis with all annual hours falling within the summer and winter comfort zones. Therefore, occupant thermal comfort is maintained for the indirect coverage configuration in this SF home.

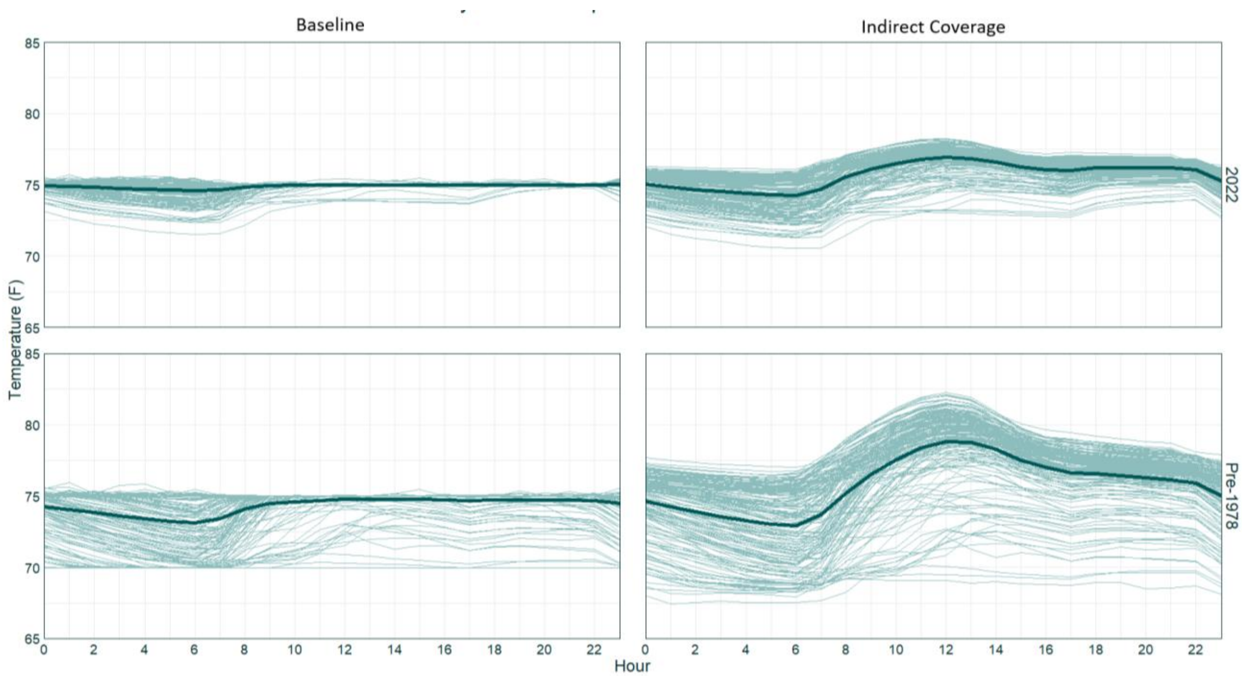


Note: For both the baseline and indirect coverage configuration, this shows the bedroom 2 of a MF north-facing middle-center unit with the door open.

Figure 38: Psychrometric chart of a 2022 SF home with ductless indirect coverage ASHP configuration compared to a baseline configuration in Climate Zone 8.

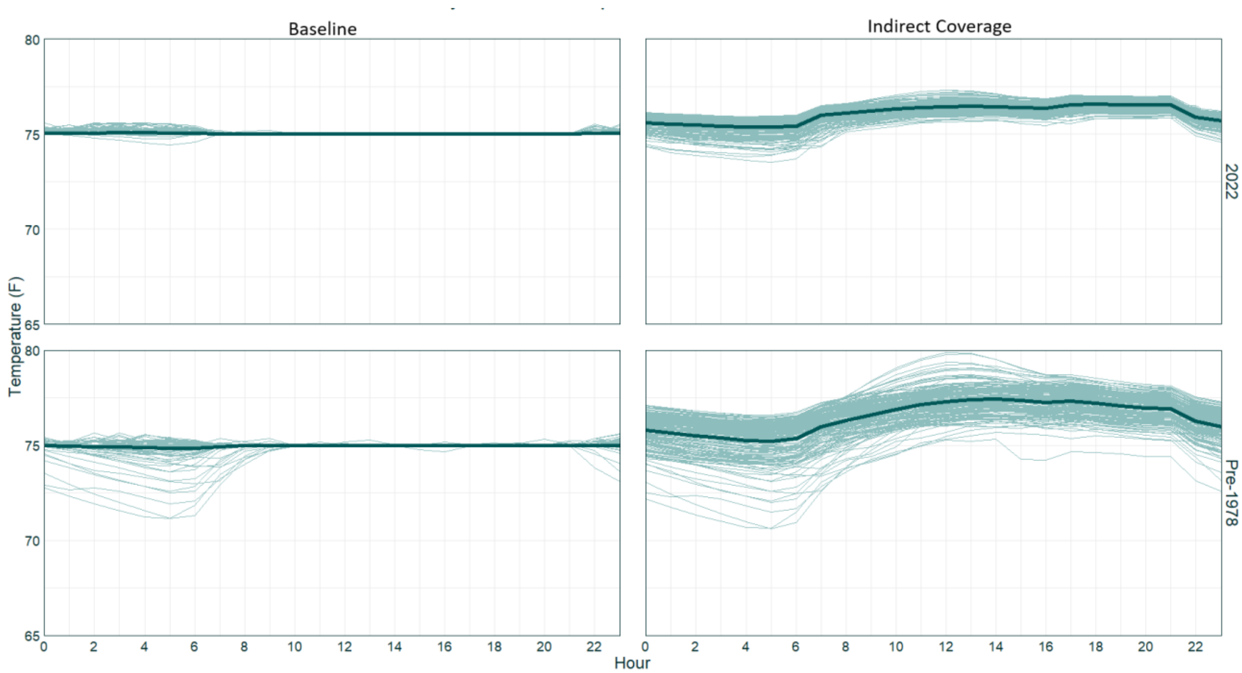
Another simplified way to look at the data is to plot the ambient air temperature for the baseline and indirect coverage ASHP system configurations. For a representative case, the project team kept the same SF north-facing home with the door open and a ductless system, in moderate Climate Zone 8, where the percent of annual hours between -0.5 and 0.5 PMV was highest.

Figure 39 shows the ambient air temperature in bedroom 2 for the winter months (September 21 through March 20) and Figure 40 shows the ambient air temperature in bedroom 2 during the summer months (March 21 through September 20). Each light green line represents a day in the year, and the dark green line is the average for the season. The baseline temperature range in the 2022 home does not vary greatly, which is due to the milder climate zone and tighter building envelope. For the pre-1978 vintage, there is more variance in the temperature, but the baseline HVAC system is still able to maintain the room temperature between 70°F and 75°F. The indirect coverage system configuration cannot keep the room between 70°F and 75°F, although there is less temperature swing in the 2022 vintage home than the pre-1978 vintage home, indicating that the homes with tighter envelopes are better candidates for indirect coverage systems. Although the ambient air temperature falls outside the 70°F and 75°F range, this may be mitigated with clothing adjustments or a transfer fan.



Note: This bedroom 2 ambient air temperature is for a SF north-facing home with the door open.

Figure 39: Ambient air temperature during the winter months in a SF home with a ductless indirect coverage ASHP configuration, compared to a baseline configuration in Climate Zone 8.

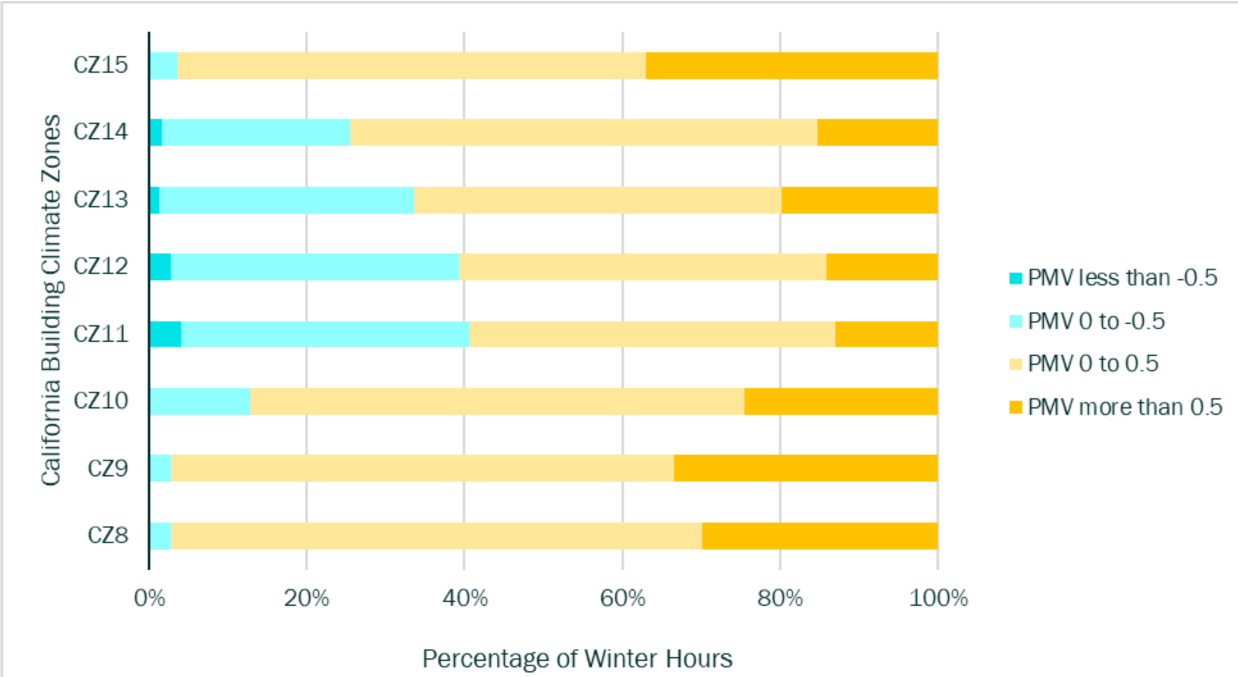


Note: This bedroom 2 ambient air temperature is for a SF north-facing home with the door open.

Figure 40: Ambient air temperature during the summer months in a SF home with a ductless indirect coverage ASHP configuration, compared to a baseline configuration in Climate Zone 8.

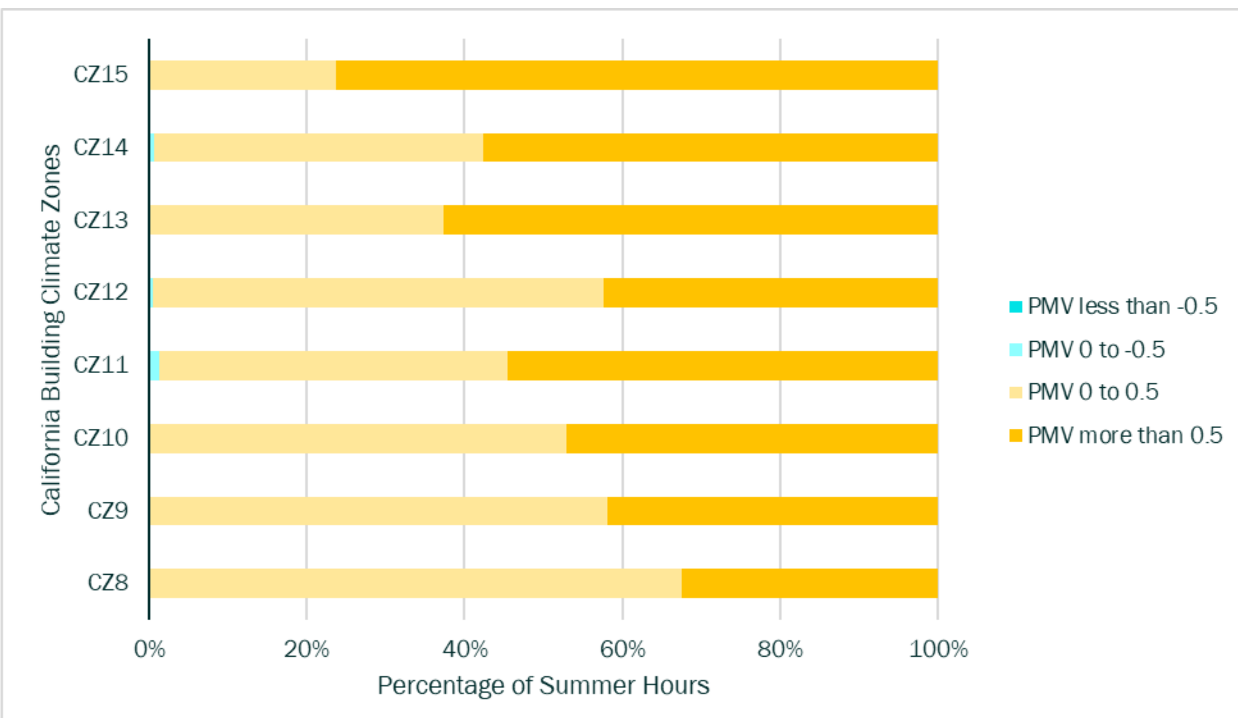
In a SF home with a 2022 vintage and a ductless indirect coverage ASHP configuration, occupants typically feel warm during the summer months when the exterior temperatures are higher, and cool during the winter months when the exterior temperatures are colder. Figure 41 shows the percentage of hours during the winter months (September 21 through March 20), and Figure 42 shows the percentage of hours during the summer months (March 21 through September 20), when the PMV is less than or greater than 0.

When the PMV is less than 0, occupants feel cool, which is represented by the blue bars. When the PMV is greater than 0, occupants feel warm, which is represented by the orange bars. The light orange and light blue bars represent slight discomfort, since the PMV is still within the -0.5 and 0.5 comfort range. As expected, occupants are typically warm during the hottest hours of the day in the late afternoon and early evening hours, and cool during the coldest hours of the day in the early morning hours. This could be mitigated by installing a transfer fan to mix the air more efficiently or clothing adjustments.



Note: This figure shows the percentage of annual hours where PMV is less than 0 or more than 0 in the bedroom 2 of a SF north-facing home with the door open.

Figure 41: 2022 SF home with a ductless ASHP during the winter months.



Note: This figure shows the percentage of annual hours where PMV is less than 0 or more than 0 in the bedroom 2 of a SF north-facing home with the door open.

Figure 42: 2022 SF home with a ductless ASHP during the summer months.

Conclusions

This project explores two different ASHP configurations, **indirect coverage** and **suitable capacity**, to determine if these configurations can offer first-cost savings while still providing occupant comfort. To approach this challenge, the project team used energy simulations on two prototype buildings to model indoor environmental conditions over the course of a year in California climate zones and then used those results to predict occupant thermal comfort. The project team also conducted contractor interviews.

For **suitable capacity ASHP systems**, the impact on thermal comfort is negligible when choosing a system that satisfied 80 percent of the design load instead of 100 percent, both for MF units and all typical one-story SF homes in California. Additionally, there was little to no effect on thermal occupant comfort from the baseline to suitable capacity configurations between climate zones, vintages, and orientations. Therefore, an ASHP designed to meet 80 percent of the home design load is a viable option—even in California's colder climate zones. Additionally, some up-front material cost savings of between $600 and $1,550 can be expected, resulting from reducing the capacity of the ASHP system.

For **indirect coverage ASHP systems**, or systems that do not provide directly conditioned air into every room of a home, there is some impact to the occupant thermal comfort in the room not receiving directly conditioned air. The indirectly conditioned spaces maintain a wider range of space temperatures compared to the rest of the home and compared to the baseline. The impact on thermal comfort could be mitigated by occupants adjusting their clothing levels or, instead of relying on occupant behavior, by installing a transfer fan to mix the air more effectively. Ducted ASHP systems provide a little higher occupant thermal comfort than ductless systems, but there are less first-cost savings with ducted ASHP systems than ductless. For ductless systems, there are material and labor first-cost savings from installing less heads in the home. However, for ducted systems, first-cost savings would only be available for homes that need ductwork replaced, repaired, or added.

This study only evaluated the first-cost savings resulting from labor or materials. The project team did not investigate lifetime maintenance cost savings or energy savings for the suitable capacity, nor the indirect coverage ASHP configurations.

Recommendations

The project team recommends contractors consider the suitable capacity ASHP configurations and resist sizing an ASHP for more than 100 percent of the home design load throughout California. Sizing an ASHP to meet 70 to 90 percent of the home design load has very little impact on occupant comfort, and a smaller system also provides first-cost savings to customers.

We also recommend carefully considering the indirect system configuration. For homes with tight envelopes in milder climates, indirect coverage systems may be a viable option. These systems have the potential to reduce the first costs of ASHP systems more than the suitable capacity configuration;

however, occupant thermal comfort may also be reduced. This could be mitigated by occupants adjusting their clothing level or installing a transfer fan to distribute the conditioned air to the spaces without directly conditioned air. A discussion with the homeowner about room usage, as well as priority between cost and comfort, will be needed to understand if the cost savings are worth the potential discomfort. This study is based on modeled data which should be calibrated and validated for further assessment. Calibrating the thermal comfort modeling would include compiling thermal sensation responses across different ASHP configurations and scenarios. We recommend conducting this calibration by monitoring either test homes or occupied homes with suitable capacity or indirect coverage of ASHP systems installed. It will be important to monitor the whole home, so a lab test room would not be sufficient. Additional research should be completed to better understand the ongoing energy and maintenance costs of these systems. The combination cases where ASHP systems could be downsized and the number of directly conditioned rooms could be reduced should also be further investigated. There is potential for additional first-cost savings, especially with ductless ASHP systems in suitable capacity and indirect coverage configurations. These first-cost savings would come from lower material costs with the reduced capacity system and lower labor costs from installing fewer heads.

The project team recommends the California code development teams review these findings and consider revising the California Title 24 limits to sizing ASHP system heating capacities. The project team plans to bring report findings to the code development team to support either making modifications, if allowed, to the 2025 residential Title 24 building code or prepare to make recommendations to clarify the Title 24 code for the 2031 code cycle.

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Appendix A: Supplemental Figures

Suitable Capacity Configuration Supplemental Figures

There is no difference in occupant thermal comfort between the baseline and suitable capacity ASHP configurations for the door open vs. the door closed, home vintage, or home orientation. The following graphs show these trends broken out by multifamily and single family.

Multifamily

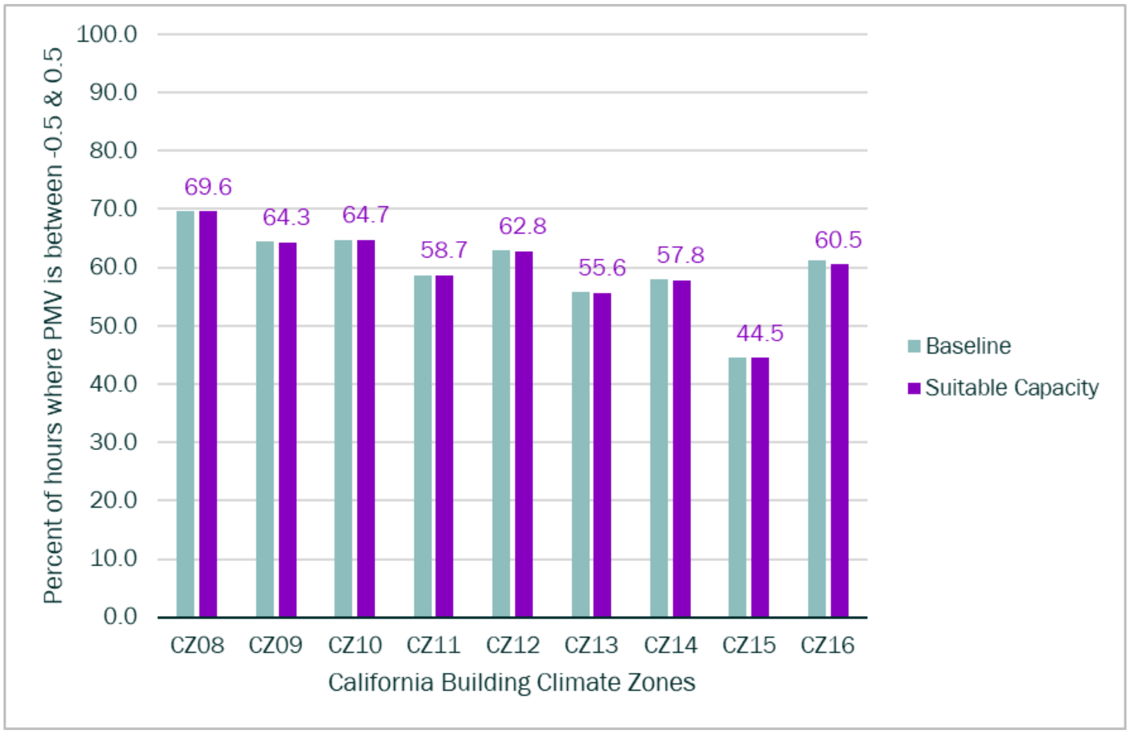

Figure 43: Percent of hours where PMV is between -0.5 and 0.5 in a pre-1978 MF upper corner unit living room facing North with door closed and a ductless suitable capacity ASHP configuration.

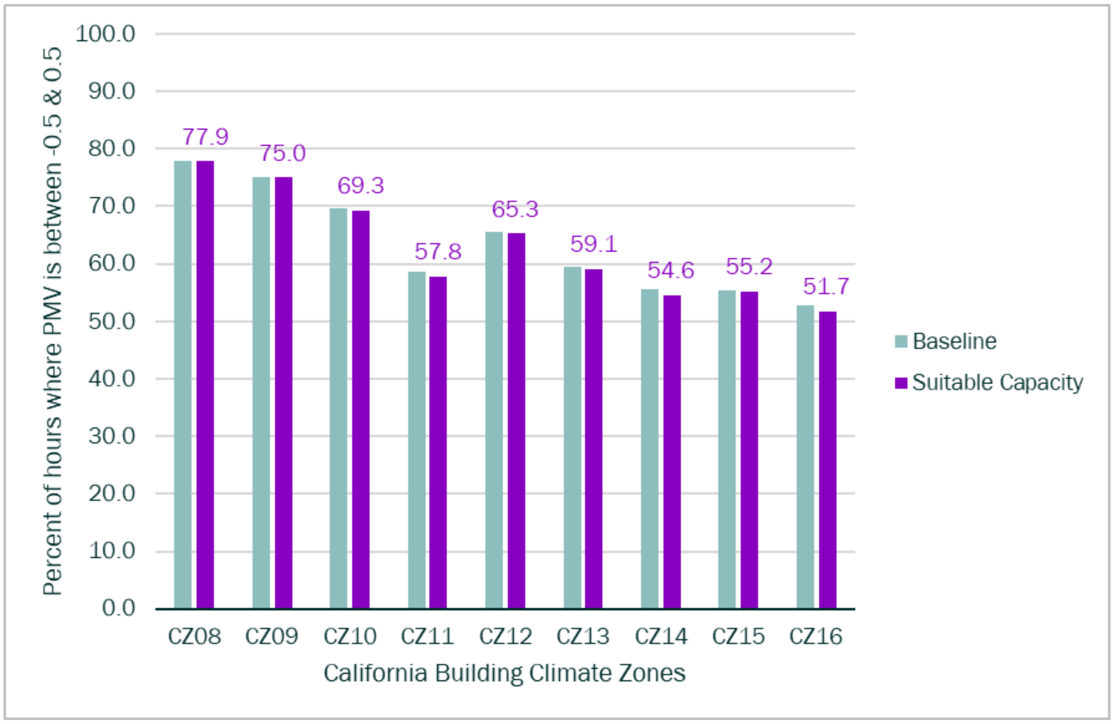

Figure 44: Percent of hours where PMV is between -0.5 and 0.5 in a pre-1978 MF upper corner unit living room facing South with door open and a ductless suitable capacity ASHP configuration.

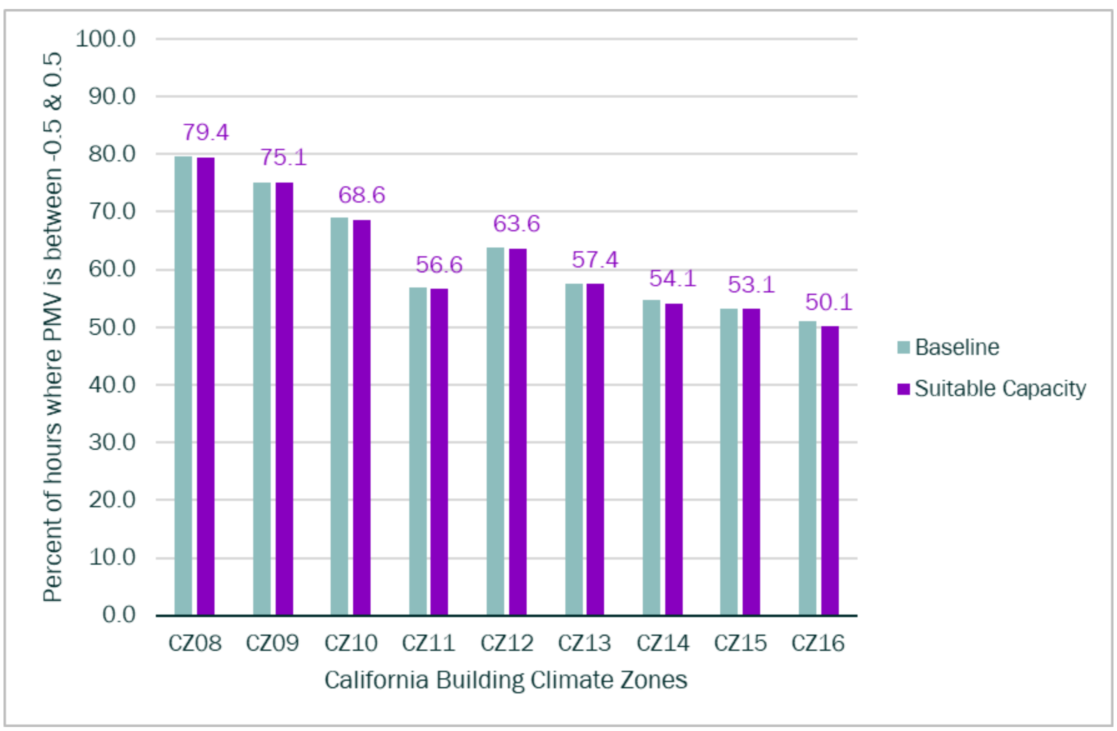

Figure 45: Percent of hours where PMV is between -0.5 and 0.5 in a pre-1978 MF upper corner unit living room facing West with door open and a ductless suitable capacity ASHP configuration.

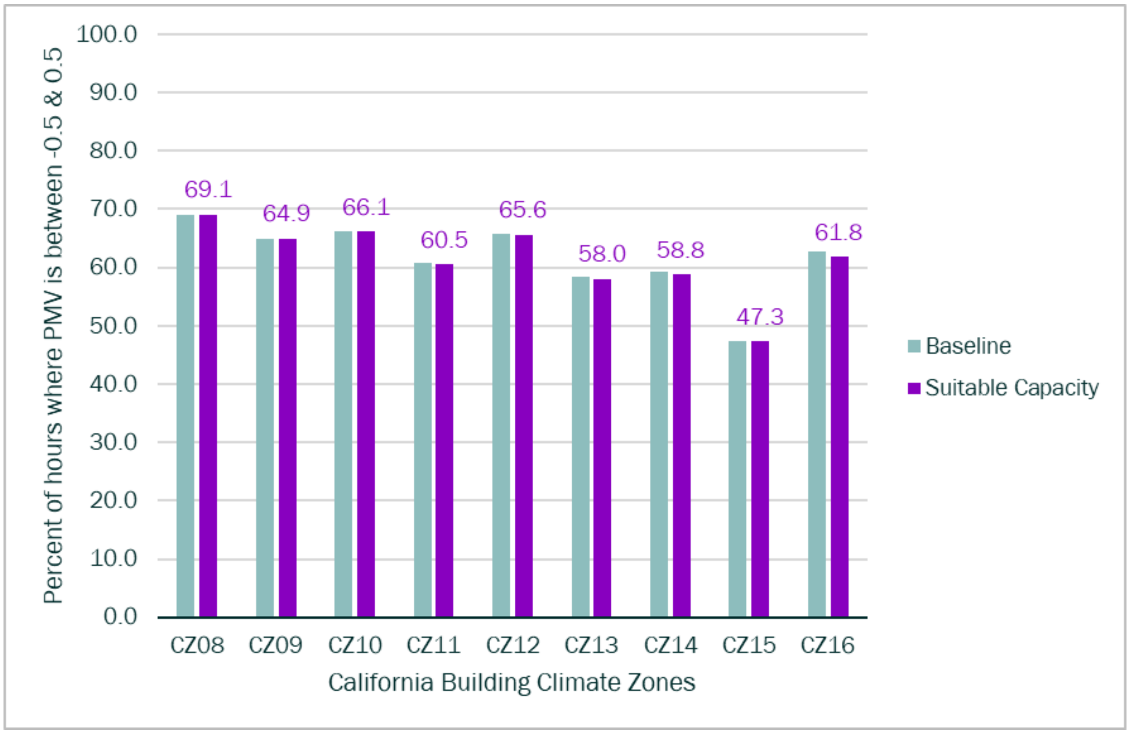

Figure 46: Percent of hours where PMV is between -0.5 and 0.5 in a pre-1978 MF upper corner unit living room facing East with door open and a ductless suitable capacity ASHP configuration

Single-Family

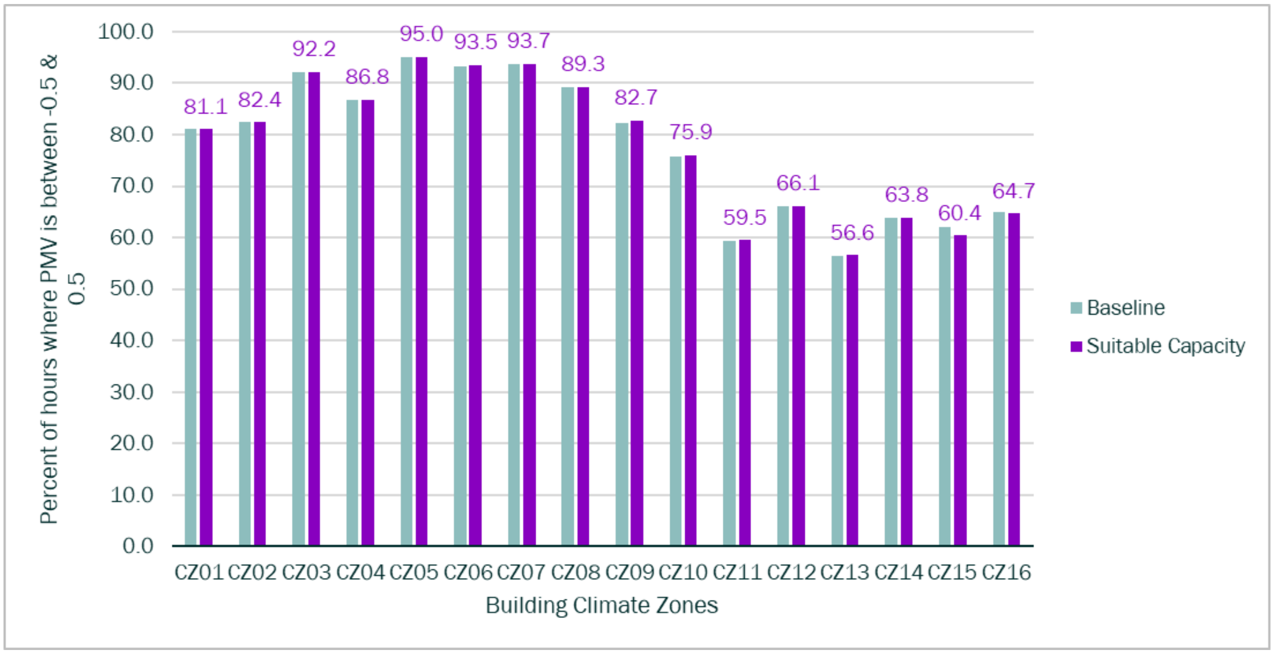

Figure 47: Percent of hours where PMV is between -0.5 and 0.5 in a pre-1978 SF living room facing North with door closed and a ducted suitable capacity ASHP configuration.

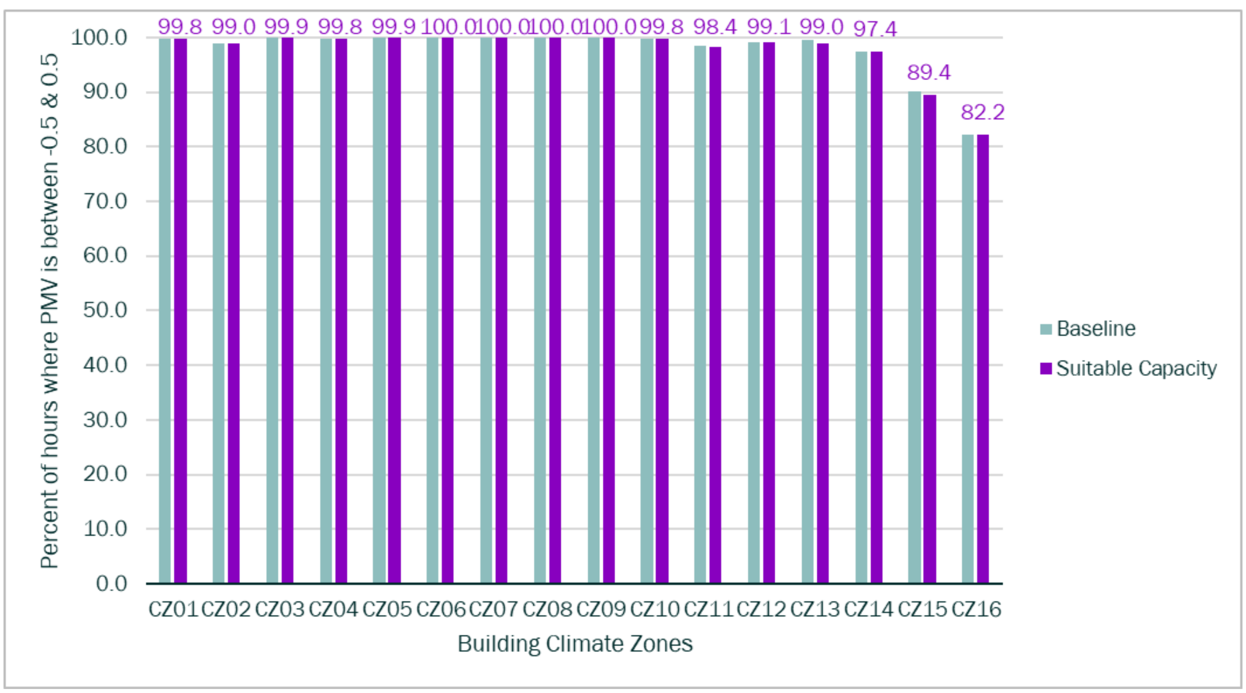

Figure 48: Percent of hours where PMV is between -0.5 and 0.5 in a 2022 SF living room facing North with door open and a ducted suitable capacity ASHP configuration.

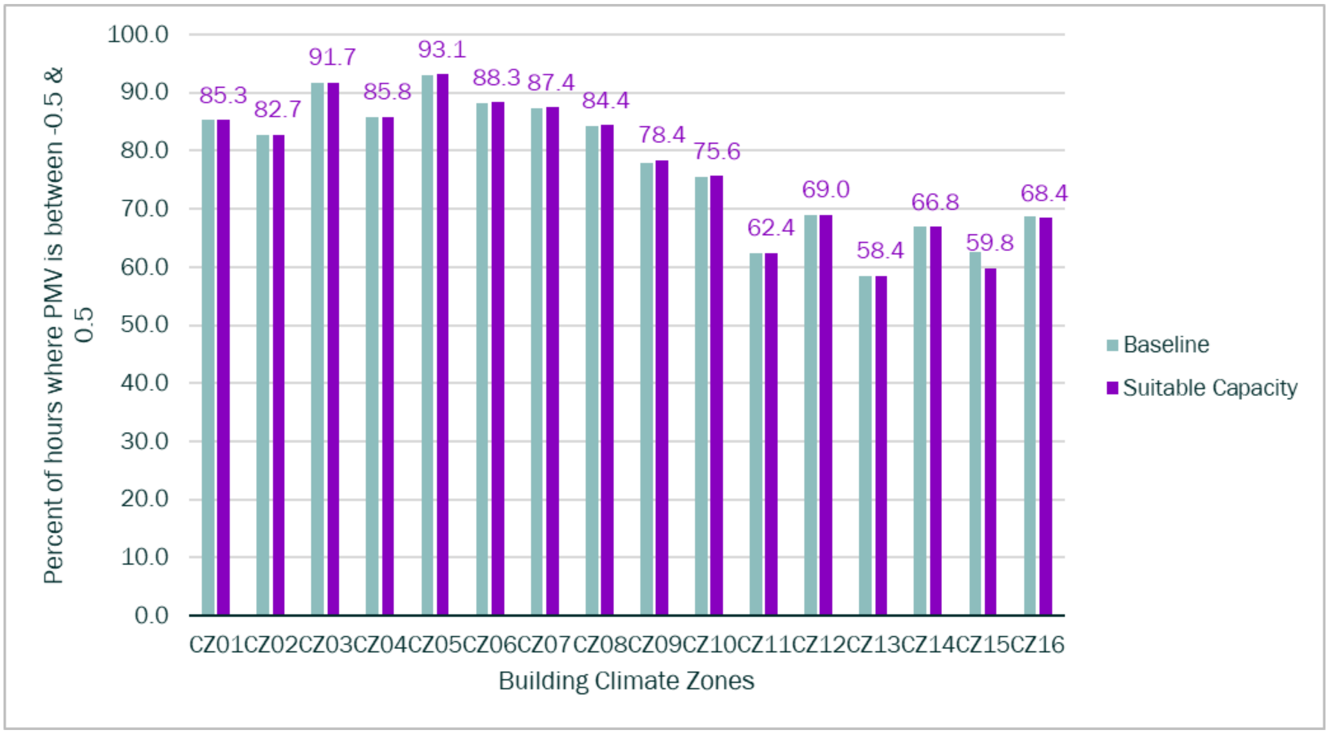

Figure 49: Percent of hours where PMV is between -0.5 and 0.5 in a pre-1978 SF living room facing South with door open and a ducted suitable capacity ASHP configuration.

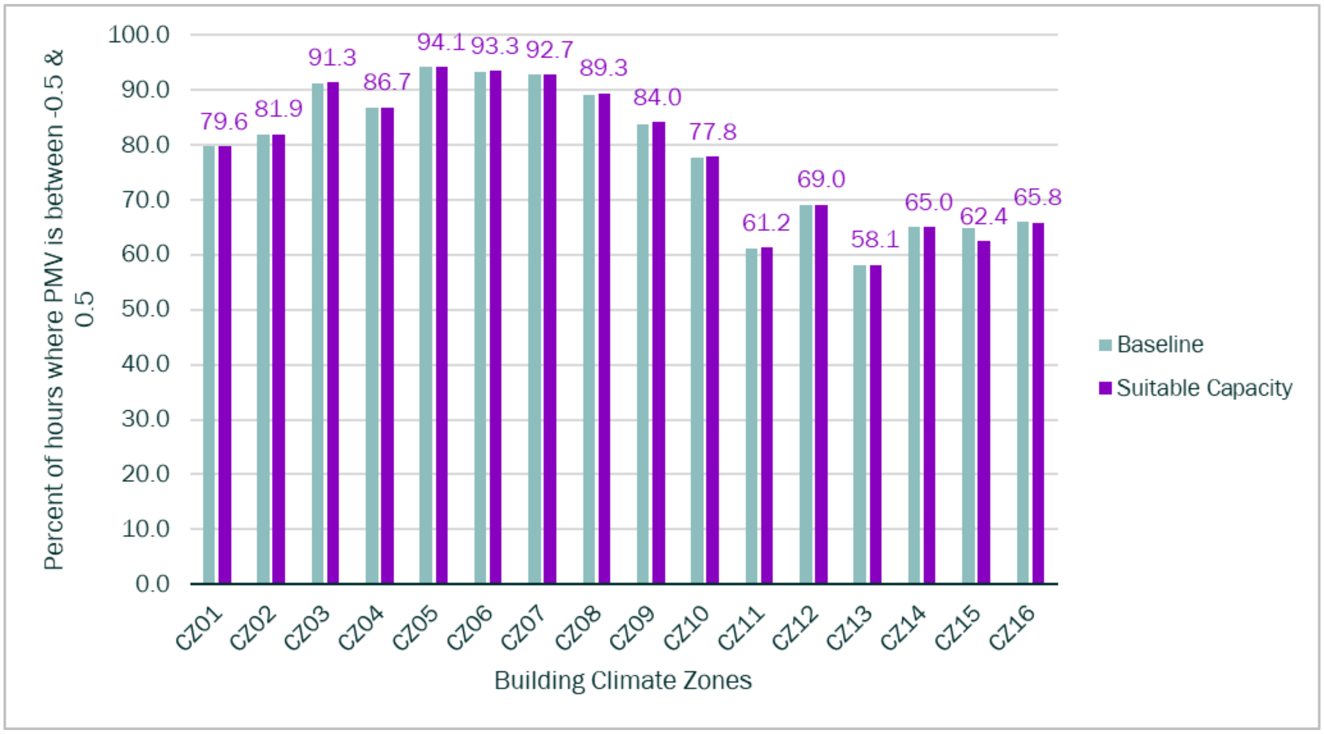

Figure 50: Percent of hours where PMV is between -0.5 and 0.5 in a pre-1978 SF living room facing West with door open and a ducted suitable capacity ASHP configuration.

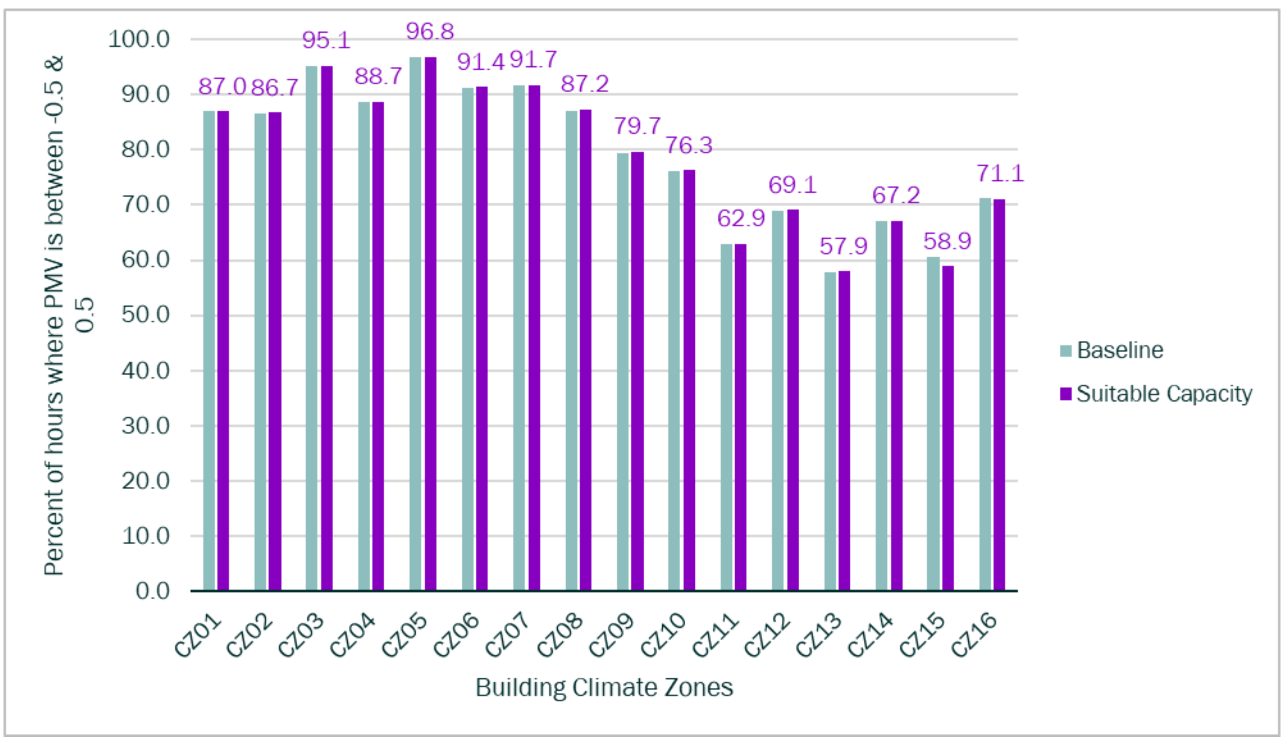

Figure 51: Percent of hours where PMV is between -0.5 and 0.5 in a pre-1978 SF living room facing East with door open and a ducted suitable capacity ASHP configuration.

Indirect Coverage Configuration Supplemental Figures

The occupant thermal comfort in bedroom 2 for the indirect coverage ASHP configuration is affected by the home vintage and home orientation. The following graphs show these trends broken out by multifamily and single-family homes.

Multifamily

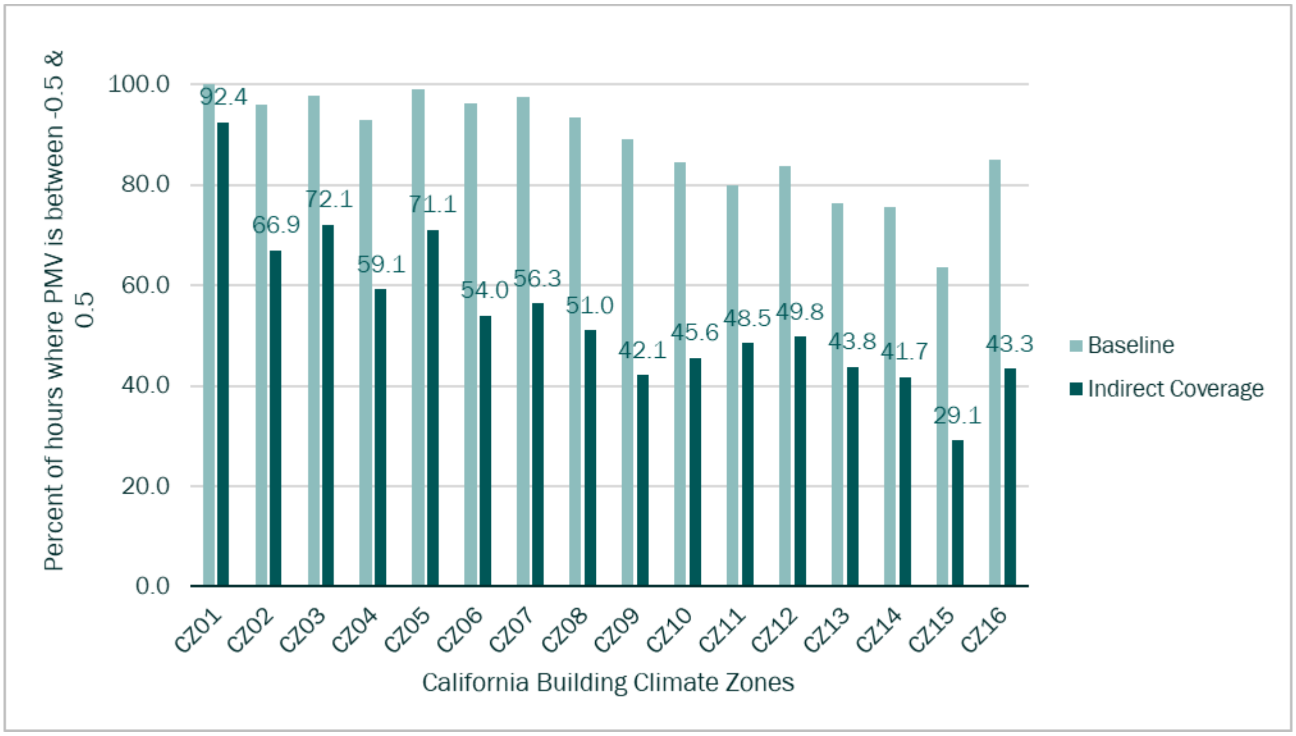

Figure 52: Percent of hours where PMV is between -0.5 and 0.5 in a pre-1978 MF middle center unit bedroom 2 facing North and the door open with a ductless indirect coverage ASHP configuration.

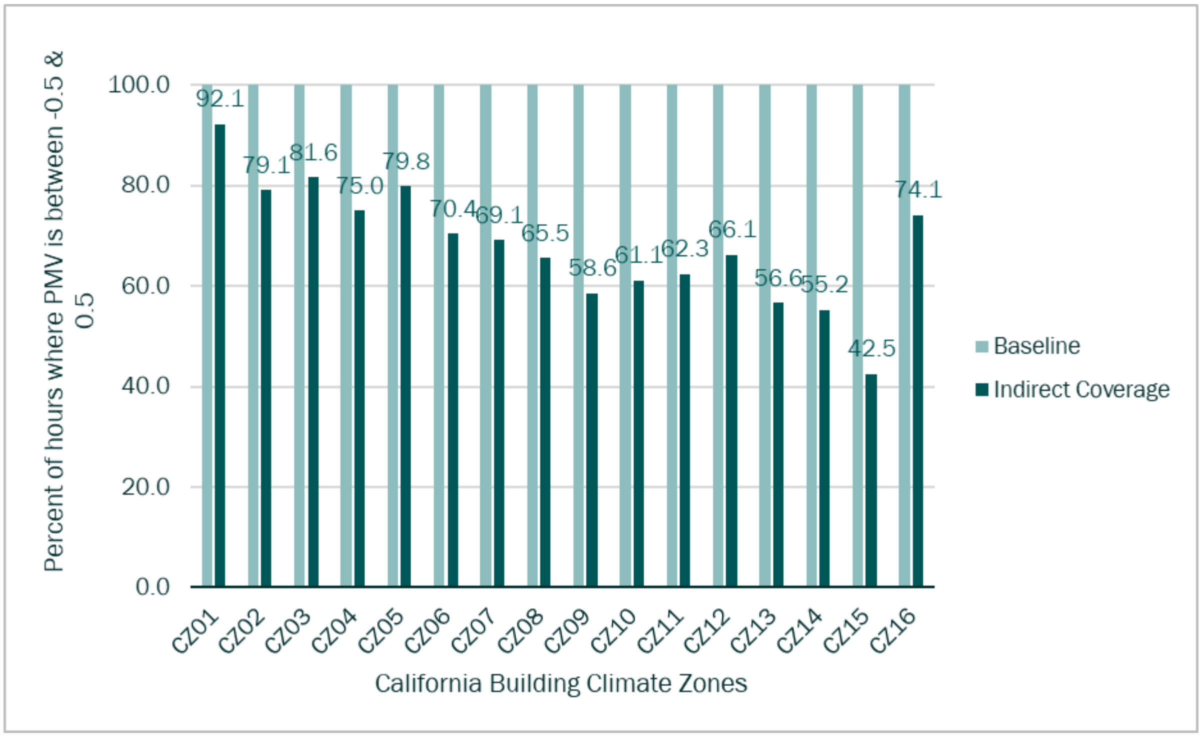

Figure 53: Percent of hours where PMV is between -0.5 and 0.5 in a 2022 MF middle center unit bedroom 2 facing South and the door open with a ductless indirect coverage ASHP configuration.

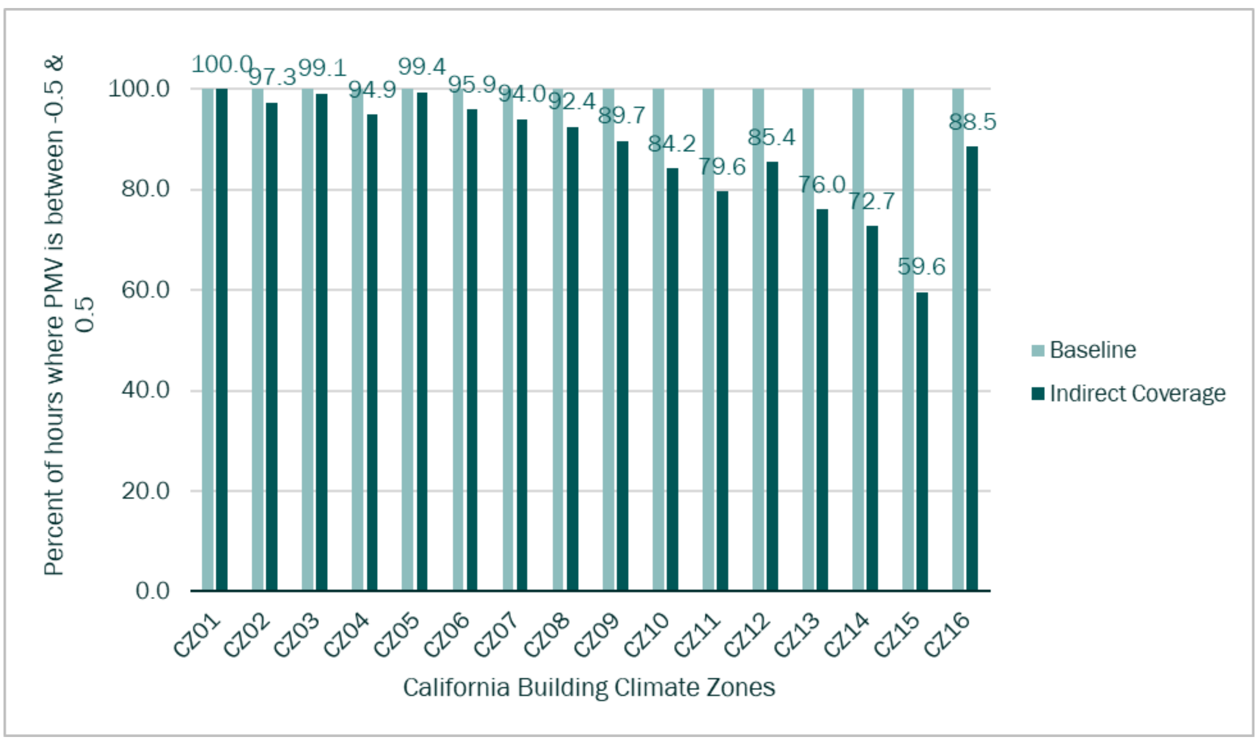

Figure 54: Percent of hours where PMV is between -0.5 and 0.5 in a 2022 MF middle center unit bedroom 2 facing West and the door open with a ductless indirect coverage ASHP configuration.

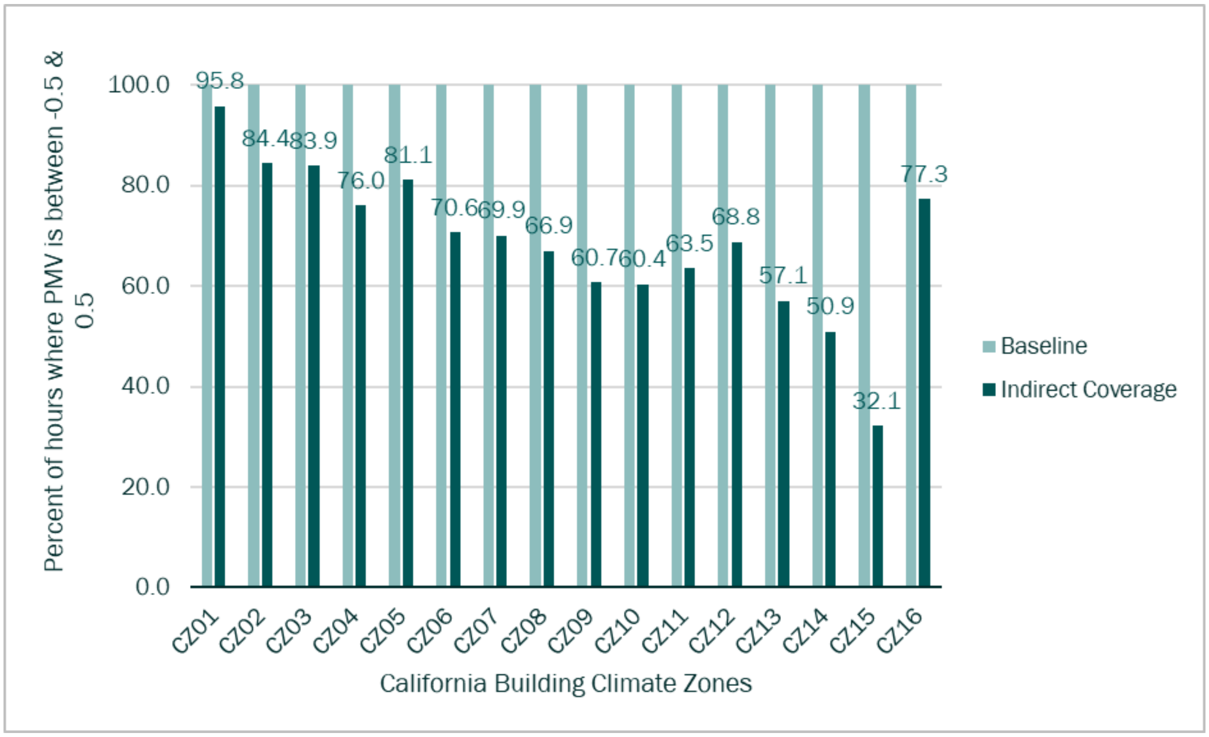

Figure 55: Percent of hours where PMV is between -0.5 and 0.5 in a 2022 MF middle center unit bedroom 2 facing East and the door open with a ductless indirect coverage ASHP configuration.

Single-Family

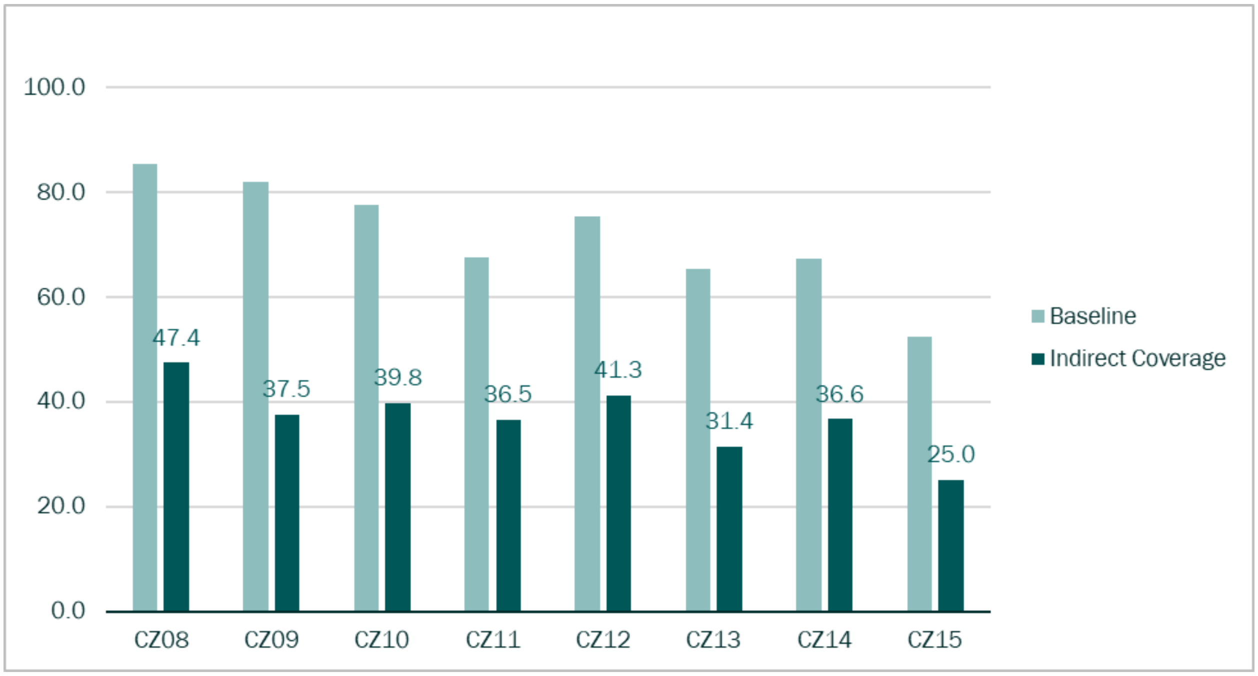

Figure 56: Percent of hours where PMV is between -0.5 and 0.5 in bedroom 2 of a pre-1978 SF home facing North and door opened with a ductless indirect coverage ASHP configuration.

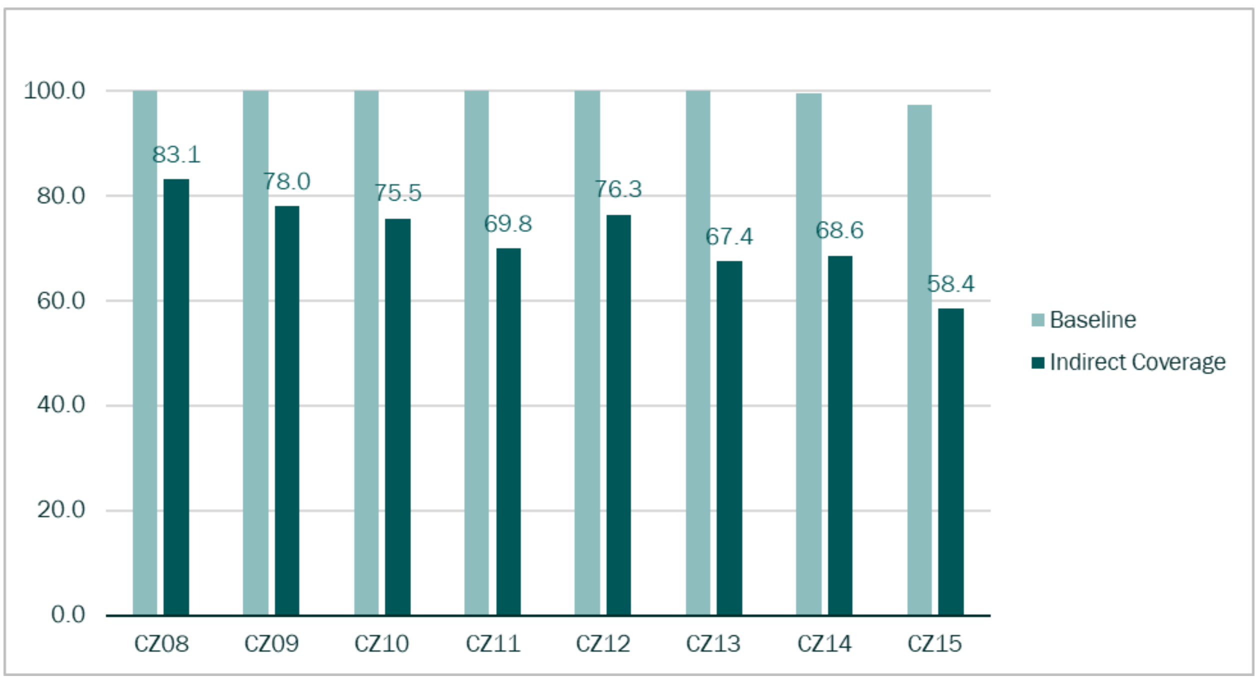

Figure 57: Percent of hours where PMV is between -0.5 and 0.5 in bedroom 2 of a 2022 SF home facing South and door opened with a ductless indirect coverage ASHP configuration.

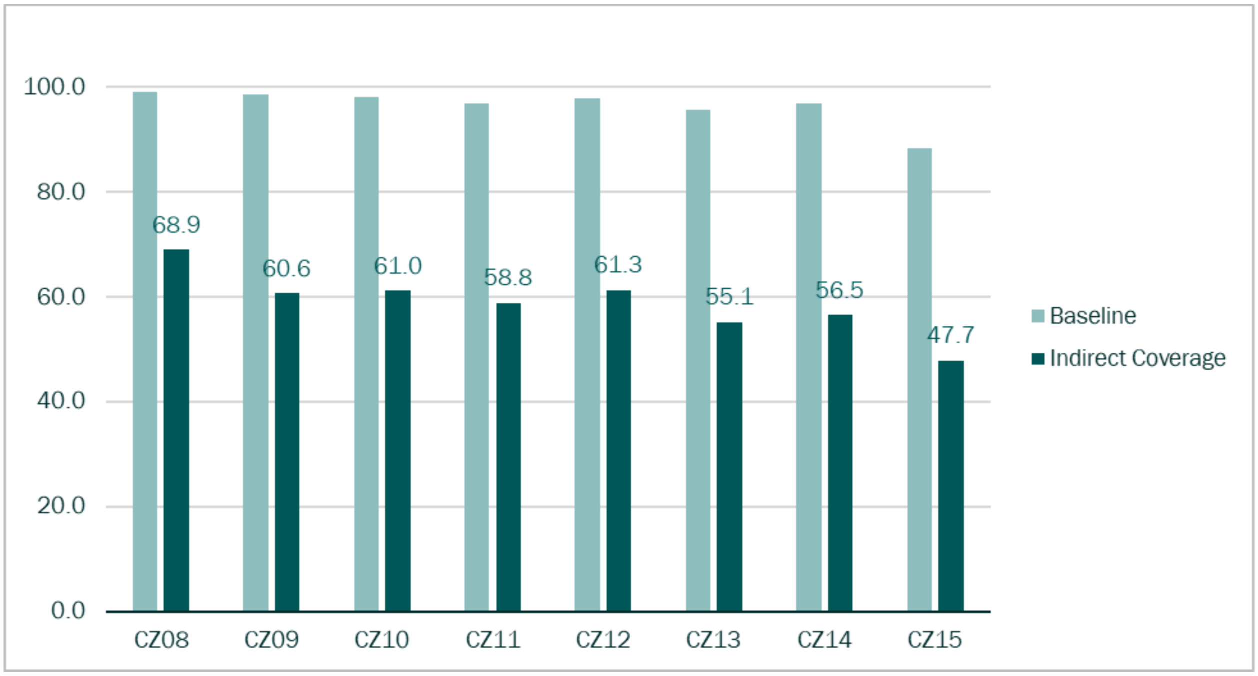

Figure 58: Percent of hours where PMV is between -0.5 and 0.5 in bedroom 2 of a 2022 SF home facing West and door opened with a ductless indirect coverage ASHP configuration.

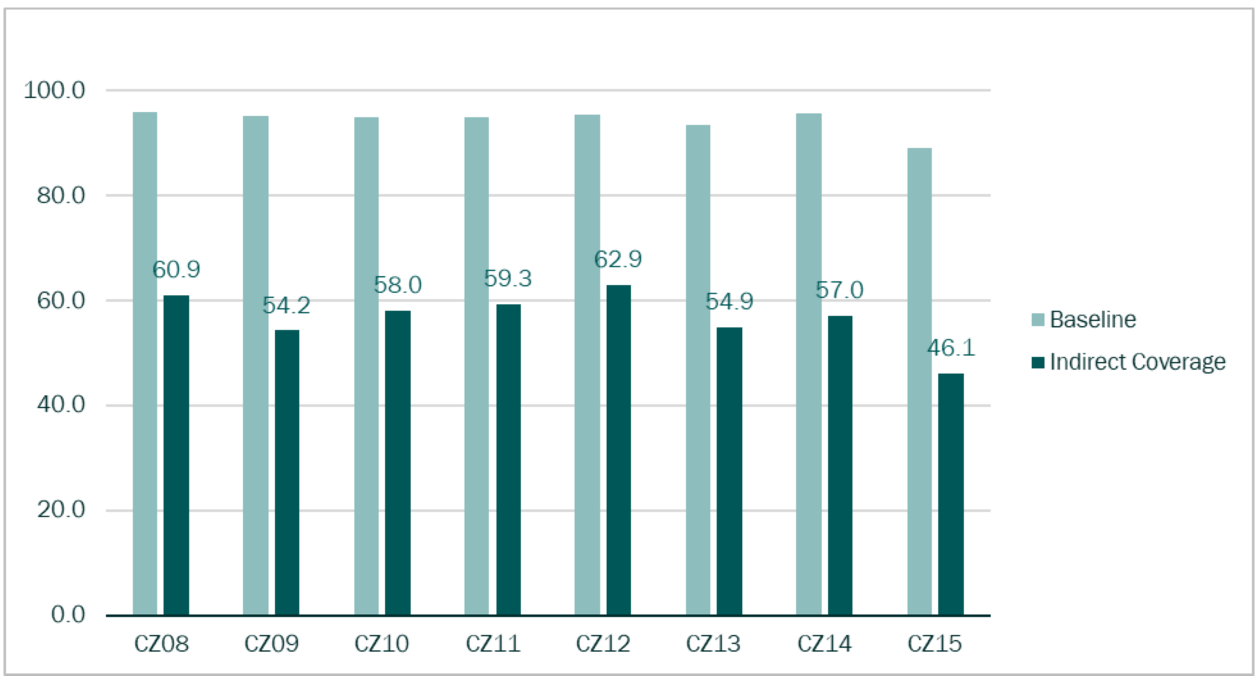

Figure 59: Percent of hours where PMV is between -0.5 and 0.5 in bedroom 2 of a 2022 SF home facing East and door opened with a ductless indirect coverage ASHP configuration.

Appendix B: Contractor Interview Guide

Section A: Introduction

A1. Hello, this is [YOUR NAME] calling from TRC. Is now a good time for you to complete a 30–45-minute interview?

IF YES, Proceed

IF NO, Reschedule

[If yes] Great, we are looking for your feedback so we can address any concerns and make improvements based on your input, so we appreciate your candid feedback. Please know that none of your responses will be attributed to you or your organization and will not be used for direct sales or marketing purposes.

The purpose of this interview is to better understand heat pump sizing practices and pricing. Are you familiar with the process for sizing heat pumps? Are you able to estimate heat pump pricing for various home loads?

IF Yes, Proceed

IF NO, Ask for contact information of someone else in the organization who is familiar

Do you have any questions for me before we get started?

[Do your best to answer any questions or let them know we will look into whatever concerns they have.]

[If technology allows]

We'd like to record today's interview for accuracy in note-taking and will only be used to make sure we capture your answers accurately.

Are you okay with me starting the recording now?

IF YES, record

IF NO, continue without recording

Section B: Contractor Details

B1. To start, please tell me a little bit about yourself and your work as a contractor?

[PROBE ON THE FOLLOWING AS NEEDED]

B1a. How long have you been working in the industry?

B1b. What is your service territory within California? / Where in California is the majority of your work completed?

B1c. What type of heat pump installations does your company specialize in?

[PROBE] Do you primarily work with single family, multifamily or commercial buildings? New construction or retrofit? Ducted or ductless systems? [IF DUCTLESS: Do you typically install mini-split or multi-split systems?]

Section C: Sizing an ASHP System Questions

Next, we would like to better understand how you typically size heat pumps.

C1. How familiar are you with sizing heat pumps for a home? (Interviewer note: Understand the contractor's familiarity with this process before proceeding. If unfamiliar, gather contact information from someone else in the organization who is more familiar and end interview.)

C1a. What steps do you typically take to determine the heat pump size needed for a home?/ How do you gather inputs for the Manual J calculations?

[PROBE as needed, what are the steps you take? Do you conduct a site visit? Talk with the home or building owner? Review architectural drawings? Take measurements of the site? Understand any improvements made to the home's shell? Any other general steps you take?]

C1b. How familiar are you with U-values, air infiltration, and other building components?

C1c. When performing load calculations do you typically design block loads or room to room loads?

C1d. Where do you pull performance data for selecting a heat pump system? [IF NEEDED, Do you use manufacturers system builders, AHRI, NEEP, etc.]

C2. We are interested in understanding the factors that require some experience to appropriately size a heat pump system. Could you talk me through some of your considerations when making decisions on heat pump sizes or equipment selections? (For example, deciding which temperature or other inputs to use for Manual J calculations, decisions made when calculating Manual S and selecting equipment, etc.)

C2a. How do you ultimately determine what indoor design temperatures to use for heating and cooling?

[PROBE IF NEEDED: How do you weigh preferred occupant thermostat setpoints with industry best practices? Can you estimate how often there is a large difference in occupant thermostat setpoint preferences vs. industry best practice?]

C2b. Do any of these considerations change if the home is located in a heating dominated climate zone versus a cooling dominated climate zone?

C3. What considerations do you take into account when sizing heat pumps for homes with low loads? [PROBE: Due to available heat pump capacities, are ductless systems an option in a home with low thermal loads?]

C4. Would you ever install transfer ducts between rooms rather than installing supplies in each room?

[IF YES] C4a. Can you describe a situation where you may recommend installing a transfer duct (or jumper duct)?

C5. Are there any cases where you may select a heat pump with a capacity smaller than what is recommended for the home's calculated thermal load? If so, please describe.

[PROBE: Any difference for homes with dominate cooling load vs. heating load?]

[IF YES] C5a. How often do you choose a smaller capacity heat pump system? [IF NEEDED, What are the circumstances that lead to this outcome?]

[IF INSTALL DUCTLESS SYSTEMS]

C6. How do you determine which spaces have indoor heads?

[IF NEEDED, Are there any spaces without indoor heads? If so, which ones? How does the size of the room or the home's thermal load factor into where the heads are place?]

[IF INSTALL DUCTED SYSTEMS]

C7. For homes with existing ductwork, how often do you use the existing ductwork when installing a ducted heat pump system?

C8. For homes with no prior existing ductwork or insufficient ductwork, how do you determine which rooms or spaces should have supply registers?

[IF NEEDED, Are there any spaces that typically do not have supply registers? If so, which ones? How does the size of the room or the home's load factor into where the supply registers are place?]

Section D: Pricing ASHP System Scenarios

Next, I'm going to talk through a few different scenarios and ask questions related to cost. Please be as comprehensive as you can, including any labor and material costs to the customer. Assume that you are replacing the existing heating and cooling system with a heat pump where there is no existing ductwork. You do not need to consider the cost of demolition and removal of the existing equipment. Assume code-minimum efficiency of equipment.

Option 1: Indirect coverage ASHP systems

FOR SINGLE FAMILY: Consider a single family home built in the mid-1990s. The home is 2,100 sq ft and single story. It has 3 bedrooms, an office, 2 baths, and an open living room. The construction parameters are outlined in this table [point to table on screen]. Please assume an indoor design temperature of 70°F for heating, 75°F for cooling, and a system capacity of 4 ton.

FOR MULTIFAMILY: Consider a multifamily building built in the mid-1990s. The residence has an open floor plan with two-bedrooms and 1 bath. It is 1,080 sqft in the middle to upper portion of a building. The construction parameters are outlined in this table [point to table on screen]. Please assume an indoor design temperature of 70°F for heating, 75°F for cooling, and a system capacity of 3 ton.

D1. What is the approximate cost to the customer (including materials and labor) of installing a heat pump system for this home?

D1a. What percentage of costs come from labor vs. materials?

[IF DUCTLESS]

D2. If you did not install a head in bedroom 2, what would be the approximate cost to the customer of installing a heat pump for the home?

D2a. Does reducing the number of heads have any affects on the labor costs or material costs to the customer? If so, please describe.

[IF DUCTED]

D3. If you are not able to use existing ductwork and you did not install a register in bedroom 2, what would be the approximate cost to the customer of installing a heat pump to the home?

D3a. Does reducing the number of supply registers have any affects on the labor costs or material costs to the customer? If so, please describe.

Now we are going to dive into more specific details regarding the costs associated with different aspects of the installation process and materials.

Ductless system:

	Material Cost	Labor Cost
D4a. Indoor heads		
D4b. Outdoor unit		
D4c. Condensate lines		
D4d. Refrigerant piping		
D4e. Commissioning and start-up	NA	

Ducted system:

	Material Cost	Labor Cost
D4f. HP outdoor unit		
D4g. HP indoor unit		
D4h. Condensate lines		
D4i. Ductwork grills/registers		
D4j. Commissioning and start-up	NA	

Option 2: Suitable capacity ASHP systems

FOR SINGLE FAMILY: Consider a single family home built in the mid-1990s. The home is 2,100 sq ft and single story. It has 3 bedrooms, an office, 2 baths, and an open living room. The construction parameters are outlined in this table [point to table on screen]. Please assume an indoor design temperature of 70°F for heating, 75°F for cooling, and a system capacity of 4 ton.

FOR MULTIFAMILY: Consider a multifamily building built in the mid-1990s. The residence has an open floor plan with two-bedrooms and 1 bath. It is 1,080 sqft in the middle to upper portion of a building. The construction parameters are outlined in this table [point to table on screen]. Please assume an indoor design temperature of 70°F for heating, 75°F for cooling, and a system capacity of 3 ton.

D5. What is the approximate cost to the customer (including materials and labor) of installing a heat pump system for this home?

D5a. Using your best estimate, what percentage of costs come from labor vs. materials?

D6. If you install a heat pump that is [FOR SF: 3 ton, FOR MF 2 ton] instead of [FOR SF: 4 ton, FOR MF 3 ton], what is the approximate cost to the customer of installing a heat pump system for this home?

D6a. Does reducing the heat pump capacity have any affects on the labor costs or material costs to the customer? If so, please describe.

Now we are going to dive into more specific details regarding the costs associated with different aspects of the installation process and materials.

Ductless system:

	Material Cost	Labor Cost
D7a. Indoor heads		
D7b. Outdoor unit		
D7c. Condensate lines		
D7d. Refrigerant piping		
D7e. Commissioning and start-up	NA	

Ducted system:

	Material Cost	Labor Cost
D7f. HP outdoor unit		
D7g. HP indoor unit		
D7h. Condensate lines		
D7i. Ductwork grills/registers		
D7j. Commissioning and start-up	NA	

Appendix C: Unique ASHP cases

Suitable Capacity Configurations

There were several SF suitable capacity iterations that required reducing the number of directly conditioned rooms in the home. The suitable capacity configurations were all ductless systems in Climate Zones 1 through 15 for homes built between 1992 and 1998, and in all climate zones for homes built in 2022.

Table 9: Summary of SF-suitable capacity configurations with indirect coverage.

Vintage	CZ
1992-1998	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 15
2022	All 16 climate zones

Indirect Coverage Configurations

There were several MF and SF iterations of the indirect coverage ASHP system configuration that required the ASHP to change the capacity from the baseline configuration. These are listed in Table 10Table 10: Summary of MF indirect coverage iterations requiring a change in ASHP rated capacity. and Table 11Table 11: Summary of SF indirect coverage iterations requiring a change in ASHP rated capacity..

Table 10: Summary of MF indirect coverage iterations requiring a change in ASHP rated capacity.

Adjacency	Vintage	CZ	Reduced ASHP Capacity	Increased ASHP Capacity
Corner Mid Corner Upper	Pre 1978	8, 9, 16	0.5 tons or less	NA
Corner Mid Center Mid	Pre 1978	15	NA	0.5 tons
Center Upper	Pre 1978	15	NA	0.5 tons
Corner Mid Corner Upper	1992-1998	15	NA	0.5 tons

Table 11: Summary of SF indirect coverage iterations requiring a change in ASHP rated capacity.

Vintage	Ducting	CZ	Reduced ASHP Capacity	Increased ASHP Capacity
Pre 1978	Ductless and Ducted	14	Less than 0.5 tons	NA
1992-1998	Ductless and Ducted	12	0.5 tons	NA
1992-1998	Ductless and Ducted	15	NA	0.5 tons
2022	Ductless and Ducted	1, 2, 3, 5, 6, 16	0.5 tons or less	NA
2022	Ductless and Ducted	7	NA	1 ton