HEAT PUMP RETROFIT STRATEGIES FOR MULTIFAMILY BUILDINGS

April 2019

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EXECUTIVE SUMMARY

Heat pump conversions of existing multifamily buildings are an important part of many climate action plans for metropolitan areas around the United States.[1,2,3,4] The main advantages of heat pumps in these action plans is to increase heating efficiency significantly beyond what even the best combustion systems can provide. In addition, moving from combustion-based heating systems to electricity-driven systems offers the benefit of using renewable energy instead of fossil fuels.[5] Multifamily buildings, defined here as having five apartments or more, that use fuel-based space heating or domestic hot water systems, have widely varying vintages and construction types across the country.[6] Retrofitting the mechanical systems of a multifamily building can be complex, depending on a mix of technical and non-technical factors.[7] While multiple effective solutions are commercially available, multifamily building heat pump integration considerations are not widely understood across the market.[8] This gap is an obstacle to adoption of heat pumps in multifamily buildings.

This report aims to help market and policy actors in the multifamily building sector better understand the technology options currently available to electrify combustion-based heating and hot water systems, in the pursuit of better environmental, economic and health outcomes. This study segments existing multifamily buildings in the U.S. into typologies based on size and existing heating system. These characteristics affect what types of heat pumps are applicable in a retrofit situation along with climate-specific considerations.

This report is not meant to describe all possible heat pump retrofits to heating systems, instead it represents many of the viable options based on today's technology. As supply of and demand for heat pumps change, along with developments of local and national regulations, new opportunities for retrofits may arise. This report is meant to illustrate potential retrofit project types, not to be conclusive in an evolving field of technology.

Section 1: Typologies of Existing Multifamily Buildings characterizes the national multifamily building stock along key attributes that govern the viability of possible heat pump retrofit projects. Each segment is roughly quantified nationally and by geographic region. The characterization generally shows that combustion-based multifamily buildings are concentrated in dense urban areas in colder climates, which frequently use whole building central heating plants. Milder climates tend to have a higher proportion of decentralized heating systems and a higher proportion of electric heating.

The key attributes of combustion-based heating system and building height are used to segment the multifamily building stock into six typologies:

- Steam heated high-rise
- Steam heated low-rise
- Hot water heated high-rise
- Hot water heated low-rise
- Forced air furnace heated
- Wall furnace or other room-by-room heated

Heat pump retrofits are segmented into major categories by location of outdoor equipment and distribution systems. The categories of retrofits are applied to the building types.

Domestic hot water (DHW) system retrofits are segmented in terms of existing conditions:

- Central DHW plant
- Distributed, tenant-space DHW plants

Section 2: Retrofit Primer for Multifamily Building Typologies describes a basic project scope, capabilities and availability of current technology for nine types of retrofits. Seven project types are for space heating and cooling, and two are for domestic hot water projects. Each combination of existing system type and heat pump technology is detailed along the lines of particular advantages, climate and geography considerations, complexity of installation, and existing barriers that need resolution to improve performance or economics. For direct comparison of key components of the projects, see Table 2 and Table 3. Key takeaways are that the lack of a simple and repeatable heat pump retrofit is a market gap that could potentially be filled by a high-performance packaged terminal unit, and that central heat pump systems may offer superlative performance, but more case studies of successful projects are needed to strengthen the value proposition.

Appendix A: Cost Estimates - Includes rough cost estimates for each technology type and for different building typologies, where applicable. Equipment costs may not vary much from one region of the country to another, but labor costs do.

Appendix B: Relative Labor Costs for Installers - Compares regional labor rates. Labor costs are roughly estimated to make up 50% of the retrofit project costs, so if labor rates are 50% less than the baseline region (New England/New York), the retrofit may cost 25% less than estimated in this paper. Costs are illustrative for general comparison between technology types, but project specific factors can multiply retrofit costs in unpredictable ways. In addition, some technologies are incentivized by utilities and governments. For example, ground source heat pumps receive federal tax credits[9] not reflected in the gross cost.

When pursuing changes to such fundamental systems in existing buildings, there are few absolute rules that predict the complexity, cost, and success of a heat pump retrofit project for any specific building. The considerations described in this paper are to help understand the main options for general categories of buildings and provide context during conversations involving retrofits of existing combustion-based systems in multifamily buildings with electric heat pumps. As more retrofits are completed across the country, case studies for specific circumstances will provide indications of convergence on considerations around cost, optimal technology, and retrofit scopes.

Further study is needed to answer open questions around:

- Real-world refrigerant leakage rates of different technologies and installation types
- How to mitigate concerns around installation complexity and refrigerants
- Repeatability of results for retrofit types across a certain building type – convergence of aspects of heat pump retrofits to enable better cost and feasibility estimates, which can help shape policy and incentive discussions going forward.

REPORT CONTENTS

DEFINITIONS

AWHP: Air-to-water heat pump, also known as a reverse-cycle chiller, which exchanges energy with outdoor air to condition water for heating and cooling. In some buildings, a source of warm air other than outdoor air may be available for use as a heating energy source, but in most multifamily scenarios, the air source will be ambient outdoor air

BA Climate Zone: Building America Climate Zone definitions used in RECS – see Appendix B for zone divisions

ccASHP: cold-climate air source heat pump, typically a split heat pump for residential or single apartment use, that can hold its rated capacity down to an ambient air temperature of five degrees Fahrenheit

DHW: Domestic hot water

EPA: Environmental Protection Agency

GHG: Those gases, such as water vapor, carbon dioxide, nitrous oxide, methane, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride, that are transparent to solar (short-wave) radiation but opaque to long-wave (infrared) radiation, thus preventing long-wave radiant energy from leaving Earth's atmosphere. The net effect is a trapping of absorbed radiation and a tendency to warm the planet's surface[10]

GSHP: Ground-source heat pump - a water source heat pump which exchanges heat with the ground using water piping

GWP: Global Warming Potential, an index used to compare the relative radiative forcing of different gases without directly calculating the changes in atmospheric concentrations. GWPs are calculated as the ratio of the radiative forcing that would result from the emission of one kilogram of a greenhouse gas to that from the emission of one kilogram of carbon dioxide over a fixed period of time, such as 100 years[11]

HPWH: Heat pump water heater, a term generally referring to integrated tank water heaters used in single family homes; technically these are a form of air-to-water heat pumps

MBH: Thousand BTU per hour, BTU being a British Thermal Unit, or 1/3,412 kWh

Mini-split: a small capacity split heat pump that can serve up to four zones (typically) with a single small outdoor unit located nearby on an outside wall or roof. These systems are commonly used to add cooling to a home as a middle ground between window air conditioner units and a whole-house central cooling system

PTAC: Packaged terminal air conditioner, sometimes paired with a heating coil from a central steam or hot water plant, or direct gas-fired or electric resistance heat

PTHP: Packaged terminal heat pump

RECS: Residential Energy Consumption Survey, a study completed by the Energy Information Agency to classify housing types across the United States

TBTU: Trillion BTU

VRF: Variable refrigerant flow, a name used in industry to define central heat pump plants with refrigerant distribution systems serving multiple spaces

WSHP: Water source heat pump, meaning a water to air heat pump in this context

HEAT PUMPS DEFINED

For the purposes of this report, the following definition of heat pumps is appropriate:

An electric heat pump is an energy efficient heating and cooling system that can heat buildings by moving heat from outdoors to indoors (during winter) and cool buildings by moving heat from indoors to outdoors (during summer). Because a heat pump moves heat rather than generating it, [heat pumps have typical efficiencies between 200 and 400 percent.]

A heat pump heats or cools buildings through a vapor-compression refrigerant cycle connecting an outdoor compressor with an indoor heat exchanger. For cooling, a heat pump is the same as an air conditioner (moving heat from inside to outside). For space heating, a heat pump reverses the flow of refrigerants and extracts heat from the outside environment - even in cold winter weather - and feeds it into the building. In addition to efficiency, a key health and safety benefit of heat pumps compared to fossil fuel-based heating is the lack of any indoor combustion emissions, such as carbon monoxide (CO), nitrogen dioxide (NO2), fine and ultrafine particles, polycyclic aromatic hydrocarbons (PAHs), and formaldehyde.[12]

Heat pumps can extract and reject heat energy from a variety of sources. Air-source heat pumps use the outdoor air and can run into capacity/efficiency constraints if the outdoor air temperature is too cold to extract heat from. The lowest operational outdoor temperature depends on the refrigerant used. Ground-source heat pumps use a water loop to extract heat from the ground or a natural body of water, where the fluctuations in temperature throughout the year are relatively small compared to fluctuations in outdoor air temperature, but additional pumping energy, though small, is needed for the ground loop and not included in efficiency ratings. Water-source heat pumps connect to a source of heat through a water loop, which can be a nearby process load, cooling load. Note that a common water-source heat pump installation in a building may use a central fuel-fired boiler as the heat source. This “boiler-source heat pump” system could be retrofitted to use a non-combustion heat source.

This report does not compare rated efficiencies, which are not representative of field performance for many retrofits. Standards are evolving to be more representative across a wider range of applications and climates.

HEAT DELIVERY METHODS

The methods to transfer heat from the heat source[13] to indoor spaces vary with the technologies.

- Packaged heat pumps keep the refrigerant circuit in a single piece of equipment. These units output heat either to the indoor air directly, or to a water loop for distribution around the building.
  - Example: a packaged heat pump that outputs to air is a packaged terminal heat pump (PTHP)
  - Example: a packaged heat pump that outputs directly to water storage is a heat pump water heater (HPWH)
  - Example: a packaged heat pump that extracts heat from water is a water source heat pump (WSHP)
- Split heat pumps have one component that extracts heat from the heat source, then sends refrigerant to a different location where heating energy is needed.
  - Example: VRFs have an outdoor unit, refrigerant piping, and indoor units in each space that transfer heat from the refrigerant to the room air
  - Example: mini-splits are like VRFs for smaller applications, particularly residential spaces
- Hybrid distribution systems are emerging that have outdoor units like a split system, but only send refrigerant to each floor, where the heat is exchanged to a water loop that distributes the heat to each room.[14] Compared to a VRF system, hybrid distribution systems require a lower volume of refrigerant, as some of the distribution system is water.

HEAT PUMPS USE REFRIGERANTS

All heat pumps use some sort of transfer fluid to move heat energy from one space to another. The most common refrigerants for comfort heating and cooling use are proprietary blends of fluorinated chemicals. Fluorinated gases such as R410a and R134a are not ozone depleting but have very high global warming potentials (GWP).[15,16] The EPA governs leakage rates of these harmful chemicals in “stationary refrigeration systems”, including comfort cooling.[17] when a refrigerant circuit has 50 pounds or more of refrigerant.[18] A central VRF plant can have more than 50 pounds of refrigerant in a circuit if the design heating capacity is greater than about 200 MBH. Such a VRF system installed today may have significant operations and leakage testing requirements imposed by the EPA.[19] Any heat pump system installed today may be impacted by future regulation governing the availability of current refrigerants and replacement equipment that is compatible with current refrigerants.

Enforcement of the requirement of the Montreal Protocol - Kigali Amendment[20] is likely[21] to require that the refrigerants in use today will be phased out from use in the U.S.[22] over the next 15-20 years.[23,24] This regulation impacts some heat pump systems more than others. Heat pumps that use split components connected by refrigerant lines such as VRF and mini-splits will be more difficult to replace because piping in occupied spaces may also need to be replaced, depending on the replacement refrigerant used. Packaged heat pumps may be easier to replace once installed, since a single piece of equipment can be swapped out for another without significant new piping. Heat pumps currently have expected lifespans of 15-20 years.[25] The overlap of refrigerant legislation and equipment life means that a potentially major technology change may be required at the end of any upcoming heat pump installation. The more complex the heat pump infrastructure in a building, the more serious a consideration this needs to be.

Refrigerant content normalized by heating capacity varies by technology type, as shown in Table 1 using an example product for each technology type. The table shows that packaged heat pumps tend to use less refrigerant to meet a given heating load. The exception is hybrid VRF systems, which use water for energy distribution to each occupied space from each branch box, reducing the amount of total refrigerant in the system, since some distribution piping is filled with water.

Table 1. Capacity-specific refrigerant content of four types of heat pumps.

Heat Pump Type	Refrigerant	GWP	Pounds of Refrigerant per 12,000 BTU/hr Heating Capacity	Packaged or field-assembled refrigerant circuit	Refrigerant leak risk
Space Heating					
PTHP[a]	R410a	2088	2.2	Packaged	Indoor coil
WSHP[b]	R410a	2088	2.2	Packaged	Indoor coil
Small split system – ccASHP[c]	R410a	2088	2.6	Field-assembled	Field-assembled piping and indoor coil
R410 VRF[d]	R410a	2088	3.7 to 10 [26]	Field-assembled	Field-assembled piping and indoor coil
R32 Hybrid Water+VRF[e]	R32	675	1 to 2.5	Field-assembled	Field-assembled piping and indoor coil
R410 Hybrid Water +VRF[f]	R410a	2088	1 to 4	Field-assembled	Field-assembled piping and indoor coil
Domestic Hot Water					
Residential DHW HPWH[g]	R744	1	1	Packaged	Outdoor unit
Central AWHP[h]	R134a	1,400	0.7	Packaged	Outdoor unit

a Based on Islandaire EZED15, heating capacity: 12,290 BTU/hr, R410a content: 36.3 ounces
b Based on ClimateMaster TRC, heating capacity: 9,500BTU/hr, R410a content: 28 ounces
c Based on Fujitsu 18RLX, heating capacity: 21,600 BTU/hr, R410a content: 74.1 ounces
d Based on Fujitsu Airstage V-II, heating capacity: 81,000 BTU/hr, R410a content: 395.2 ounces
e Based on Mitsubishi R32 HVRF R2, heating capacity 127,950 BTU/hr, R32 content: 183.5 ounces – 448 ounces
f Based on Mitsubishi R410 HVRF R2, heating capacity 127,950 BTU/hr, R410a content: 183.5 ounces – 1334 ounces
g Based on Sanden SanCO2, heating capacity 15,400 BTU/hr, R744 content: 22 ounces
h Based on Colmac HPA15, heating capacity 267,100 BTU/hr, R134a content: 250 ounces

SECTION 1: TYPOLOGIES OF EXISTING MULTIFAMILY BUILDINGS

SPACE HEATING AND COOLING TYPOLOGIES

Typology generation focused on relevant characteristics for converting fuel-based systems to electric-based systems. This report does not focus on buildings that are already using electricity for heating or hot water, since a low-efficiency electric to high-efficiency electric conversion is a different category of retrofit than a fuel switch from gas or oil to electricity.

Six major typologies are defined based on heating system layout and building height. These characteristics are key to describing the infrastructure in the building and overall building shape and envelope characteristics, resulting in the following categories:

Steam High Rise – mostly older (pre-1980s) large multifamily buildings in cities use a steam boiler and steam pipes throughout the building to each room. Cooling, if present, is typically done with window or through wall AC units.

Steam Low Rise – garden-style 2-3 story apartment complexes with boiler plants in a basement or mechanical room, sometimes using underground piping between buildings to share a boiler plant. Cooling, if present, is typically done with window or through wall AC units.

Hot Water High Rise – taller and newer (1980s and on) buildings with either baseboard heating or fan coil units. Cooling is sometimes provided through the same piping but can also be with PTACs or standard window or through wall ACs.

Hot Water Low Rise – garden-style 2-3 story apartment complexes with hot water boilers in a basement or mechanical room feeding baseboards or fan coil units in each room. Cooling is typically done with window or through wall AC units.

Furnace/ Hot Air – most likely low-rise buildings with individual ductwork heated with a central gas furnace per apartment, usually with a built-in air conditioner unit. Found in smaller buildings with more individualized systems.

Room-by-room – gas-fired packaged heating units, sometimes referred to as gas wall furnaces, are in each room, mostly in smaller multifamily buildings. Many come in the form of gas PTACs and look like electric PTACs with a gas line to each room for heating.

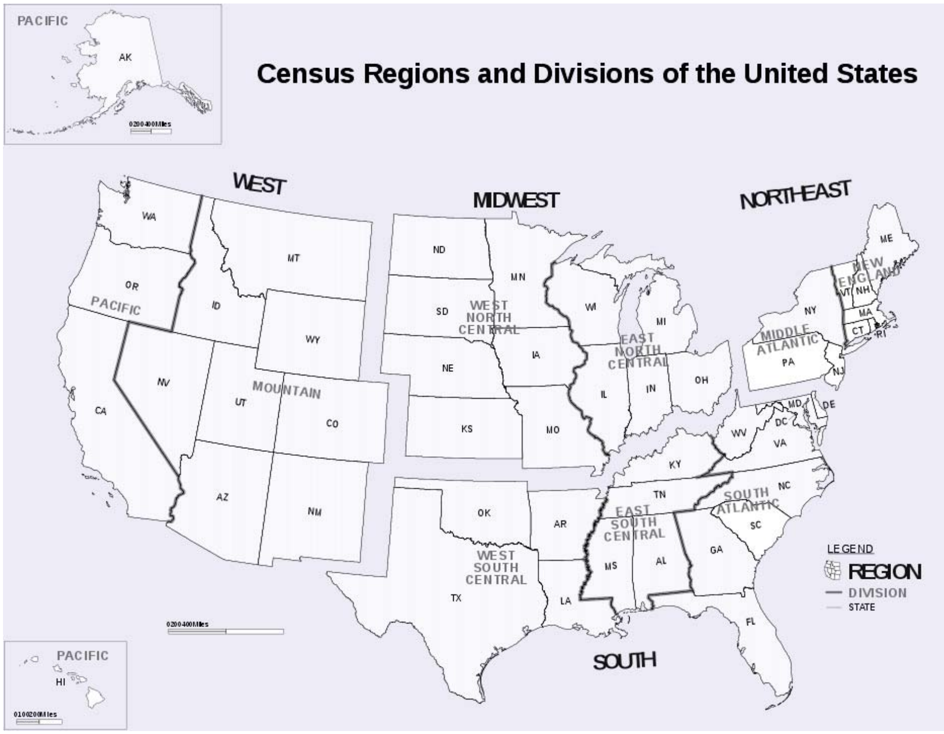

Figure 1. Census Divisions by U.S. Census Bureau[27]

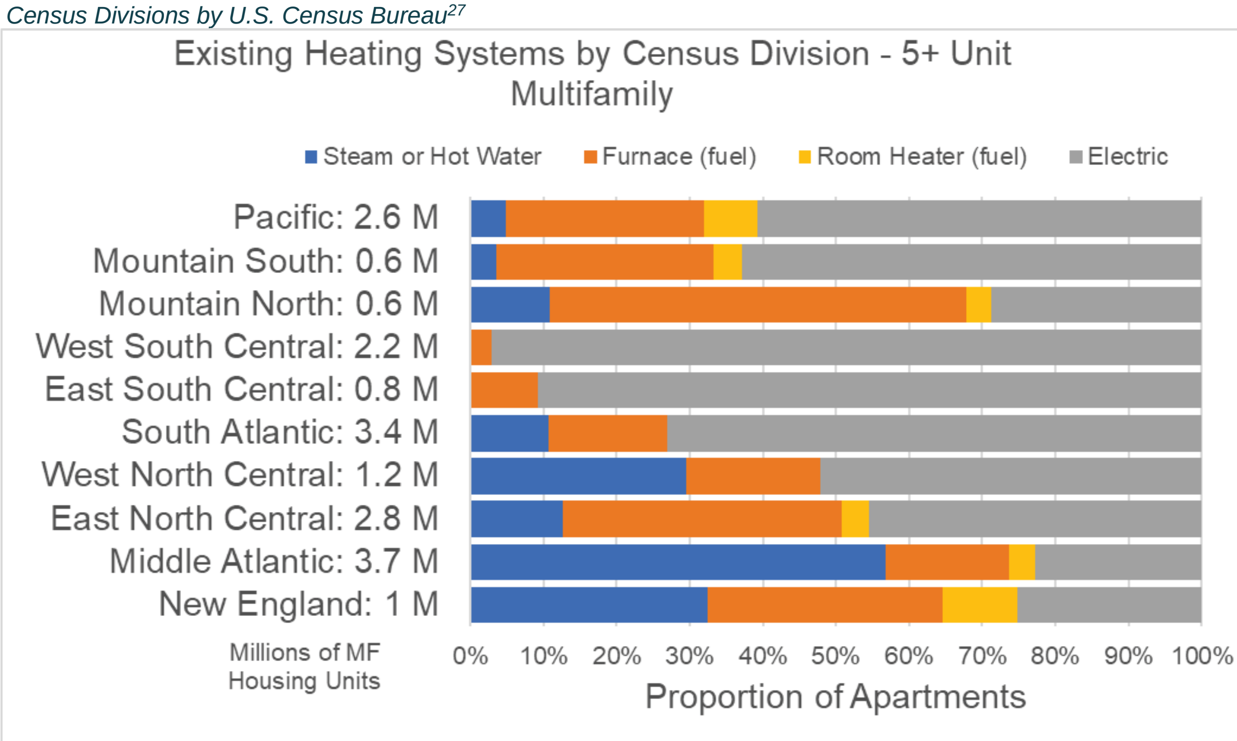

Figure 2. RECS 2015 data summarized by heating type per census division. Grey segments are some form of electric heating. The fuel-based categories – Steam or Hot Water, Furnace (fuel), and Room Heater (fuel)- are focused on as starting points in this report.

Building Height

The low-rise cutoff is three stories or less – four stories and up is high-rise - consistent with code structuring and subsequent differences in building and system layout. Heat pump retrofit considerations depend on building height, which can make it challenging to centralize or distribute new heat pump equipment and infrastructure throughout a multifamily building.

Fuel-Based Heating Systems

Using the 2015 Residential Energy Consumption Survey (RECS) data set, a nationwide and regional view of multifamily housing was assessed to understand heating systems and energy use. This data breaks out multifamily housing with five units or greater per building.

Figure 2 identifies several dominant fuel-based heating system distribution types. Going from most centralized to least centralized systems in a given building:

- Multi-apartment – Steam or hot water: The first major system is the steam or hot water system, generally classified as "hydronic". In general, hydronic systems are made up of a central plant and piping distributed around multiple apartments in a multifamily building.
- Single-apartment, multi-room – Furnace: The second major heating system type is the hot air furnace. Furnaces in multifamily buildings are typically fuel-fired appliances serving a single apartment with ductwork to multiple rooms.
- Single-room – Unitized/room heater or wall furnace: The third major type of fuel-fired system is the room heater/unitized gas heater, which serves a single room. This heating type includes gas PTACs, which include an air conditioning component in the same box.
- PTHPs/Electric Resistance -- Besides gas room heaters, many multifamily buildings use low-performance PTHPs and electric resistance PTACs. While not a fuel conversion to an electric system, moving electric resistance baseboards, PTHPs, and PTAC to high-performance PTHPs is still a priority in the goal of space heating energy reduction.

Distinguishing Heating System Types

While this section combines steam and hydronic heating systems, the two are differentiated in the typology definitions because of a key difference in the retrofit strategy. There is currently no workable technology retrofit that can maintain the use of a steam distribution system with a heat pump providing the steam. The steam infrastructure can therefore not likely be reused when installing a heat pump system to provide space heating. In contrast, hydronic systems with hot water circulation can potentially reuse existing distribution infrastructure to circulate hot water that is heated by a central heat pump. Retrofit strategies for a building with a hot water hydronic system should therefore include that consideration.

Furnaces and room heaters are also broken out separately based on their frequency of use in heating climates determined in the analysis below.

Note that the absolute values of these energy quantities may not be accurate, since they rely on engineering assumptions made during the RECS analysis, and not a detailed utility analysis. According to the RECS documentation[28] (page 10), space heating and cooling end use consumption values are calculated based on

> *"…an approach of first estimating an underlying conditioned load based on building characteristics and weather/climate variables and then estimating how much energy is required to meet that load given the efficiency of the equipment and fuel used in the housing unit (e.g., a natural gas furnace that is 10 to 14 years old)."*

Still, the relative magnitudes indicate where significant amounts of fuel energy are used for space heating.

Heating System Types Mapped to Select Cities

Each geographic region of the country will have different mixes of these system types and, importantly, different space heating needs based on climate. The Building America Climate Zones, with a map shown in Appendix A, divide up the country according to the intensity of heating and cooling needs. For context, here are major cities and their respective climate zones:

Building America Climate Zone	Cold/Very Cold	Hot-Dry / Mixed Dry	Hot-Humid	Marine	Mixed-Humid
Large Metro Areas Located in Climate Zone*	Boston	Sacramento	Miami	San Francisco	New York
	Chicago	San Diego	Austin	Los Angeles	Philadelphia
	Minneapolis			Seattle	Washington DC
	Milwaukee			San Jose	Atlanta
	Detroit				
Combined Apartment Units in 5+ Unit Buildings[1]	2,082,292	486,477	1,156,118	2,523,942	4,439,178
Combined Apartment Units in 20+ Unit Buildings[1]	1,134,146	224,695	753,844	1,429,823	2,822,627

**Including surrounding metro areas; source is American Housing Survey 2015 5-year estimates.*
https://factfinder.census.gov/faces/nav/jsf/pages/searchresults.xhtml?refresh=t
1 Total unit counts are for the listed metro areas in each climate zone, not the entire climate zone

The total amount of gas and oil heating energy is greatly concentrated into the two colder climate zones, both in terms of total heating energy and heating energy use per building:

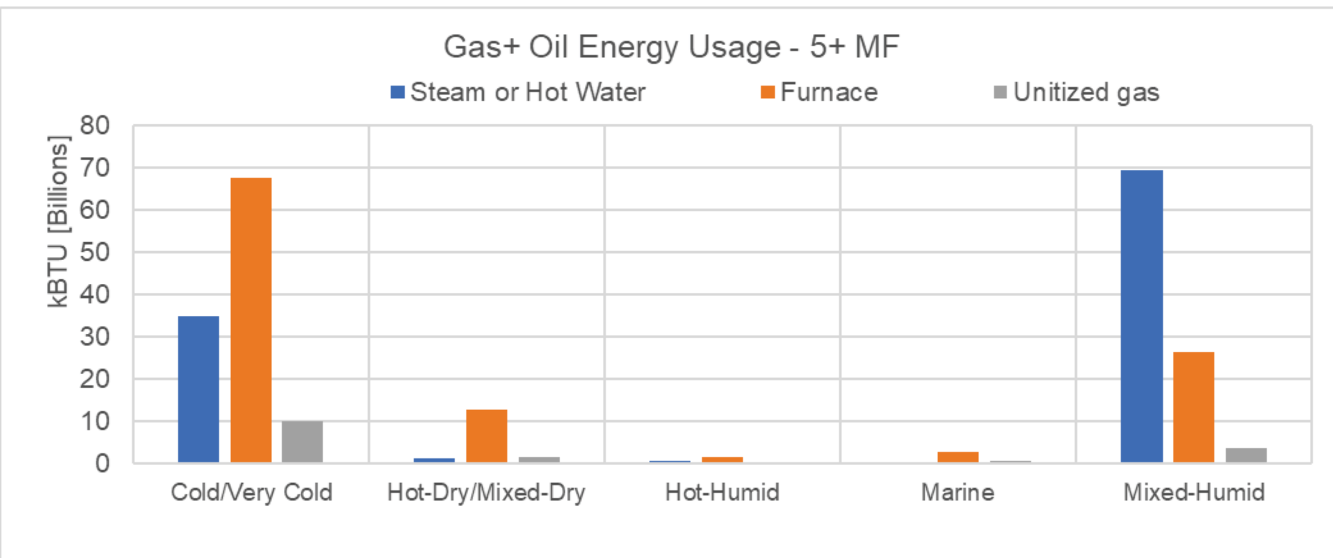

Figure 3. Total gas and oil energy use spread across the different Climate Zones, showing the concentration in the colder climates.

Overall, the primary heating fuel is natural gas, shown in Figure 4. The retrofit strategies in this report are agnostic to the existing fossil fuel used. Fuel oil has a greenhouse gas (GHG) intensity 30% higher than natural gas per energy unit burned[29]. This difference means that the potential GHG reductions when converting to heat pumps are greater for oil than gas, so converting away from fuel oil should be prioritized if the choice arises. Oil also tends to be more expensive than gas per unit energy, so a stronger financial case can be made for oil to electric conversions. Electricity GHG intensity varies greatly depending on the composition of local generation sources.[30]

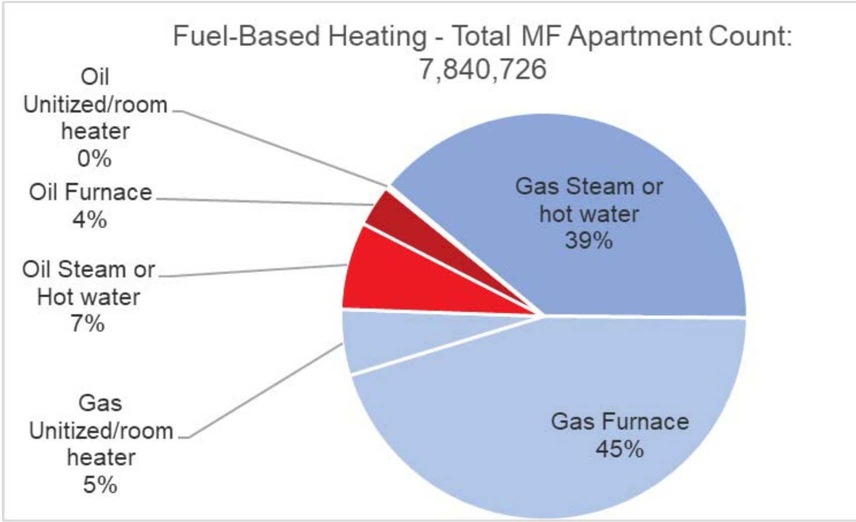

Figure 4. Portion of fuel-based heating apartment units using gas and oil.

Cooling System Types

Most multifamily building cooling systems do not use fuel-based systems for cooling. In this sense, cooling is already electrified. Unlike fuel-based heating systems, heat pump-based heating systems have cooling capabilities built in. A summary of cooling types for fuel-heated buildings is shown in Figure 5. In this chart, “Central A/C” is whole-apartment cooling via a split system with a condenser unit located outside.

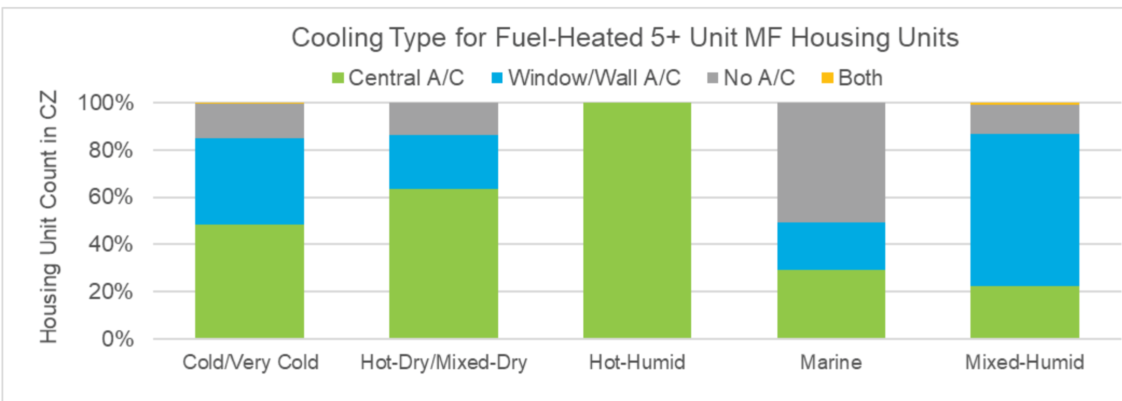

Figure 5. Cooling types in different climates. A substantial portion of buildings in the Marine climate do not have cooling of any type and may not need to consider adding one as part of a heat pump retrofit. However, most mixed-humid and cold climate buildings already have some type of cooling, which could be upgraded through a heat pump retrofit of the heating system.

Steam or hot water heating systems have a separate cooling system, mostly room-by-room but a small amount of central cooling systems. Marine climates may not have a need for cooling equipment, relying instead on fresh air ventilation and a small number of window AC units where desired. Furnace heating systems may be combined heating/cooling systems with a condenser unit feeding the same ductwork in most cases, except perhaps in very cold climates where not much cooling is needed. Where there are room or unit heaters, such devices often provide cooling as well (as with PTACs). If room heaters do not include cooling, cooling may be provided separately by window ACs.

Space Heating and Cooling Retrofit Strategies

Each system type can move to be more centralized or less centralized (more distributed). The direction to take depends partly on the technical difficulty of the transition and partly on the desired level of control by occupants and/or building owners and staff. A centralized system is more dependent on the building owners and staff, while a decentralized system is more dependent on occupants in each apartment or room. This dependence is both from a maintenance and a set point control/operations perspective.

For example, a hot water-heated building could replace the entire system with a central heat pump plant, which would be a similarly centralized system. This new system would require the building staff to maintain the central heat pumps and control the day-to-day operation of the heating system.

Alternatively, the building could decommission the hot water system, remove it, and install PTHPs in each room, which would be a move from a centralized system to a decentralized system. The residents would have the day-to-day control of their heat pumps while building staff would be involved in more substantial work such as replacement and periodic maintenance.

Figure 6 relates retrofit paths to existing heating typologies.

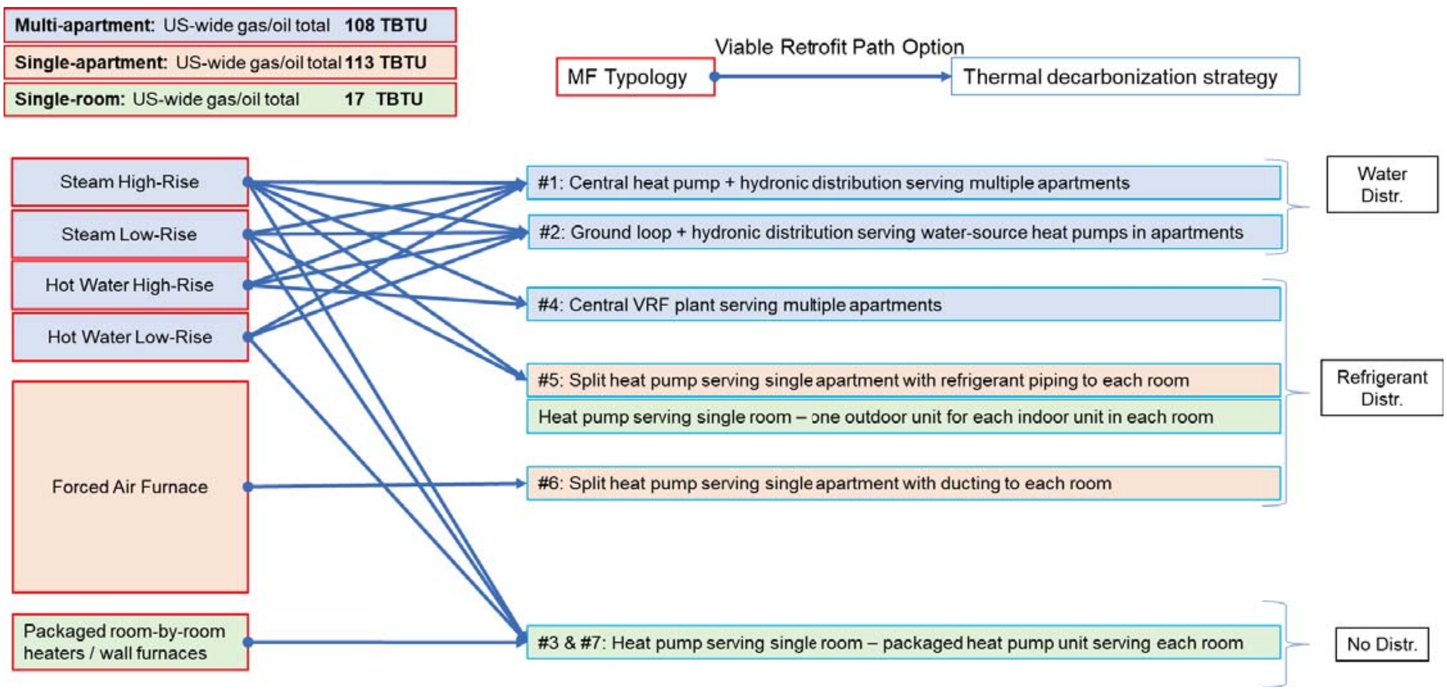

Figure 6. Space heating retrofit path options for each typology.

DOMESTIC HOT WATER

Two major typologies are defined, based on existing heating plant layout and space heating and cooling needs:

1. Central water heating plant serving all apartments from a mechanical room with hot water distribution piping; and
2. Per-apartment water heaters located in the apartments or very close by in a mechanical closet

Domestic Hot Water Typology Determination Methodology

The generation of domestic hot water (DHW) comes in two forms: central or per-apartment. Some central plants can be made up of a set of smaller residential-scale water heaters. The practical maximum for this is in the 25-apartment range. Above that, it makes more sense both in existing buildings and for future retrofits to pursue an engineered solution using a commercial-scale water heater. Either a group of small modular water heaters or a single larger unit is technically feasible, and the market of technology offerings may change to make certain products more viable in the future.

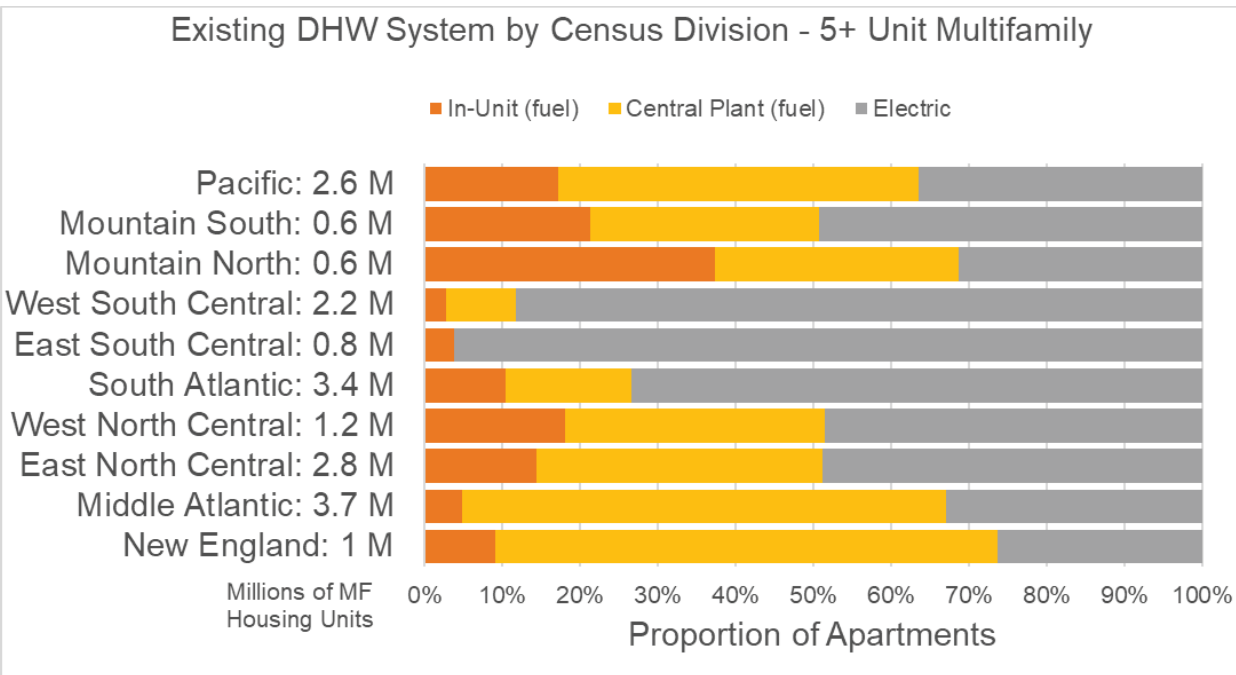

Figure 7. DHW system types by census division, from RECS 2015 data.

The strategy for DHW generation is also dependent on the best heat source for a new heat pump water heater. In climates where space cooling is needed for much of the year, the heat source can be inside the building. In climates where space heating is needed for a good portion of the year, the heat source should not be the indoor air, as this would add to the heat load of the building and/or create discomfort for the residents. This is a larger consideration for per-apartment DHW equipment than for central equipment.

DHW Retrofit Strategies

Buildings that currently have central DHW plants would likely not have available space in apartments to transition to residential scale heat pump water heaters (HPWHs) in each unit. Central HPWH plants come in the form of high capacity commercial grade heat pumps or as banks of residential scale HPWHs. Either can work for most multifamily buildings; determining the optimal strategy depends on required capacity of the plant and available indoor/outdoor space for the heat pumps.

For those buildings that already have per-apartment water heaters and are in cooling dominated climates, a HPWH can provide cooling to the apartment while generating hot water, using best practice installation techniques.

For those buildings that already have per-apartment water heaters and are in mixed climates or those with significant heating needs, a HPWH located in the conditioned space will use heat from the apartment and increase heating load. Retrofits in these climates need careful consideration of the overall heating load impact when the water heaters will use warm air from inside the apartments. If the space heating plant is inefficient or unhealthy, only outdoor air should be used as the heat source. There are two potential options if the space heating plant is inefficient or unhealthy for these climate zones, depending on the space heating and cooling setup in the building:

1. Install a residential scale split system, which uses an outdoor unit for each indoor storage tank. This method results in a space demand for outdoor units, which is more viable for spread out apartment complexes.
2. Take advantage of the hydronic space heating distribution as the heat source and use a small water-source heat pump to heat domestic hot water. The hydronic distribution must either supply heating energy year-round, or the water heater needs to switch to a different heat source.

These retrofit options are described in detail starting on page 38. Figure 8 relates the retrofit paths to the DHW typologies.

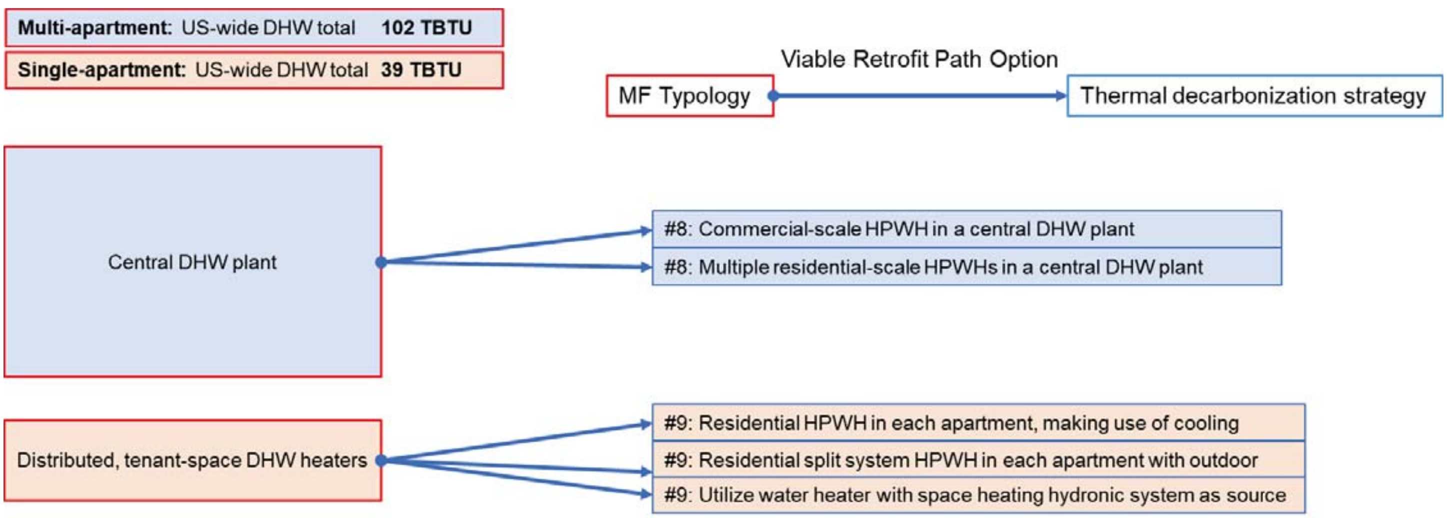

Figure 8. Retrofit strategies for DHW systems in multifamily buildings, depending on existing systems and space heating and cooling needs.

SECTION 2: RETROFIT PRIMER FOR MULTIFAMILY BUILDING TYPOLOGIES

This section describes several illustrative retrofits and their relative merits and barriers. Each sub-section is meant to:

- Describe illustrative retrofit projects to install heat pumps in apartment buildings for the primary multifamily typologies. As applicable, describe use of system for space heating, space cooling, and domestic hot water.
- Identify what determines plausibility of installing heat pump technology as a central system and unitized alternatives. Provide detail on any illustrative or model projects.
- Describe applicable heat pump technology for major configurations. Are products on the market (U.S. or other countries) for each of the major configurations in apartment building retrofits? Identify if there is a technology or product "gap" from a manufacturer or retailer perspective.
- Identify the implications of removing the existing system or keeping it as a backup system when installing the heat pump system.
- If applicable, describe opportunities to implement the retrofit in phases (e.g., replacing in-unit systems as such systems fail), and if applicable, how a phased strategy might look.
- Identify barriers that prevent apartment building owners from pursuing heat pump retrofits (e.g. availability of technology in the U.S., trained workforce, electricity cost, etc.)

RETROFIT PROJECT 1: STEAM OR HOT WATER → CENTRAL HEAT PUMPS WITH HYDRONIC DISTRIBUTION

Cost	Hydronic buildings: \$5/SF for new central plant + \$2/SF for new room heaters Steam Buildings: \$5/SF for new central plant + \$10/SF for new distribution piping and room heaters Equipment labor split: 50/50
Complexity	Low/Medium – new room heaters are likely, new piping if not already hot water; room heater replacement can be done at turnover.
Technology and/or Market	Technology offerings in the US are not as good as other countries, nascent technology and market in the U.S. with few completed projects.
Major Considerations	Hydronic distribution systems have a long life expectancy and can be paired with new central plants as needed, reducing the burden of future upgrades as technology and regulation evolves.

What: Description of the Technology

Buildings with steam or hot water heating can remove the existing central plant to install a central air-to-water heat pump (AWHP) plant. A refrigerant circuit moves heat from the outdoor air to the space heating hot water loop. Buildings with steam systems will need to replace most distribution piping and room heaters, but hot water systems can reuse existing piping and potentially the room heaters. The major difference is that the central plant is converted from a gas or oil boiler to a plant that uses heat pumps to heat the water. Some central AWHP equipment can also provide chilled water for cooling.[31] Cooling can be provided using the same distribution system if fan coil terminal units are used - baseboard convectors or radiators will not work. For heating, the room heater configuration needs to be compatible with low supply water temperatures (fan coil units or low-temp radiant panels/floors), as today's large, HFC-based heat pump plants may not be able to produce very hot water on particularly cold days. Where possible, heat pump systems should be designed to minimize any form of supplemental electric resistance heating, as this will sacrifice heating efficiency when heating loads are the highest. Domestic hot water can be produced with this system in most climates, except for very cold climates where the outlet temperature may drop to less than 140°F required to charge a central storage tank. If cooling is being provided, a water-to-water heat pump can use rejected energy from the cooling loop to heat the DHW system, making use of otherwise rejected heat. Recovery of otherwise rejected energy should be a top priority during system design as the use of this energy reduces energy needs from external sources.

Achieving the best performance from current heat pump technology requires that the water returning from the building loop is at a relatively low temperature. The heaters may need to be replaced or modified to allow for lower return water temperatures and valves added to control water flow and balance the system. No major work to existing hot water risers needs to take place in a hot water heated building.

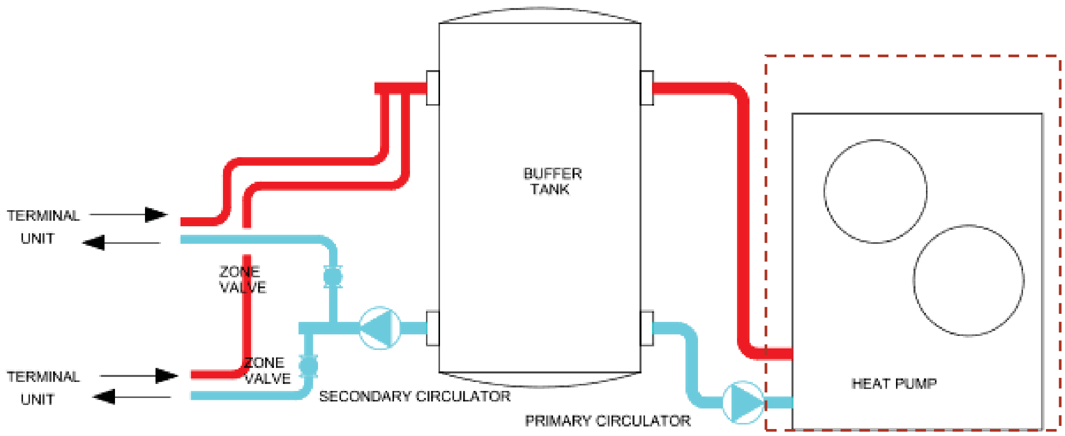

Figure 9. Central AWHP with hydronic distribution schematic. Dashed box indicates outdoor components. Image source: http://www.radiantprofessionalsalliance.org/Documents/EducationPresentations/HowtoSpecifyAWHP.pdf

Where: Use Today and Retrofit Applications

Central heat pumps that generate hot water are used around the world for domestic hot water and process loads. Similar technology can be used to provide hot water for space heating. Commercial-scale (larger than for a single-family home or single apartment) AWHPs are available in the U.S. but are only starting to be used for DHW and space heating applications in mild climates. Because the systems are not in wide use, designers and installers need education on the applications and navigating local requirements to implement AWHPs.

Centralized steam and hot water heating are used in approximately 3.6 million apartments (46%) in 5+ unit multifamily buildings across the US. Most of these are in older urban areas such as the northern Midwest, New England, and Middle Atlantic regions (see Figure 1).

Why: Benefits of this Typology

Unlike central heat pumps with a refrigerant distribution system, a hydronic distribution system uses the same water for space heating that is used in millions of homes nationwide. The distribution system can be designed, installed, and serviced the same as typical hydronic systems. For a building using hot water space heating, the difference in each apartment is relatively minor, and any modifications to the heaters may be completed in a day or less. Any required distribution work can be done by the same professionals who install and maintain hydronic equipment.

Both high rise and low-rise buildings can convert to this system. High-rise buildings can use heat exchangers to break the building up into sections, just as tall hot and chilled water buildings do today. Distribution pumps, zoning, and local controls do not fundamentally change from the existing system. Water distribution systems have lifespans of several decades and most buildings using hot water for space heating now will have piping that is in good enough condition to remain in use with the new central plant.

The entire refrigerant circuit is packaged in a single piece of equipment, which eliminates the need for modification or assembly of the refrigerant circuit during installation. The equipment has a factory sealed refrigerant circuit, requiring field-assembled water connections, not refrigerant connections. For central plants that require more than one heat pump to meet capacity, the refrigerant is packaged in each unit with water passing through each to carry the thermal energy.

As technology changes, the central heat pump plant can be modified and upgraded with little impact on the distribution system. Better heat pumps, refrigerant technology, or a different heat source altogether can replace the heat pump plant, and the same hot water distribution system can be used. This modularity provides insurance against the unknown technology and regulatory future.

With radiant and unforced convective heat, air velocity in the room is kept to a minimum, so occupants may be comfortable at a lower temperature. In contrast, fan coil and ducted heat should be designed with low air velocities in occupied areas to maintain thermal comfort.

Hot water distribution with central heat pumps give low-rise buildings in a garden-style or multi-building complexes the additional ability to potentially tie together buildings as a district heating system. This can be beneficial if nearby buildings have cooling loads while the residential buildings require heating, since a central exchanger or heat pump can transfer energy between the buildings via a district water loop. As noted in the introduction, district systems can bring efficiency benefits through this heat recovery mechanism but also introduce risks since underground water piping infrastructure can be very difficult to repair over the decades required for service, as well as being much more complicated to manage.

Whether a new hydronic distribution system is installed or existing infrastructure is used,[32] upgrades are needed to maximize system efficiency. Circulation pumps should be properly sized for the required flow rate of the new heaters and should have variable frequency drives (VFDs) to modulate flow. In conjunction, each heater should be balanced for proper flow rates using pressure independent control valves (PICVs), which stop water flow to a heater when that room's thermostat is satisfied. These upgrades reduce pumping energy and ensure adequate heat is delivered to each heater without overheating rooms.

Benefits Specific to Hot Water Buildings

A highly optimized hot water building with low temperature room heaters and a balanced distribution system may not need much or any distribution work at all. In this case, upgrades are limited to the central plant.

Benefits Specific to Steam Buildings

Large-building steam distribution systems require a delicate balance of steam, air, and water movement to provide even heat to all spaces.[33] Hot water heating systems typically use less energy than steam heating systems by distributing heat more efficiently and by being more intuitive to manage and adjust. Converting from steam distribution to hydronic distribution while maintaining a fuel-fired boiler can result in significant savings.[34]

If a building has deteriorated steam piping, putting in new hot water piping is a long-term investment that, with proper design and maintenance, can last well beyond the end of life of the central heat pump components.

Why Not: Plausibility Concerns

Major drivers of cost are the central plant and new room heaters, which likely need to be upgraded to enable lower temperature water without sacrificing heating capacity (see the What: Description of the Technology section). If fan coil heaters are to be used, new electricity service may be needed to the outer wall, though this is 120 volt (V) service, not the more expensive 230V.[35]

Heat pump conversion cost is more than the business-as-usual cost for a failing steam or hot water plant. The business-as-usual cost may come in at $1-$3/SF, with comprehensive distribution improvements estimated at another $1-$3/SF. Very few steam buildings budget for major riser replacement as a part of capital planning, so replacing the distribution system is a cost over planned work.

Central heat pumps have an expected lifespan of 15-20 years,[36] considerably less than a boiler system at 30-40 years, resulting in a higher overall equipment cost as replacements may be needed more often.

The simplest incarnation of this system would be with passive radiators or convectors, which provide space heating but not cooling. In climates with mild cooling needs and with the right building upgrades (i.e., high performance windows, balanced and controlled ventilation, air sealing for humidity control), many buildings may not require cooling. Therefore, climate zones that do not use much cooling now (see page 13) could be the best candidates for this retrofit. Climates that need some form of cooling will require buildings with this retrofit to add a second system or leave cooling up to the tenants, either adding cost or sacrificing heating/cooling performance or both. Of course, the existing mode of cooling in the building, such as window air conditioners, can go on serving the building. If supplying cooling is a priority, consider a more complex system, such as the room-by-room heat pumps described in the PTHP retrofit section of this report. A hot-water/chilled-water system can be used but the piping needs to be properly protected against corrosion from condensation when the pipes are chilled in the summer. Condensation on the outside of pipes shortens their life and can cause moisture issues behind walls and in chases. In addition, the room heaters need to be compatible with cooling, which generally means fan coil units, not heating radiators or convectors. Fan coils and designing the hydronic system is an incremental cost and complexity over a heating-only system without proven cooling energy savings compared to individual window or through-wall AC units.

Available Technology

There are several global manufacturers of central AWHPs including Colmac, Daikin, Mitsubishi, Sanden, and others. In the US, technology is limited in a few ways. Many AWHPs cannot provide water at temperatures sufficiently high enough for space heating while maintaining efficiency. With more emphasis on cold-climate-capable AWHPs, manufacturers may develop new products to enable more widespread use for space heating purposes. Technology development should focus on replacing old R-410 and R-134 designs with lower-GWP alternatives, such as R32 (a potential R410a replacement), R1234-yf (a potential R134 replacement), and R-744 (CO_2) equipment.

Outside the US, the moniker “Eco-Cute” refers to a product category of AWHPs that use R-744 (CO_2) as the refrigerant fluid to heat water for DHW purposes. The technology is common and has been in use for over a decade. With safety listing and certification in the US, several product offerings could hit the market once manufacturers decide there is a profit to be made.

Third-party control systems can be overlaid on the AWHP and hydronic system for billing and other building system integration purposes. Hydronic systems can be sub-metered for energy use, a common practice in the EU. Implementing a sub-metering program can drive significant energy savings through conservation by occupants.

When: Opportunities for Phased Retrofit

A phased retrofit is not possible for steam systems; changing out the central plant for an AWHP, upgrading the distribution system, and installing new room heaters would need to happen simultaneously.

An existing hot water system can be phased such that the apartment work is done at turnover, with the central plant replacement occurring once apartment and distribution work is complete. The balancing valves on each room heater and the new room heaters, which allow for lower return water temperatures, can be installed at apartment turnover. Room heaters and valves should be installed together. New hydronic piping, or significant modifications such as adding insulation, can be completed one zone at a time, or the entire building can be upgraded simultaneously. The existing fuel-fired boiler plant can continue to provide heating to the building while the distribution work is happening, so the project can be phased over time.

Barriers to Consider

As with all heat pumps, the cost of electricity relative to fuel should be fully analyzed. Large multifamily buildings with steam heating systems tend to have inefficiencies due to steam balancing and overheating, so there is a better chance to overcome the higher cost of electricity. Hot water systems tend to have less waste and better control, but most would still benefit from holistic assessment to optimize water temperatures, heat delivery amounts and timing, and pumping energy.

The current generation of AWHP technology is not commonly used for multifamily space heating, as many past products were not optimized to provide adequate hot water temperature or capacity on cold days. As a result, the only parties that are aware of this application are early adopters. A significant amount of consumer and engineer education could potentially enable more widespread use of the technology as an alternative to split heat pump systems.

Thermal storage plays a more important role with AWHPs because, unlike boiler plants designed to have a large maximum output and shorter firing cycles, AWHPs are typically designed to maximize runtimes with less cycling. More thermal storage is needed to compensate for the lower heating capacity during peak demand; storage is less expensive than more heat pumps to meet capacity. The new sizing requirements may require additional training of designers, including input from the AWHP manufacturer and building staff that can contribute site-specific considerations.

RETROFIT PROJECT 2: STEAM OR HOT WATER → GROUND LOOP HYDRONIC WITH ROOM-BY-ROOM HEAT PUMPS

Cost	$30+/SF
Complexity	High– new room terminal units, new condenser water piping is likely needed, ground wells or field excavation needed
Technology and/or Market	Technology is readily available for ground-source condenser loops and water-source heat pumps
Major Considerations	Ground loops introduce additional cost and complexity compared to air source alternatives.

What: Description of the Technology

Buildings with steam or hot water heating distributions can remove the central plant entirely. A ground source water loop directly feeds the building hydronic distribution, and console water-source heat pumps (WSHPs) in each room provide heating and cooling. Console, or packaged, water source heat pumps have minimal to no ducting. Each room's water source heat pump can switch between heating and cooling based on that space's controlling thermostat setting. The common water loop, known as the condenser water loop in this application, provides heat recovery so cooling and heating during the shoulder seasons can be provided simultaneously. Alternatives on this design include using a natural or man-made body of water as a heat source/sink, or, in mild climates, using a cooling tower and central heat pump injection to the condenser loop.

The ground loop can also be used to extract heat for DHW production using a central water-water heat pump. These systems are available from several manufacturers. In the summer, the use of a water-to-water heat pump for DHW on the ground loop will improve cooling efficiency by cooling the loop water.

Figure 10. Ground loop hydronic system with room-by-room heat pumps. Image source: https://www.airdistributors.com/userfiles/file/Cat_1104.pdf

Where: Use Today and Retrofit Applications

There are a few case studies of the system in new construction projects, but market penetration in the retrofit sense is minimal. In multifamily buildings, a WSHP setup with a condenser loop is often used with a central boiler plant and cooling tower. The high first cost of the room heat pumps and the pumping energy costs[37] drives this boiler loop heat pump system to be used in lieu of a ground exchange system, mostly in luxury multifamily or commercial buildings because of the high first cost.

Why: Benefits of this Typology

The benefits from the previous retrofit type apply to the hydronic conversion component of this retrofit – potential reuse of the distribution system with a long useful life using water and packaged heat pump circuit without field refrigerant connections.

There is no central plant. The central equipment is a set of circulation pipes and pumps between the ground wells and the building. The new pumping and distribution equipment will take up less space and does not have the same ventilation or exhaust requirements as a fuel-fired boiler.

Because ground temperature varies much less than air temperature, the efficiency of a ground-source heat pump remains high even on the coldest days of the year. With the best heating performance, the electricity demand on the coldest winter days doesn't spike as much as if the heat pump used outdoor air directly, so this solution may provide a benefit to the electricity grid by being a more stable and predictable load.

Heat pumps are in apartments, and the associated electricity load can be easily attached to residential electricity meters, effectively sub-metering most of the heating and cooling energy. Pumping energy for the bore field and building circulation falls on the common area meter.

Unlike packaged air source heat pumps and apartment split units, which all require 230V electricity service to each apartment, it is possible to use 120V service to power WSHPs up to 12,000 BTUh, a heating capacity sufficient for most single rooms in an apartment. If larger heating capacities are needed, higher voltage service is required with current technology offerings.

As technology changes, the terminal heat pumps can be replaced with better versions with little impact on the distribution system. Heat pumps and/or refrigerant technology can be upgraded while continuing to use the same water distribution system. This modularity provides insurance against the unknown technology and regulatory future.

District Heating and Cooling

A central condenser water loop can be compatible with a district energy solution, since the condenser water loop can absorb energy from cooling and supply energy for heating. This can be beneficial if the complex has simultaneous heating and cooling loads since the distributed heat pumps can switch to meet the heating or cooling needs of each individual space, and the common loop allows for energy recovery between heated rooms and cooled rooms. Other types of buildings and spaces can be tied in to provide a more balanced heating/cooling profile. For example, bringing a supermarket into the condenser loop can provide a significant year-round cooling load, which offsets the heating energy needed from the ground loop.

Plausibility Concerns

Many of the same concerns as the previous retrofit apply here, with some additions:

Space on the property must be drilled or trenched to install the bore field. Examples of potentially usable spaces are parking lots, playgrounds, or otherwise open areas. Wells can't be installed everywhere, since some ground conditions have natural formations which inhibit ground wells. In urban areas, underground infrastructure may block any wells. A geothermal feasibility assessment is needed for every installation. The required number of wells, and the resulting required land area, is a function of building size, so low-rise buildings with more surrounding space relative to the size of the building may be better candidates for this retrofit. High-rise buildings, especially those located in urban areas, may not have enough space for the ground wells.

Major drivers of cost are the bore field, new hot water distribution piping (depending on if the building's piping can be reused), and the terminal heat pumps in each room.

Water-source heat pumps have an expected lifespan of 10-15 years, considerably less than room radiators or convectors, resulting in more frequent equipment replacement than existing room heaters.

Available Technology

Several manufacturers in the U.S. offer console water source heat pumps, including Daikin/McQuay, Trane, and others. Console units are similar in size to radiators and convectors and can be installed in the same location as the heaters they replace.

All available WSHPs use typical refrigerants materials, mostly R410a and R134a, as the heat transfer fluid. Unlike split systems like VRF, these heat pumps are packaged and therefore at lower risk of leakage from installation issues.

When: Opportunities for Phased Retrofit

There is little opportunity for phasing this sort of retrofit. However, it is possible to install the ground loop bore field and the accompanying balance of plant while the existing heating system continues to function. When that is complete, and during a second concerted effort, the distribution work would need to be done along with installation of water source heat pumps in each apartment. The water distribution piping can't be reused, whether the existing system is steam or hot water, since the flow requirements are significantly different for today's WSHPs compared to hot water fan coils or baseboards.

Barriers to Consider

There are site-specific limitations to installing a ground loop for a building – available space is a key concern for dense urban environments, where large multifamily buildings can take up nearly all space on a lot. As with other ground loop systems, the subterranean conditions need to be assessed during a feasibility study.

There is likely a limited population of installers with the knowledge to appropriately scope and design a larger-than-residential ground loop system, so regional training can bring benefits to the potential workforce.

As with all heat pumps, the cost of electricity relative to fuel needs to be understood. Large multifamily buildings with steam heating systems tend to have inherent inefficiencies due to steam balancing and overheating, so there is a better chance to overcome the higher cost of electricity. Hot water systems tend to have less waste and better control, but the distribution upgrades can still yield considerable fuel and pumping electricity savings.

Useful Resources

Green Riverside explanation of closed loop water source heat pump systems: https://www.energydepot.com/RPUcom/library/HVAC012.asp

Daikin/McQuay console water source heat pumps compatible with this retrofit: http://www.daikinapplied.com/o365/GetDocument/Doc100/ASP_31-417_Enfinity_Console_WMHC-WMHW_LR.pdf/

Case Study: Multifamily case study of ground-source heat pumps compared to VRF, authored by BPA and Ecotope: https://www.bpa.gov/EE/Technology/EE-emerging-technologies/Projects-Reports-Archives/Documents/BPA%20Puyallup%20MV%20Report%20-%20Final.pdf

RETROFIT PROJECT 3: STEAM OR HOT WATER → PACKAGED TERMINAL HEAT PUMPS (PTHP)

Cost	\$6-\$12/SF
Complexity	Low – moderate planning consideration and minimal space disturbance; can be done at turnover, though new wall penetrations may be needed if the building does not have PTACs already.
Technology Gaps	Limitations in cold weather performance, particularly around capacity maintenance and lacking defrost strategy, exclude the current technology offerings from being viable for any climate where freezing winter temperatures are likely
Major Considerations	Best for mild climates until cold-climate performance improves, removes the potential for distribution waste in space heating systems and removes split incentive of energy cost vs energy use if tenants pay for the electricity.

What: Description of the Technology

PTHPs are reversible packaged air conditioner units installed in a wall penetration in each room. PTHPs can switch from cooling to heating, using the same refrigerant circuit and hardware to control and manage both. In heating mode, the heat source is the air directly outside the room. In cooling mode, heat is rejected into the air outside the room. Buildings that currently use a steam or hot water plant would convert each room's heater to use a PTHP for heating and cooling. The steam or hot water system would be decommissioned unless desired for use as a backup system (note: this is not typically done and requires analysis and implementation of switchover controls). The system capacity should be designed for the larger load in each room to ensure that both heating and cooling needs can be met for the building's specific climate.

Many large multifamily buildings produce DHW with the central heating plant, so the DHW system would need to be separated and retrofitted to a new technology, or the existing plant would remain to provide DHW.

Where: Use Today and Retrofit Applications

Currently, PTHP technology is typically only employed in warmer climates of the U.S. because of performance shortfalls at low temperatures. Hotels use PTHPs in climates where heating and cooling needs can vary greatly from one room to the next. The hospitality sector makes up one-half to two-thirds of all PTAC shipments in the country and may constitute a similar portion of PTHP shipments. PTACs are very similar in size and operation to PTHPs and are fairly common in newer buildings coupled with either electric resistance or a central hot water or steam plant for heating. Buildings with existing PTACs are prime candidates for a PTHP retrofit, since an opening in the wall already exists and maintenance requirements for PTHPs are similar to PTACs, making the operations transition relatively simple.

Why: Benefits of this Typology

Each heater maintains complete independence from other room heaters and the PTHP can be connected to the apartment's electricity panel. Tenants are thus in control of their own heating and cooling and are incentivized to save energy and money.

PTHPs are a relatively simple pieces of equipment and can be maintained by building staff. Compared to a radiator or convector, PTHPs require the additional maintenance of periodic filter cleaning, but compared to a steam or hot water PTAC or a hydronic fan coil unit, the maintenance remains the same.

While PTHPs use the same fluorinated gas refrigerants as VRFs and split systems, packaged heat pumps are factory assembled and leak-tested, so there are fewer opportunities for refrigerant leakage from installation. Installation is also simplified since there is no requirement for field leak testing, which requires a return visit by the installer.

Centralized fuel-based heating systems make up a large proportion of the overall multifamily fossil-fuel use as shown in Figure 3, across all vintages and styles of building. However, the complexity of centralized heating systems in the existing building stock results in energy waste and challenges in operations and maintenance. Converting to a heat pump system is an opportunity for departure from the centralized heating plant and movement towards a more distributed mechanical setup. Centralized systems burden the building owner and staff with the responsibility of operating the system to meet the needs of the tenants and they make it more challenging to meter usage by each tenant. Centralized systems may be able to tie into district heating infrastructure, which have been shown to have upfront energy benefits[38] but can also carry a risk of underground leaks,[39] which are difficult to locate and repair in dense urban environments where many multifamily buildings are found.

Compared to steam or hot water PTACs, a packaged heat pump replacement may be equivalent in equipment cost.

Why Not: Plausibility Concerns

There are many different sizes of wall openings for existing steam or hot water PTACs. High-performance PTHPs may not be offered in all sizes, so wall opening modifications could be required to fit new equipment. The envelope work can be coordinated with other required façade work, but wall modifications may add $0.5-$1/SF to a PTHP retrofit.

While product design and installation can reduce thermal bridging and air leakage, a PTHP requires a wall penetration that has neither the insulation, thermal mass, nor the air tightness of a solid wall.[40] Insulation and air sealing may be sidelined as cost-cutting measures in the design and installation of PTHPs, so care in the technology development and selection, as well as in the skill of the installers, is very important to realizing energy efficiency gains without introducing new energy penalties.

The equipment requires an electrical outlet rated for 230V. Any currently available PTHPs that operate using a lower voltage do not have the capacity to meet a typical apartment heating load when outdoor temperatures are below 40°F. With drastic heating load reductions through a heat-load-reducing retrofit, a single room in an apartment in a Mixed-humid or warmer climate may be able to be served by a 120V, 6,000 BTUh or less PTHP or through-wall air conditioner with heat pump heating, but this would require significant envelope and mechanical work beyond the heating system conversion.

Available Technology

In mild climates, where below-freezing temperatures are infrequent, most PTHPs will work reasonably well because they can maintain operation in heat pump mode. However, most PTHPs currently on the market are unable to efficiently meet the heating loads in colder climates such as Mixed-humid and Cold/Very Cold. As described in the *Barriers to Consider* section below, there are significant technological shortcomings of the current packaged heat pump offerings for use in cold climates. The limitations of the current technology are driven by a few factors. First, PTHPs are generally seen as the least-cost option for heating and cooling by the building industry, and manufacturers have responded by trying to be the least-cost option among competitors, cutting high quality features and technology to do so.[41] Second, the size and packaging of the PTHP makes for challenging design of adequate airflow past coils and condensate/ice melt removal.

A cold-climate PTHP offering needs to be developed by manufacturers so that moving from a centralized steam system to a distributed PTHP solution becomes viable.

There are several manufacturers of packaged heat pump systems including Amana, General Electric, Frigidaire, and Magic-Pak. Of the available units, some use an inverter-driven compressor which allows for incremental efficiency improvement, but those units are not tuned for cold-weather operation and no current product offering has an effective defrost strategy without serious performance compromises.[42]

Third party controls can be paired with PTHPs for monitoring and occupancy sensing remote control. However, manufacturers differ on the sophistication of controls for other building system integration purposes. The control system of most packaged heat pumps needs optimization to maximize runtime in heat pump mode instead of reverting to electric resistance backup. Many packaged heat pump solutions now have the capability to integrate remote thermostats and controls that can help optimize performance, but the on-board controls typically result in poor efficiency.

With project-specific engineering to optimize the control scheme, current PTHPs can likely improve performance reaching nearly the claimed ratings, but it is currently somewhat engineering-intensive to do so. The added controls and installation engineering cost somewhat offsets the low hardware cost of PTHPs. The combination of optimized controls, basic defrost functionality, and cold-weather capacity improvements through hardware component upgrades can make PTHPs a viable technology for the Mixed-humid climate zone and warmer.

When: Opportunities for Phased Retrofit

While PTACs are easier to replace than radiators, either can be replaced with the packaged heat pump solution when necessary, so this retrofit can be phased to coincide with normal equipment replacement cycles. This is especially true for buildings where no additional masonry or wall opening modifications are necessary (i.e., with existing PTACs). If the packaged heat pumps can be directly installed with no other modifications, then the building can simply start ordering the new part number as they would the old part number and replace worn out units normally. Existing packaged room heaters are typically replaced at a rate of 5-10% per year, so following a normal replacement schedule would have nearly all units replaced after 10 years.

Barriers to Consider

As described in the *Available Technology* section, the biggest barrier to the widespread use of packaged heat pumps is that there isn't a product on the market that can operate in heat pump mode in cold climates where the most heating energy is needed. Current products will work in mild climates, but once temperatures get close to freezing and lower, packaged heat pumps mostly revert to electric resistance heating, destroying the efficiency and economics argument for this retrofit.

With all heat pumps, the cost of electricity relative to fuel should be fully analyzed. Large multifamily buildings with steam heating systems tend to have inherent inefficiencies due to steam balancing and overheating, so there is a better chance to overcome the higher cost of electricity. If the performance of PTHPs can be improved through hardware and controls upgrades, then the packaged solution with no distribution losses and good efficiency in cold weather can likely overcome the baseline cost of steam and hot water buildings, but it is still unlikely to have an attractive financial payback.

RETROFIT PROJECT 4: STEAM OR HOT WATER HIGH RISE → CENTRAL HEAT PUMPS WITH REFRIGERANT DISTRIBUTION

Cost	$15-$20/SF, higher to include energy recovery; equipment cost / labor cost: 50/50
Complexity	High – significant upfront planning and disturbance to all spaces; can't be done at turnover
Technology and/or Market	No major issues – technology is available across the country and is increasingly installed in multifamily new construction
Major Considerations	Capital costs can't typically be justified by utility savings unless the heating and cooling distribution systems need to be completely redone; comfort and amenity benefits could create other cost recoupment

What: Description of the Technology

Commonly referred to as Variable Refrigerant Flow (VRF) systems, a central heat pump with refrigerant distribution retrofit provides heating and cooling in one system by exchanging energy with the outdoor air or a ground/water source.[43] High-rise buildings with steam or hot water heating distributions can remove the central fuel-fired plant, distribution piping, and room heaters to install a central heat pump plant (or plants), refrigerant distribution piping, and fan coil heating and cooling units in each room. Regardless of the existing system being used, all new equipment is required. The exchange with the energy source happens in a central plant location, like the old steam or hot water heating plant, though the new plant can be located on the roof or outside, not necessarily in the basement.

Domestic hot water can be produced using the VRF central plant. Some manufacturers offer water heating versions of the indoor units that can pull heat off the refrigerant loop to heat water. These indoor units can be distributed throughout the building or located centrally. They do, however, come with some limitations on which types of VRF systems they work with. For instance, with a VRF system that can only provide heating or cooling, the DHW generator may not be able to produce hot water when the system is in cooling mode.

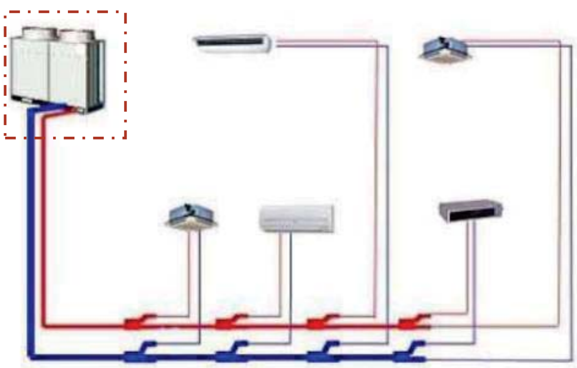

Figure 11. VRF component layout. Dashed line surrounds outdoor components. Image source: NYSERDA/Taitem[43]

Where: Use Today and Retrofit Applications

Central heat pumps are used in larger multifamily and commercial buildings with increasing use in new construction and gut rehabs of existing buildings. There are few existing buildings in the U.S. that install central heat pumps as a retrofit. Other regions of the world, particularly those with high cooling loads, use this technology more often.

Outside of major dense metropolitan areas such as New York City, most steam buildings are not high-rise, so the total number of high-rise steam buildings may be small compared to hot water and low-rise steam buildings. For example, in the Chicago metro area, 96% of multifamily buildings are low-rise, with 70% of those having central steam or hot water boilers.[44,45] High-rise buildings are likely the best candidates for VRF versus shorter building types because floor area is at more of a premium in high-rise buildings.

Why: Benefits of this Typology

This layout has advantages in large buildings that are structured to have central piping systems with minimal envelope penetrations and low-power heating units in each room. VRF heat pumps require minimal penetrations for refrigerant piping through exterior walls compared to PTACs or sleeve ACs. This can tighten the building envelope and reduces the overall heating and cooling load. The existing riser space for the steam system can provide potential space for the VRF piping.

While VRF systems do have maximum vertical and horizontal lengths of refrigerant piping runs, VRF manufacturers can design piping layouts using VRF plants on intermediate floors for even the tallest and largest buildings. In contrast, residential-scale heat pumps such as mini-splits require relatively short piping runs that present significant challenges for high-rise buildings.

Having a central plant means having central control and monitoring capabilities, an advantage for a large building with many apartments. Each manufacturer has a control system for their heat pump technology. These control systems are typically proprietary and not interchangeable amongst manufacturers. Residents get improved temperature zoning and control opportunities in each occupied space and will likely see this as an amenity upgrade. Central heat pump technology brings the option of metering each space and billing residents for what they use, even when utilizing common piping.

Buildings with a lot of working capital and the ability to take on a major upgrade can pursue this retrofit. High-rise buildings with market rate apartments, co-ops, or condominiums may be the best candidates because of the ability to meter occupants for heating and cooling costs.

Why Not: Plausibility Concerns

Current cost estimates for a VRF retrofit start at ~$15 per square foot and double from there, depending on desired system amenities and regional labor rates. Major drivers of cost are the central plant, piping installation throughout the building, which could involve drilling through floors and walls or mounting piping on the exterior of the building, and apartment hardware, possibly including electricity service upgrades (230V) to each room. This cost is substantially more than the replacement cost for a failing steam or hot water plant, which may come in at $1-$3/SF. While a complete heating distribution piping change is considerably more expensive, there are very few buildings that need new steam or hot water piping. Because of the high cost for VRF, large buildings would need to have large existing heating and cooling loads that could be reduced in the retrofit and inexpensive electricity to make this retrofit strategy worthwhile from a financial perspective.

The refrigerant concerns detailed in Heat Pumps Use Refrigerants manifest most seriously in VRF systems. Analysis of available installations points toward rates of refrigerant leakage that may affect the systems' carbon benefit.[46]

Heat pump systems that utilize split components connected with refrigerant lines have a shorter expected life span than the steam or hot water units they replace. Existing steam or hot water heaters are passive equipment, while new heat pump indoor units are active equipment, utilizing an assortment of electronics, fans, motors, and controls that are fundamentally different from the steam or hot water room heaters being replaced.

Central heat pump plant retrofits make the most sense in climates that require both heating and cooling such as Mixed-humid. The mild shoulder seasons may result in coincident heating and cooling loads within a building. To take advantage of this, the VRF system needs to include additional components for heat recovery. This feature adds cost and complexity, and in most multifamily buildings the added cost may not be worth the benefit. The costs and benefits of this additional feature need to be fully evaluated for each retrofit case.

Climates with little need for cooling, such as Very Cold and the drier Marine regions, can't take full advantage of VRF benefits because there is no existing cooling system to improve, making the technology less attractive for the price. Hot climates with little heating load have lower energy cost savings incentive and would not benefit enough from this retrofit compared to other technologies.

Buildings with a central heating plant and room air conditioning may see increased use of cooling with a central VRF system, and cooling energy could potentially increase. However, each building's savings will depend on baseline energy use and occupant use of cooling.

For high-rise buildings with steam or hot water heating systems and significant cooling needs that can be met with a central heat pump plant, a VRF distribution system with either an air or ground source is a plausible near or mid-term retrofit. However, the complexity of the system, relatively short lifespan of components, and extensive use of environmentally harmful refrigerants in a leak-prone installation should limit how and where this technology is promoted and recommended. For an air-source VRF system, the rooftop is typically a viable installation location because the heat pumps can get sufficient airflow and noise concerns are usually avoided.

Available Technology

There are several global manufacturers of central heat pump systems including Daikin (VRV), Fujitsu ("Airstage™"), LG ("MULTI V"), Mitsubishi ("CITY MULTI®"), Panasonic ("ECOi"), and others. Current offerings are manufacturer specific, so a single manufacturer would provide the central plant, piping distribution design, and room units, as well as the integrated control system.

Central units typically start at around 72 MBH heating capacity and can be installed in banks to achieve nearly any capacity, space permitting. Central heat pump plants can use air as the heat source/sink or a water loop to exchange energy with the ground or cooling tower. The physical size of the heat pumps, either air source or water source, are similar by capacity, but water source heat pumps do not require large volumes of air and can thus be installed in tighter areas. However, because of the amount of refrigerant they contain, locating the heat pumps indoors may be difficult while complying with ASHRAE Standard 34[47], which is integrated into many local codes and the International Mechanical Code (IMC)[48]. This regulation sets limits on the amount of possible refrigerant that could leak into a confined space, which would displace air and present a safety concern for occupants. The size and noise of VRF outdoor units makes them well-suited to be placed outdoors on rooftops, though some installations place them in distributed mechanical rooms throughout the building.[49]

Third-party control systems can be overlaid on the VRF system for billing and other building system integration purposes, though the actual control mechanisms and detailed algorithms are typically customized software by each manufacturer and do not allow complete integration.[50]

When: Opportunities for Phased Retrofit

The nature of the central heat pump system is a complete departure from a steam or hot water system, and the new system cannot reuse any existing components. There is little opportunity for phasing this retrofit over time and replacing components in certain areas of the building before others. The only real way to stage the project in phases is to replace a hot water or steam riser, which typically travels vertically up through all floors of a building, serving one apartment on each floor. All apartments on the riser line would need to be replaced at the same time with a central plant and distribution system that serves only those apartments. Each riser line can be completed separately. Following this strategy removes most opportunities for a completely central plant that can serve all apartments, instead creating one central plant for each riser line, though central heat pumps can be collocated as they are installed. The best timing for a retrofit is when the existing central plant and existing distribution system will need replacement in the next 2-5 years, which allows time for design and planning of the new system while the existing system is still operational.

Barriers to Consider

As with all heat pumps, the cost of electricity relative to fuel should be fully analyzed. Large multifamily buildings with steam heating systems tend to have inherent inefficiencies due to steam balancing and overheating, so there is a better chance to overcome the higher cost of electricity. Hot water systems tend to have less waste and better control, so the economics of converting to VRF will likely be unattractive. Compared to the high cost of installation, there is nearly no chance for a financial payback in energy savings alone.

The installation of a VRF system requires trained professionals certified by the manufacturer of the equipment. Installation quality is paramount because of the field-connected refrigerant piping and the risk of refrigerant leakage, which can quickly eliminate any environmental benefit of electrification. VRF systems currently require refrigerant piping to be joined together with hundreds of different junctions throughout the building. Each junction is an opportunity for leakage, and the quality of these junctions has historically ranged from leak-free to highly-leaky. Smaller and more decentralized heat pump systems use much less or no field-connected piping that is less prone to refrigerant leakage.

RETROFIT PROJECT 5: STEAM HIGH-RISE AND STEAM OR HOT WATER LOW-RISE → MINI-SPLIT HEAT PUMPS SERVING SINGLE APARTMENTS

Cost	$10-$18/SF; 50/50 split between equipment and labor
Complexity	Medium – significant upfront planning and disturbance to all spaces; can be done at turnover; need to find outdoor space near each apartment for the outdoor unit
Technology and/or Market	No major issues – technology is increasingly installed in multifamily new construction. Hardware is a direct transfer from the mature single-family home market.
Major Considerations	Quality control is critical to the success of this retrofit. Unlike other heat pump retrofits, system design and installation quality are optional add-ons, and specific language to ensure load sizing, system selection, and proper installation can determine the success of the retrofit.

What: Description of the Technology

Commonly referred to as mini-splits or ductless split systems, a residential-scale (up to ~4-ton capacity) min-split heat pump can be installed outside each apartment with relatively short piping runs to each room, providing heating and cooling for 1-5 rooms. Regardless of the existing steam or hot water system's condition, all new equipment is required. Cooling is provided by the new system. Each apartment's heating and cooling system consists of a single outdoor unit serving indoor units in each room, connected by refrigerant piping. Refrigerant pipe length requirements for these residential scale units is a maximum of around 160 ft, and performance increases with shorter line lengths. To keep the piping runs as short as possible, the outdoor unit should be placed on the exterior wall of the apartment (there are aesthetic/architectural considerations with this), on the ground outside, or on the roof, if space is available. Domestic hot water production needs to be decoupled when using this strategy.

Figure 12. Single-apartment multizone heat pump schematic[51] and common outdoor units on a rooftop.[52]

Where: Use Today and Retrofit Applications

Split heat pumps are nearly the same hardware and layout as ductless split air conditioners seen across the world in hot climates. In the past few years, many manufacturers have developed cold-climate air source heat pumps (ccASHP), which are tuned to provide sufficient heating capacity in colder climates such as the northeast U.S. The same hardware used for residential applications can be used in multifamily applications, though there are few examples of multifamily buildings that have implemented this retrofit strategy. There are a few instances of new construction multifamily that use ccASHP for each apartment and have good results.

Why: Benefits of this Typology

This retrofit is particularly useful for low-rise buildings that use steam. Low rise buildings that use hot water for space heating may more easily use a central heat pump that reuses the hot water distribution. Mini-split heat pumps have matured over the past few decades to the point that field efficiency is good, there is a high-quality installer base, and hardware costs are low enough that installation cost is not an insurmountable hurdle. Low-rise buildings typically have adequate ground or roof space, or the exterior walls are accessible enough to realize this optimal placement. High-rise buildings will have more difficulty in siting outdoor units.

The indoor units use little power for the fan coil and can be hooked up to each apartment's 120V electrical circuit. Often indoor fan coils are powered through outdoor units with wires that are bundled with refrigerant piping. The outdoor unit requires 230V service and can either be connected to a common area circuit or tied in to the apartment circuit if it has 230V service available. Connecting all heat pump components to the apartment meter makes heating and cooling cost allocation simple and transferring the cost of heating to the apartments can be viewed as a cost savings for the building owner. If direct metering is not desired, connecting the outdoor unit to the common area electricity account ensures that residents are not burdened with the cost of heating and cooling. With thermostat feedback and in-apartment controls, residents can be given adequate feedback to encourage energy conservation, while avoiding regulatory issues with direct metering space heating energy in affordable housing. All equipment can be connected to a central control overlay for monitoring and temperature limiting controls, as well as for errors and maintenance issues.

The benefit of split heat pumps over a more central VRF system is that the load for each apartment can be matched with a single outdoor unit. in this sense, each piece of equipment can be optimized for the space being served. Field studies indicate that simpler heat pump setups, where the outdoor units are best matched to the load and are not oversized, have the highest efficiency.[53]

Why Not: Plausibility Concerns

While a retrofit of split heat pumps can be less complex than a VRF retrofit, design and installation quality is just as important, which adds to overall project cost. Current cost estimates for multifamily buildings pursuing split heat pumps are around $10 per square foot for a quality installation. The installation cost is significantly higher than a replacement steam boiler, which ranges between $1-3SF. Per square foot. Major drivers of cost are labor and materials for the modifications to the building during installation, and, to a lesser extent, the equipment itself, which has decreased in cost over the past few years. Design of the system is an additional cost that should be included, as proper sizing and layout of the equipment may not be provided by the installer.

There are many issues that can decrease the efficiency of the installed heat pumps, including: excessive line lengths, equipment oversizing, poor pipe insulation, and poor siting of outdoor and/or indoor units. A study by CADMUS[54] has some discussion of these issues and how they correlate with heating performance. In general, system designers and installers need to thoroughly understand the manufacturer requirements, site-specific considerations for siting equipment, and estimated post-retrofit heating and cooling loads to ensure an efficient heat pump retrofit. At this point in the stage of the technology, it may be more worthwhile to ensure quality installation than to push for incremental hardware improvements from manufacturers.

Heat pump systems that utilize split components connected with refrigerant lines have a shorter expected life span than the steam or hot water units they replace. In addition, heat pump indoor units are typically more fragile and prone to damage compared to hot water baseboards. Existing steam or hot water heaters are passive equipment, while new heat pump indoor units are active equipment, utilizing an assortment of electronics, fans, motors, and controls that are fundamentally different than the steam or hot water room heaters being replaced. The building staff and ownership needs to make sure that residents understand the differences between the old and new systems so that equipment can be maintained and properly operated to maximize comfort and efficiency.

The split heat pump retrofit makes the most sense in climates that require both heating and cooling, and it is important to size the system based on the larger design load.

For low-rise buildings with steam heating systems and significant cooling needs that can be met with a heat pump plant, split air-source heat pump systems for each apartment are a plausible near to mid-term retrofit. However, the complexity of the installation to the outside of a large building and extensive use of environmentally harmful refrigerants in a leak-prone installation should limit how and where this technology is promoted and recommended.

Available Technology

There are several dozen manufacturers of split heat pump systems. An excellent resource for ccASHPs is the product listing maintained by the Northeast Energy Efficiency Partnership (NEEP).[55]

Typically, a single manufacturer provides the outdoor and indoor units, integrated controls, and piping requirements for installation. Third-party control systems can be overlaid on the equipment for building system integration purposes.

When: Opportunities for Phased Retrofit

The retrofit can be done at apartment turnover. While the split system can be installed when the apartment is occupied, it does require new penetrations in the wall, plus removal of the old steam heater and piping. Installing the heat pumps also includes leak testing, which is a several-hour or overnight process, so the work can’t be done in a single day. Doing work at turnover may be least disruptive to residents but requires ongoing work from the installer, as well as longer overall project time and cost compared to doing the entire building retrofit at once. Batching apartments for retrofit is likely the best way to minimize cost and improve installation consistency. One method for smaller buildings on a larger development is to retrofit one building at a time and decommission the steam heating system for each building upon completion. The retrofit could be phased according to how the current heating system is laid out, replacing one “zone” (one building, one riser, one floor) at a time.

Heating savings for the existing steam system would be realized as each heating zone can be decommissioned, reducing the building load on the central steam system.

Barriers to Consider

As with all heat pumps, the cost of electricity relative to fuel should be fully analyzed. Multifamily buildings with steam heating systems tend to have inherent inefficiencies due to imbalance and overheating, so there is a better chance to overcome the higher cost of electricity. Hot water buildings can also be overheated but tend to deliver more balanced heating. Compared to the high cost of installation, current economics show little chance for a financial payback in energy cost savings alone, but this can change if market incentives and prices adjust over time.

There are many ways to cut installation costs; reducing outdoor units by serving multiple indoor units, cutting down leak test time, using on-board controls instead of a more accurate remote thermostat, and others. These cost-cutting measures put lifetime performance and durability at risk, so cost-cutting measures should be highly scrutinized when proposed to proliferate the technology.

The installation of a split heat pump system requires trained professionals. Installation quality is paramount because of the field-connected refrigerant piping and the risk of refrigerant leakage, which can quickly eliminate any environmental benefit of electrification. Split heat pumps require refrigerant piping to be field-connected at multiple junctions between the outdoor and indoor units.

RETROFIT PROJECT 6: HOT AIR FURNACE → SPLIT HEAT PUMPS SERVING SINGLE APARTMENTS WITH DUCTING

Cost	$8-$12/SF
Complexity	Low – simple replacement to outdoor and indoor units; can be done at turnover
Technology and/or Market	No major issues – Hardware is a direct transfer from the mature single-family home market.
Major Considerations	Quality control is critical to the success of this retrofit. Unlike other heat pump retrofits, system design and installation quality are optional add-ons but can determine the success of the retrofit.

What: Description of the Technology

A central air system that has ductwork with fan coils (in a central air handler unit) can upgrade the fan coils and outdoor condenser unit to a ccASHP that provides heating and cooling. Ductwork is reused, and the fuel-fired furnace is decommissioned and removed. A residential-scale (up to ~4-ton capacity) heat pump can be installed outside each apartment with relatively short piping runs to the air handler, providing heating and cooling for 1-5 rooms. Domestic hot water production needs to be decoupled when using this retrofit strategy.

Figure 13. Single-apartment heat pump ducted components. Boxed component is outdoors, exemplified in the image on the right. Image source: https://www.trane.com/content/dam/Trane/residential/downloads/brochure/ductless/72-1287-05_HR.pdf (left) https://www.swinter.com/party-walls/air-source-heat-pumps-cold-climates-part-iii-outdoor-units/ (right)

Where: Use Today and Retrofit Applications

Ducted split heat pumps are nearly the same hardware and layout as ducted split air conditioners seen across the country as a central air conditioning solution. In the past few years, many manufacturers have developed cold-climate air source heat pumps (ccASHPs), which are tuned to provide sufficient heating capacity in colder climates such as the northeast U.S. The same hardware used for residential applications can be used in multifamily applications, though there are few retrofits of multifamily buildings that have implemented this strategy.

Why: Benefits of this Typology

This retrofit is particularly useful for buildings where each apartment has an air handler and ducting to each room. Ducted split heat pumps have matured over the past few decades to the point where field efficiency is good, there is a high-quality installer base, and hardware costs are low enough that installation cost is not an insurmountable hurdle. Each apartment's heating and cooling system consists of a single outdoor unit and a single indoor unit integrated into the air handler, with refrigerant piping in between. Refrigerant pipe length requirements for these residential scale units is a maximum of around 160 ft, and performance increases with shorter line lengths. Keeping the piping runs as short as possible, the outdoor unit should be placed on the exterior wall of the apartment, on the ground outside, or on the roof, if space is available. The best location may not be where the existing AC condenser unit is. Low-rise buildings typically have adequate ground space, or the exterior walls are accessible enough to realize this optimal placement.

The indoor fan coil uses the same power as an existing furnace air handler as the air handler fan moves the air over the coil. The outdoor unit requires 230V service and can either be connected to a common area circuit or tied into the apartment circuit if it has 230V service available. Connecting all heat pump components to the apartment meter makes heating and cooling cost allocation simple, and the newly transferred cost of heating to the apartments can be viewed as a cost savings for the building owner. In contrast, connecting the outdoor unit to the common area electricity account ensures that residents are not burdened with the cost of heating and cooling. All equipment can be connected to a central control overlay for monitoring and temperature limiting controls, as well as for errors and maintenance issues.

The benefit of split heat pumps over a more central VRF system is that the load for each apartment can be matched with a single outdoor unit. In this sense, each piece of equipment can be optimized for the space being served. Field studies indicate that simpler heat pump setups, where the outdoor units are best matched to the load and are not oversized, have the highest efficiency.[56]

Why Not: Plausibility Concerns

This retrofit is plausible for buildings that use ducted air handlers for heating and cooling. Adding ductwork can be challenging, though some apartment layouts may allow for a fairly simple and effective short-ducted retrofits. Ductless split systems can have higher-rated heating performance, though installed performance may vary, and ducted systems can have better field performance if properly installed.

While a retrofit of split heat pumps can be less complex than a VRF retrofit, design and installation quality is just as important, which adds to overall project cost. Current cost estimates for multifamily buildings pursuing split heat pumps are around $10 per square foot for a quality installation. The installation cost is significantly higher than a replacement steam boiler, which ranges from $1-3 per square foot. Major drivers of cost are labor and materials for the modifications to the building during installation, and, to a lesser extent, the equipment itself, which has decreased in cost over the past few years. Design of the system is an additional cost that should be included, as proper sizing and layout of the outdoor units may not be provided by the installer.

There are many issues that can decrease the efficiency of the installed heat pumps, including: excessive line lengths, equipment oversizing, poor pipe insulation, and poor siting of outdoor units. There are guides to good installation and design practice that need to be followed.[57]

The ducted split heat pump retrofit makes the most sense in climates that require both heating and cooling, and it is important to size the system based on the larger design load.

Available Technology

There are several dozen manufacturers of split heat pump systems. An excellent resource for ccASHPs is the product listing maintained by the Northeast Energy Efficiency Partnership (NEEP).[58] A single manufacturer provides the outdoor and indoor units, integrated controls, and piping requirements for installation.

Most split heat pump systems do not have enough refrigerant to be subject to the EPA inspection laws, so installation quality is important to minimize refrigerant leakage. Future regulation will likely require that these refrigerants be banned in the next 15-20 years. Although split heat pump systems installed today may not last 20 years, there is a potential need for new refrigerant piping to comply with updated refrigerant materials, even if only the compressor or other mechanical systems fail.

Third-party control systems can be overlaid on the equipment for building system integration purposes.

When: Opportunities for Phased Retrofit

The retrofit can be done at apartment turnover. Depending on the layout of the existing air handler, the new heat pump fan coil may be installed with minimal access to an occupied apartment. However, existing ductwork should be thoroughly inspected and tightened to improve airflow, which aids in overall efficiency. Installing the heat pumps also includes leak testing, which is a several-hour or overnight process, so the work can't be done in a single day.

Barriers to Consider

Installation cost-cutting measures should be highly scrutinized. Common cost-cutting measures could be: reducing leak testing, not refurbishing ductwork, and not ensuring proper commissioning of systems.

The installation of a mini-split heat pump system requires trained professionals. Installation quality is paramount because of the field-connected refrigerant piping and the risk of refrigerant leakage, which can quickly eliminate any environmental benefit of electrification. Split heat pumps require refrigerant piping to be field-connected between the outdoor and indoor units. Each junction is an opportunity for leakage, and the quality of these junctions has historically ranged from leak-free to highly-leaky.

RETROFIT PROJECT 7: PACKAGED GAS ROOM HEATERS → PACKAGED TERMINAL HEAT PUMPS (PTHP)

Cost	\$4-\$8/SF; equipment cost to labor cost ratio: 80/20
Complexity	Low – moderate planning consideration and minimal space disturbance; can be done at turnover
Technology Gaps	Limitations in cold weather performance, particularly around capacity maintenance and lacking a defrost strategy, preclude the current technology offerings from being viable for any climate where freezing winter temperatures are likely
Major Considerations	Best for mild climates until cold-climate performance improves. Requires 230V electricity service at the exterior walls for the PTHPs (available if a gas PTAC is used).

What: Description of the Technology

Buildings that currently use a room-by-room gas heater arrangement or gas-fired heaters combined with packaged terminal air conditioners (gas PTACs) can convert each room's heater to use a PTHP for heating and cooling. PTHPs are reversible packaged air conditioner units that can switch from cooling to heating, using the same refrigerant circuit and hardware to control and manage both. In heating mode, the heat source is the air directly outside the room. The equipment only requires an electrical outlet rated for 230V, which is already present if the existing gas heater has an air conditioning cooling component.

Domestic hot water is completely decoupled from the existing system and would be retrofit separately.

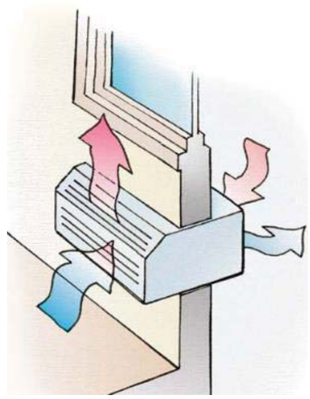

Figure 14. PTHP schematic. Image source:
https://www.greenbuildingadvisor.com/app/uploads/sites/default/files/Heating%20Options%20for%20a%20Small%20Home.pdf

Where: Use Today and Retrofit Applications

PTHP technology is employed in warmer climates of the U.S., especially in hotels where room-by-room heating and cooling needs can vary greatly. Approximately 400,000 apartments in the U.S. (5%) have gas room heaters or gas wall furnaces, the majority of which are in the Cold/Very Cold climate zones. Gas PTACs may also be found in hotels.

Why: Benefits of this Typology

Gas room heaters are generally located on the exterior wall of a room in an apartment for gas venting purposes and for the condenser component of any combined cooling equipment in the case of a gas PTAC. The location of the equipment, the required electrical service to the location, and the existing wall penetration are all required for a PTHP installation. While some modifications to the wall opening size may be needed, the retrofit of PTHPs to replace gas room heaters is the most straightforward path from gas heating to electric heat pumps. Many gas room heaters have a similar size electric heat pump version, sometimes by the same manufacturer.

Each heater maintains complete independence from other HVAC equipment and energy use billing is as simple as making sure the electricity used by the PTHP ties into the occupant's electricity panel.

Maintenance requirements are the same as for a gas PTAC, though any gas heater component of the maintenance routine is removed. There is no need for exhaust venting of a gas component.

Packaged heat pumps are factory assembled and leak-tested, so there is little chance of refrigerant leakage due to installation quality compared to split systems or central heat pump systems. Installation is also simplified since there is no requirement for field leak testing, which requires a return visit by the installer.

Compared to gas PTACs or similar equipment, a packaged heat pump replacement may be equivalent in equipment cost. Labor for potential wall opening modifications is the only source of additional cost, making this technology the least expensive option for electrification of fossil fuel systems.

Why Not: Plausibility Concerns

The limited current PTHP technology offerings will likely require some amount of envelope modification to fit the new equipment. The envelope work can be coordinated with other required façade work, but in any case, wall modifications are an added complexity to a PTHP retrofit.

While product design and installation can reduce thermal bridging and air leakage, a PTHP requires some, typically large, wall penetration that has neither the insulation, thermal mass, nor the air tightness of a solid wall. Insulation and air sealing may be sidelined as cost-cutting measures in the design and installation of PTHPs, so care in the technology development and selection, as well as in the skill of the installers, is very important to realizing energy efficiency gains.

Available Technology

There are several manufacturers of packaged heat pump systems including Magic-pak, Amana, General Electric, Frigidaire, and others. Current offerings are somewhat specific to the size of the wall penetration and available cabinet space, but most common sizes and layouts will have a heat pump offering for retrofit.

Third party control systems can take input from the packaged heat pumps for monitoring and occupancy sensing remote control. However, manufacturers differ on the sophistication of controls for other building system integration purposes. The control system of most packaged heat pumps needs optimization to maximize runtime in heat pump mode instead of reverting to electric resistance backup. Many packaged heat pump solutions now have the capability to integrate remote thermostats and controls that can help optimize performance, but the on-board controls typically result in poor efficiency.

Implications to Cooling and DHW Systems

Packaged heat pump systems can provide both heating and cooling for each room, so both systems are replaced with this retrofit. The system capacity should be designed for the larger load in each room to ensure that both heating and cooling needs can be met for the specific climate that the building is in.

Domestic hot water can't be produced by a packaged heat pump unit, so the two mechanical systems remain unlinked. In buildings with gas room heaters, the DHW is produced separately already, so this is not a departure for the typology.

When: Opportunities for Phased Retrofit

Each room heater can be replaced with the packaged heat pump solution when necessary, so this retrofit can be phased to coincide with normal equipment replacement cycles. This is especially true for buildings where no additional masonry or wall opening modifications are necessary. If the packaged heat pumps can be directly installed with no other modifications, then the building can simply start ordering the new part number and install/replace worn out units normally. Existing packaged room heaters are typically replaced at a rate of 5-10% per year, so following a normal replacement schedule would have nearly all units replaced after 10 years. Gas infrastructure needs to be carefully decommissioned as gas heaters are replaced with electric units.

Barriers to Consider

As with all heat pumps, the cost of electricity relative to fuel should be fully analyzed. Buildings using packaged gas heaters likely operate at relatively high efficiency since there are no heating distribution losses. Additionally, each room already has a thermostatic control, so overheating is not an issue. These factors add up to a low baseline energy cost, making an electrification retrofit less financially appealing.

The biggest barrier to the widespread use of packaged heat pumps is a technological one: there isn't a product on the market that can operate in heat pump mode in cold climates such as Mixed-humid and Cold/Very Cold, where buildings use the most heating energy. Current products will work in mild climates, but once temperatures get close to freezing and lower, packaged heat pumps mostly revert to electric resistance heating, destroying the efficiency, economics, and environmental argument for electrification. There are initiatives to develop better hardware based on the latest in mini-split system technology, but it appears that there will not be a viable cold-climate PTHP for the next 2-3 years. Since most packaged gas room heaters are located in Cold/Very Cold climates, the inability of current PTHPs to perform in cold climates makes this retrofit a non-starter.

RETROFIT PROJECT 8: DHW: CENTRAL DHW PLANT → CENTRAL AWHP PLANT

Cost	$1.5-$3/SF
Complexity	Low – does not require tenant space access but finding a suitable outdoor installation location may be difficult
Technology Gaps	Limitations in cold weather performance, though adequate products are available overseas. Refrigerants used by U.S.-available commercial units are HFCs. Residential-scale units use R-744 (CO_2).
Major Considerations	CO2-refrigerant units are available globally and increasingly available in the US. Unlike other heat pump applications, this retrofit can be completed with no disturbance to tenant spaces.

What: Description of the Technology

Domestic hot water is delivered via the existing distribution system, and the central plant is replaced by a large AWHP with adequate thermal storage. Alternatively, single-family size AWHPs can be joined together for smaller buildings to create a central plant. The existing water heaters can be removed or remain in place for backup.

HPWHs are best operated using long runtimes with minimal compressor cycling. This runtime strategy necessitates a buffer from the demands of the building in the form of thermal storage. By including thermal storage in the design, overall plant capacity can be decreased, since the tank acts as a buffer for demand spikes. A central storage tank can be located where space is available.

The same central AWHP plant can provide hot water energy for space heating and DHW. The system does not integrate with a steam heating system but can integrate with a hot water heating system.

The AWHPs cool air to heat water, and this cooled air may be used for some form of cooling. This cooling effect depends on hot water use, though, so the amount and timing of the cool air could be difficult to tightly control. In theory, some space cooling could be provided, offsetting other cooling equipment.

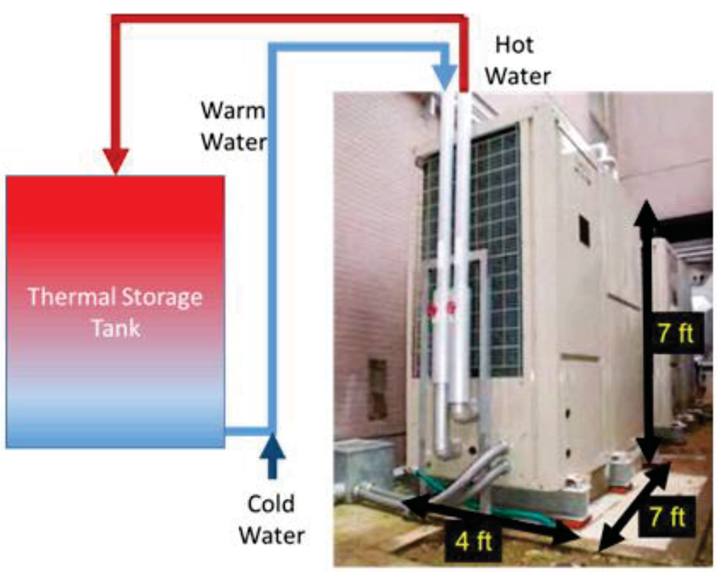

Figure 15. AWHP schematic. Image source: SWA/ Mayekawa

Where: Use Today and Retrofit Applications

Commercial-grade heat pump water heaters using fluorinated refrigerants are available in the U.S. from a few manufacturers.[59] Residential-sized products are available domestically from many manufacturers. These systems come in two varieties: units that are located inside of the thermal envelope, and units that harvest heat from outside of the thermal envelope. Current offerings for internal units use fluorinated refrigerants and are widely available at home improvement stores. One model using R-744 (CO_2) is available and can be installed to harvest heat from indoors or outdoors, even in cold climates. Residential products can be used in central plants for some multifamily buildings, with site-specific considerations.[60]

Alternative refrigerants such as R-744 (CO_2) are used for DHW generation in international markets, and these products should be brought to the U.S. market.

Why: Benefits of this Typology

The transition from fuel-fired DHW plants to heat pumps can be a low-cost way (relative to space heating) to electrify building systems. The tie-in to the existing DHW water distribution system can be reused from the existing system, so very little distribution work needs to be done specifically for this retrofit.

Central fuel-fired DHW plants are typically located somewhere in the building with access to outdoor air for ventilation and exhaust. A central AWHP plant also needs ventilation and exhaust. The ventilation required for fuel-fired equipment intake and exhaust may be reused (with some modification based on AWHP airflow requirements).

Because a heat pump water heater operates year-round and heats water by cooling air, the plant can also serve as a kind of air chiller. With careful planning and design, the DHW plant can serve to provide cooling to a space in the building that needs it, such as a building lobby or community room. These integrations of systems can double the electrical efficiency of the new heat pump plant when cooling is needed. Underground garages, basement spaces containing condensers from other systems, or other spaces with heat gains and no conditioning needs can be middle ground options. These spaces are warm enough for the heat pump to operate at high efficiency, but the space cooling does not offset a mechanical cooling load.

With easy access to equipment, operational adjustments and maintenance is less challenging for central HPWH plants than for HPWHs in each apartment. The only tenant-dependent component of the DHW energy use is consumption, which can be lowered with low-flow water fixtures and education about water conservation.

Why Not: Plausibility Concerns

AWHPs need enough airflow to operate properly. Indoor locations for a central plant may be challenging for adequate airflow ducting, since the heating plant exhaust may still be in use or can't be reused as a pathway for AWHP airflow. Many older buildings have DHW infrastructure in the basement, which may have limited opportunities for adequate airflow without significant ducting. Putting the AWHP at ground level for shorter piping connections to the basement could be difficult if there is insufficient outdoor space. One option is to put the AWHP on the roof, but this can result in long water piping and expensive electrical service to the roof if existing service is not adequate.

System design is important to enable the plant to operate as efficiently as expected. Inlet water temperature to the heat pumps needs to be appropriate for the product. Adequate thermal storage is needed with stratification to control water temperature requirements.

Outdoor water piping to and from the AWHP needs to be adequately protected from freezing in the winter. This can be accomplished with insulation, heat trace wiring, and drain-back systems in the event of power failure. Nevertheless, outdoor water piping should be minimized as much as possible.

The usage of a large AWHP may coincide with peak demand periods in a residential building and neighborhood. This new load can put additional strain on the electricity grid at critical times. To mitigate this, controls can be used to run the AWHP plant to charge the storage tank at off-peak times as much as possible. These controls may need to be customized for the building and are thus an additional engineering and software expense. Conversely, these controls can maximize runtime during windows of over-production from solar PV arrays.

Available Technology

Known suppliers of cold-climate capable large-scale AWHPs are Aermec S.P.A. and Colmac Water Heat, though others have had products in the past such as Mayekawa[61] and AO Smith. Several manufacturers sell AWHPs internationally, including Mayekawa, Mitsubishi, and Panasonic. Some AWHPs are classified as reverse cycle chillers, which are fundamentally the same thing.

The Sanden SANCO2 product uses a mini-split-sized outdoor unit with a CO_2 refrigerant circuit. Outdoor units can be grouped together outdoors with a common water manifold that feeds a building's DHW distribution. The Sanden units operate at full output capacity down to an outdoor temperature of -5°F, making them suitable for nearly all climates.

A different type of DHW generation is to use the outdoor heat pump units from a VRF system and install an indoor unit that uses the VRF refrigerant lines to heat water. This type of system requires a VRF system, and each VRF manufacturer has a specific indoor unit to tie into their VRF infrastructure. This option can only work in VRF systems that have heat recovery, since DHW is needed even when the rest of the building needs space cooling.

When: Opportunities for Phased Retrofit

The AWHP plant can be installed to replace the existing DHW plant whenever desired. No apartment access is needed for a typical installation. It is recommended to install the heat pump, electrical service, storage tank, and tie-ins all at once.

Barriers to Consider

Installation cost presents a significant barrier to owners compared to fuel-fired or electric resistance alternatives. As with all heat pumps, the cost of electricity relative to fuel should be fully analyzed.

The poor low temperature performance of non-CO_2 heat pumps necessitates supplemental systems for cold climates. In the case of steam and hot water buildings with an existing boiler, the backup may already be available. However, for buildings that are also replacing boilers with heat pumps, especially distributed heat pumps with no central plant, the backup system needs to be added in to the cost of the retrofit.

Historically there has been little demand for AWHPs for domestic hot water. Even in the residential market, heat pumps do not make up a large portion of the DHW market.

There are only a handful of installations of large-scale HPWHs in the U.S., so there is an extremely limited selection of personnel with the knowledge to design and install such systems. While design considerations are different, the level of difficulty is similar to fuel-fired boiler plant design. Education of installers and designers around the country may be needed to properly design the systems and to specify AWHPs in retrofit projects.

RETROFIT PROJECT 9: DHW: PER-APARTMENT DHW → PER-APARTMENT HEAT PUMP WATER HEATERS

Cost	$1.5-$5/SF
Complexity	Medium – replacing in-unit gas water heaters with heat pump water heaters requires unit access and new penetrations to the exterior to place outdoor units for split systems. Can be done at unit turnover.
Technology Gaps	Limitations in cold weather performance, though adequate products are available overseas. Refrigerants used by U.S.-available units are HFCs.
Major Considerations	CO2-refrigerant units are available globally and increasingly available in the U.S.

What: Description of the Technology

The existing gas-fired water heater in each apartment would be replaced with a heat pump water heater. Heating and cooling systems would not be affected, though an integrated HPWH would affect space heating and cooling loads if the HPWH uses indoor air as a heat source.

In very efficient apartments, there is a chance that a split HPWH can contribute to space heating water as well as DHW, but the two systems would typically be decoupled. Integrated HPWHs actively cool a space in a relatively uncontrolled way and should not be considered a primary cooling method but can contribute to cooling.

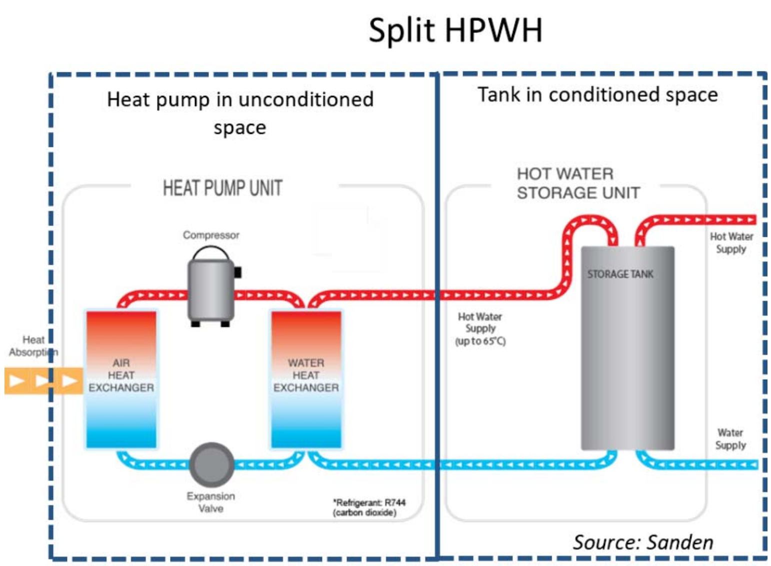

Figure 16. HPWH schematic showing one outdoor unit to one indoor tank, as would be installed per apartment or for a small cluster of apartments. Note that the split is not splitting the refrigerant circuit, just the connection between the heat pump and the water tank. Image source: Sanden

Where: Use Today and Retrofit Applications

Internationally, alternative refrigerants such as R-744 (CO_2) are more commonly used for DHW generation and are starting to become available in the U.S.[62]

Why: Benefits of this Typology

Regardless of region and climate zone, the transition from fuel-fired DHW plants to heat pumps can be a relatively low-cost way to electrify building systems. In buildings with distributed single water heaters for each apartment or a cluster of 2-4 apartments, residential HPWHs can provide excellent efficiency and utilize CO_2 instead of HFCs as a refrigerant.

The refrigerant circuit is completely housed in the outdoor unit, removing safety concerns in a leak event, and substantially reducing the chance for any leakage with the factory-sealed and tested packaged unit. No field connections of refrigerant lines are needed.

If an integrated HPWH unit is used, the apartments are eliminating what could be the only combustion appliance in the apartment, eliminating the inherent risks with a fuel-fired system in an occupied space.

Because a heat pump water heater operates year-round and heats water by cooling air, the plant can also serve as a kind of air chiller. In climates where nearly year-round cooling is needed, an integrated tank heat pump water heater can be a baseload air conditioner while heating water. However, the controls need to be carefully managed so that spaces are not overcooled during mild or cold days, and the added controls complexity may outweigh the benefits of an easier installation. In cooling-dominated climates, making use of an integrated HPWH's cooling system can double the effective electrical efficiency of the new heat pump plant when cooling is needed.

The electricity use of the heat pump can either be placed on the tenant meter or on the common area meter. Transferring the DHW energy cost to tenants when the old gas appliance was master metered can be an attractive cost reduction for building owners.

Like electric resistance water heaters, HPWHs can interact with the electricity grid to provide stabilization of short-term spikes and valleys at the grid level. Grid-enabled water heaters aggregated in multifamily buildings provide substantial grid benefits by serving as distributed energy storage, smoothing out the diurnal electricity demand profile. As electricity grids develop more renewable sources, demand flexibility is becoming increasingly important to coincide demand with available supply.[63] Reducing absolute electricity load is important for long term goals but reducing the diversity factor of the local electricity grid can make utility-scale renewable sources more useful as a baseload, enabling a greener grid. Residential HPWHs can play a role in demand flexibility.[64]

Why Not: Plausibility Concerns

Split HPWHs can be twice the material cost of integrated HPWHs and four times the cost of a gas heater. Installation of a new split system heat pump is also more expensive, requiring new water lines to the outdoor unit and mounting of the outdoor units.

If an integrated HPWH heater and tank is being proposed, the benefits and costs should be weighed regarding the additional heating load that will be put on the apartment. Unless the HPWH can use unconditioned cold air, an integrated tank HPWH installed inside the building envelope will increase the heating load. Using ductwork for the inlet or exhaust is possible, but in a cold climate, the outdoor air may not be useable per the manufacturer's specification.[65] Depending on the efficiency of the space heating system, the overall energy use of the apartment could increase with the addition of a HPWH. The apartment will also have an appliance that cools interior air and blows it around the apartment, which can make occupants cold and uncomfortable.

In-unit heat pumps require higher voltage service, which may be available in the apartments if an electric resistance heater was in use. If replacing a gas-fired water heater, electrical service may need to be upgraded for the HPWH. With a split HPWH, electrical service is only needed for the outdoor unit, so new wiring may be less invasive to the apartment. With an integrated tank HPWH, the higher voltage service is needed at the unit, and could be coordinated with an electrical service upgrade such as installing induction stoves in the apartments to replace gas stoves.

Outdoor water piping to and from the AWHP needs to be adequately protected from freezing in the winter. This can be accomplished with insulation, heat trace wiring, and drain-back systems in the event of power failure. Nevertheless, outdoor water piping should be minimized as much as possible.

When the cost of electricity is dependent on time of use, such as with large master-metered buildings, the usage of many HPWHs during the evening may coincide with peak demand periods in a residential building and neighborhood. This new load can put additional strain on the electricity grid at critical times. To mitigate this, controls can be used to run the HPWHs to charge storage tanks at off-peak times as much as possible. These controls may need to be customized for the building and are thus an additional engineering and software expense.

Available Technology

Integrated tank HPWHs are available nationwide and are a good fit for mild climates where outdoor air temperature rarely drops below 45 degrees. Some products now enable ducting of outdoor air, so the heat pump and tank can remain indoors without cooling the indoor air.

The split HPWH system is described in the previous retrofit section.

When: Opportunities for Phased Retrofit

With a split HPWH installation, there is likely a benefit to doing much of the exterior work at the same time or in groups of apartments. Indoor components in apartments can otherwise be replaced at tenant turnover.

An integrated HPWH installation can be performed at tenant turnover, though any electrical service upgrades may be better done in clusters or by building if the work is substantial.

Barriers to Consider

Low temperature performance of non-CO_2 heat pumps necessitates backup heat for cold climates. Integrated HPWHs have backup electric resistance heat, which often gets used when the tank temperature drops. Most integrated HPWHs are not made to use direct outdoor air in cold weather, so those units are not recommended any climates with significant heating loads.

Heat pumps do not make up a large portion of the DHW market. The equipment carries a cost premium over electric resistance and gas-fired units, so incentives may be necessary to encourage adoption as replacement for gas water heaters.

Table 2. Heat Pump Technologies – Major Considerations

Retrofit Project	Major Considerations
1. Central AWHPs	Existing hydronic distribution systems have a long life expectancy and can be paired with new central heat pump plants as needed, reducing the burden of future upgrades as technology and regulation evolves.
2. Ground loop + WSHPs	Ground loops introduce additional cost and complexity compared to air source alternatives.
3. Central to PTHPs	Best for mild climates until cold-climate performance improves, removes the potential for distribution waste in space heating systems and removes split incentive of energy cost vs energy use if tenants pay for the electricity.
4. VRF	Capital costs can't typically be justified by utility savings unless the heating and cooling distribution systems need to be completely redone; comfort and amenity benefits could create other cost recoupment
5. Mini splits	The much wider variety of contractors capable of installing this equipment compared to more complex central system improves choice in the market and also may make training especially important.
6. Furnace to mini splits	The much wider variety of contractors capable of installing this equipment compared to more complex central system improves choice in the market and also may make training especially important.
7. PTAC to PTHP	Best for mild climates until cold-climate performance improves. Requires 230V electricity service at the exterior walls for the PTHPs (available if a gas PTAC is used).
8. Central AWHP DHW	CO2-refrigerant units are available globally and increasingly available in the US. Unlike other heat pump applications, this retrofit can be completed with no disturbance to tenant spaces.
9. Unitized HPWH DHW	CO2-refrigerant units are available globally and increasingly available in the US.

Table 3. Comparison of heat pump retrofit projects.

Retrofit Project	Climate Zone	Installation Complexity Compared to Existing Systems	Technology Gaps
1. Central AWHPs	All	**Low/Medium –** New room heaters are likely, new piping if not already hot water; room heater replacement can be done at turnover.	**Moderate** – Technology options and completed projects in the U.S. lag some other countries,
2. Ground loop + WSHPs	All, Particularly Good for Cold/Very Cold	**High –** New room terminal units, new condenser water piping is likely needed, ground wells or field excavation needed	**Low** - Technology is readily available for ground-source condenser loops and water-source heat pumps
3. Central to PTHPs	All except Cold/Very Cold	**Low –** Moderate planning consideration and minimal space disturbance; can be done at turnover, though new wall penetrations may be needed if the building does not have PTACs already.	**Significant** - Limitations in cold weather performance, particularly around capacity maintenance and lacking defrost strategy, exclude the current technology offerings from being viable for any climate where freezing winter temperatures are likely
4. VRF	All	**High –** Significant upfront planning and disturbance to all spaces; can't be done at turnover	**Low** - Technology is available across the country and is increasingly installed in multifamily new construction.
5. Mini splits	All	**Medium** – Significant upfront planning and disturbance to all spaces; can be done at turnover; need to find outdoor space near each apartment for the outdoor unit	**Low** - Technology is increasingly installed in multifamily new construction. Hardware is a direct transfer from the mature single-family home market.
6. Furnace to mini splits	All	**Low** – Simple replacement to outdoor and indoor units; can be done at turnover	**Low** – Hardware is a direct transfer from the mature single-family home market.
7. PTAC to PTHP	All except Cold/Very Cold	**Low** – Moderate planning consideration and minimal space disturbance; can be done at turnover	**Significant** - Limitations in cold weather performance, particularly around capacity maintenance and lacking a defrost strategy, preclude the current technology offerings from being viable for any climate where freezing winter temperatures are likely
8. Central AWHP DHW	All	**Low** – Does not require tenant space access but finding a suitable outdoor installation location may be difficult	**Moderate** - Limitations in cold weather performance, though adequate products are available overseas. Refrigerants used by U.S.-available commercial units are HFCs. Residential-scale units use R-744 (CO_2).
9. Unitized HPWH DHW	All	**Medium** – Replacing in-unit gas water heaters with heat pump water heaters requires unit access and new penetrations to the exterior to place outdoor units for split systems. Can be done at unit turnover.	**Moderate** - Limitations in cold weather performance, though adequate products are available overseas. Refrigerants used by U.S.-available units are HFCs.

APPENDIX A: COST ESTIMATES

Common Assumptions	Value	Units	Source data and notes
Average rooms per apartment	2.5		1 heater per room
Average floor area per apartment, including common areas	1,000	SF	TWG link: http://www.nyc.gov/html/gbee/downloads/pdf/TWGreport_2ndEdition_sm.pdf
Design heat load of an apartment, assuming EE measures undertaken	12,000	BTU/hr	For generic equipment sizing
Baseline/BAU: Steam or Hot water boiler replacement	**Value**	**Units**	**Source data**
Distribution work to optimize system	$1.2	per SF	TWG page 64
New, optimal boiler plant	$0.58	per SF	TWG page 55 (average of "Right size steam boilers at end of life" and "Replace atmospheric boilers with sealed combustion boilers"
Total Cost	**$1.8**	**per SF**	
Central Heat Pumps with Hydronic Distribution	**Value**	**Units**	**Source data**
Cost of hot water piping and pumps if new to building	$10	per SF	TWG page 63
Passive room heaters to allow low temps, including hardware and software controls	$300	each heater	source: https://www.houseneeds.com/heating/hydronic-radiators/myson-radiator-baseboard-t6-ivc-t622-4-10
Comprehensive controls and balancing, hydronic	0.3	per SF	TWG page 63
Cost of central heat pump plant, total	$4	per SF	
Total, starting point 1: non-hydronic system	**$15**	**per SF**	
Total, starting point 2: hydronic system	**$5**	**per SF**	
Ground loop with WSHPs	**Value**	**Units**	**Source data**
Cost of vertical well	$1,000	per 12,000 BTU	source: https://www.oit.edu/docs/default-source/geoheat-center-documents/publications/heat-pump/tp38.pdf?sfvrsn=2
Cost of each heat pump	$4,000	per heater	
Apartment interior work per WSHP	$500	per heater	
Cost of condenser piping and pumps	$10	$/SF	TWG page 63
Cost of 230V electrical service to exterior wall	$7	per SF	
Total cost	**$29**	**per SF**	

PTHPs	Value	Units	Source data
Cost of 230V electrical service to exterior wall	$7	per SF	
Cost of PTHP units, including controls hardware and software	$1,500	per heater	Assuming 50% more than today's PTHPs for performance improvements
Installation labor for masonry opening and sleeve installation	$500	per heater	5 hours of work at $100/hr
Total	**$12**	**per SF**	
VRF	**Value**	**Units**	**Source data**
VRF retrofit quote	**$25**	**per SF**	Pursuing Passive: https://be-exchange.org/wp-content/uploads/2018/10/BEX_PursuingPassive_181101.pdf ~$3M for a 123,000 SF building

APPENDIX B: RELATIVE LABOR COSTS FOR INSTALLERS

To approximate the difference in labor costs, the Bureau of Labor Statistics May 2017 publication was summarized by mean annual wage for “Heating, Air Conditioning, and Refrigeration Mechanics and Installers”. The data is summarized in the map below. The retrofit work described in this report will vary in cost based on labor rate differences around the country. The costs written in each section represent New England/New York estimates, which may be higher than many areas of the country due to these labor rate differences. Most multifamily buildings exist in metropolitan areas, most of which appear to have similar labor rates.

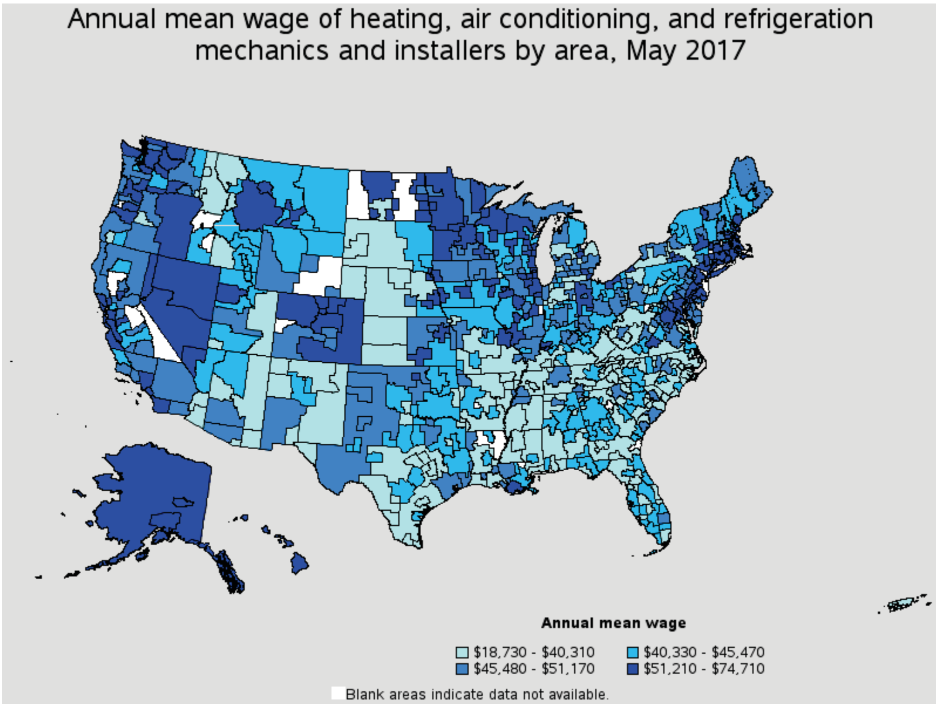

Figure 17. Color-coded map showing states with anticipated higher and lower average wages for heat pump installers. Chart source: https://www.bls.gov/oes/current/oes499021.htm#st

APPENDIX C: GEOGRAPHIC DIVISION AND CLIMATE ZONE MAPS

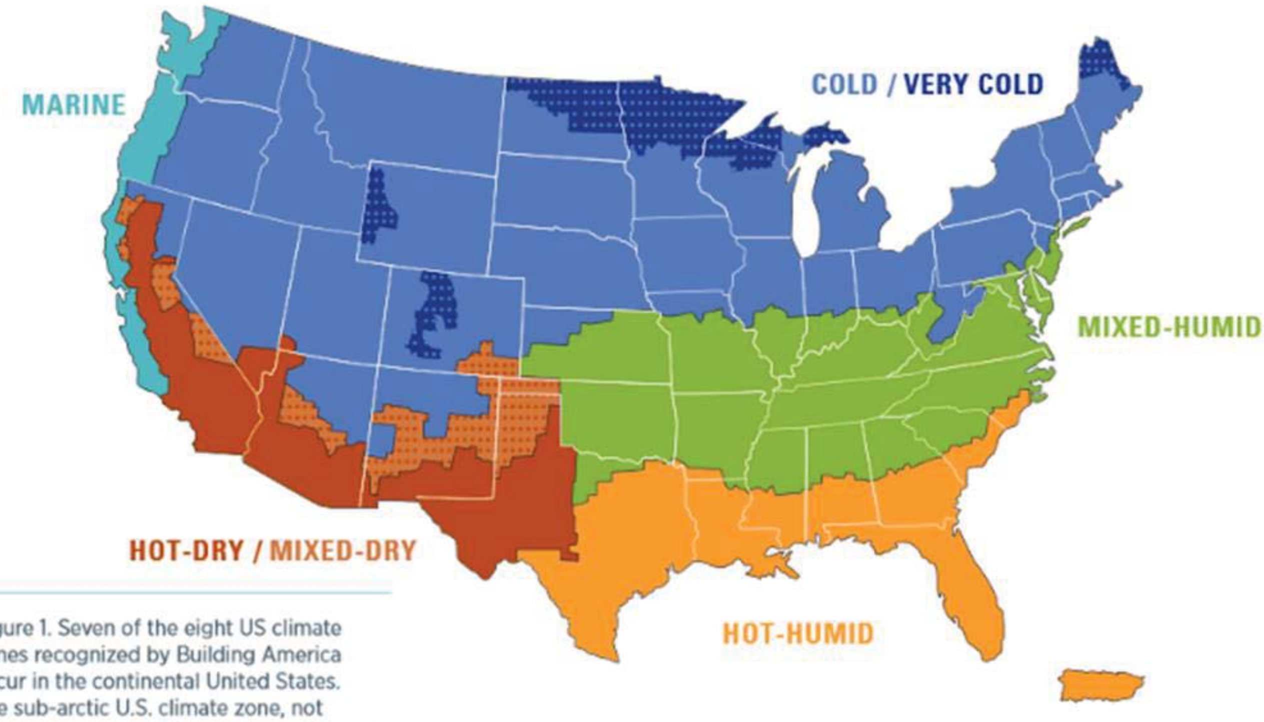

Figure 1. Seven of the eight US climate zones recognized by Building America occur in the continental United States. The sub-arctic U.S. climate zone, not shown on the map, appears only in Alaska.

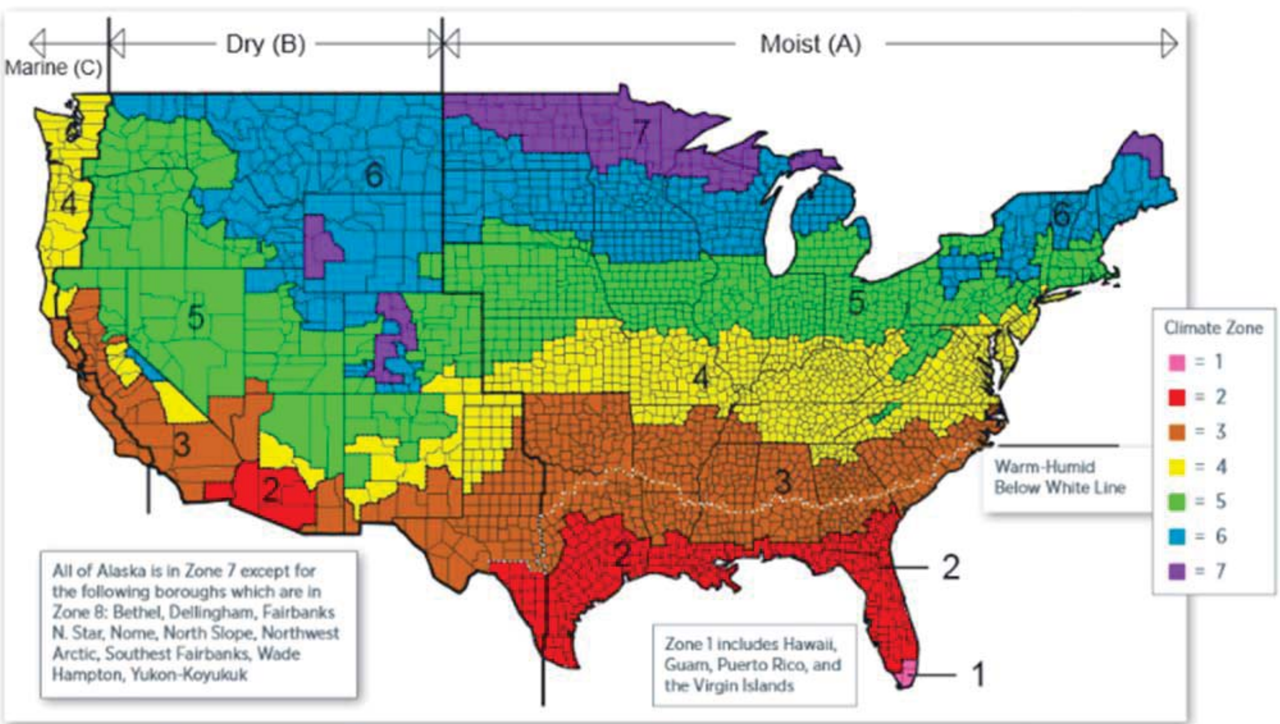

Figure 2. International Energy Conservation Code (IECC) climate regions

Figure 18. Climate zone maps from Building America (top) and IECC (bottom).

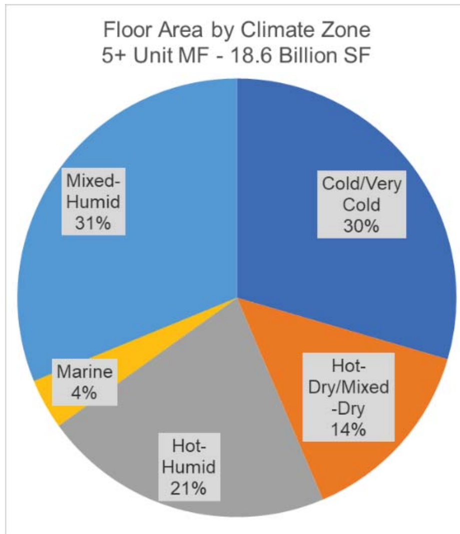

Figure 19. Proportion of housing area in each Building America Climate Zone.

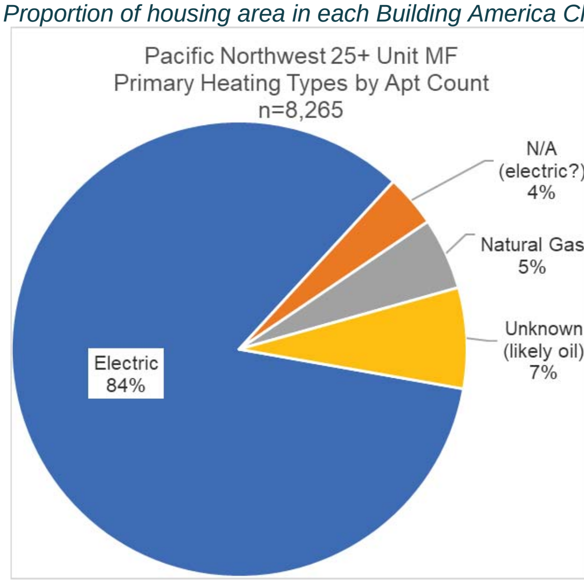

Figure 20. Pacific Northwest: The great majority of buildings use electric heating of one form another. The non-electric heating is on-site oil, wood, or natural gas. For buildings with more than 25 apartments that are not heated with electricity, audit and survey data indicates that 4% of units have stoves/fireplaces, 2.4% have furnaces, and 1.2% have boilers, and 4.6% are some other non-electric heating system.

TABLE F5. SPACE HEATING FUEL SHARES BY BUILDING SIZE

	Buildings with 5-49 units			Buildings with 50 or more units		
State	**Electric**	**Natural Gas**	**Fuel Oil**	**Electric**	**Natural Gas**	**Fuel Oil**
Georgia	72%	27%	0%	81%	18%	0%
Illinois	30%	68%	0%	40%	56%	0%
Maryland	51%	47%	0%	58%	39%	0%
Michigan	27%	69%	0%	31%	64%	0%
Missouri	58%	39%	0%	73%	25%	0%
North Carolina	88%	11%	0%	90%	9%	0%
New York	21%	58%	17%	19%	44%	33%
Pennsylvania	48%	46%	0%	53%	41%	0%
Virginia	66%	32%	0%	69%	28%	0%

Figure 21. Nationwide fuel vs electricity heating types for affordable housing. [66]

[1] New York City Mayor's Office of Sustainability. New York City's Roadmap to 80 x 50. (2016). https://www1.nyc.gov/assets/sustainability/downloads/pdf/publications/New%20York%20City's%20Roadmap%20to%2080%20x%2050_Final.pdf

[2] Farhamand, F. Palo Alto Electrification Final Report. (2016). TRC Energy Services. Page 3: *"To mitigate the emissions associated with utility-provided natural gas, the city [Palo Alto] is interested in the code feasibility and cost effectiveness of electrifying buildings."* https://www.cityofpaloalto.org/civicax/filebank/documents/55069

[3] Hopkins, Takahashi, Glick, Whited. "Decarbonization of Heating Energy Use in California Buildings". October 2018. Synapse Energy Economics, Inc. Page 1: *"…California will need to turn its attention to an overlooked corner of the emissions picture: the fossil fuels widely used to heat the buildings where Californians live and work."* http://www.synapse-energy.com/sites/default/files/Decarbonization-Heating-CA-Buildings-17-092-1.pdf

[4] Blanford, G. "Electrification and Decarbonization". Presentation at Energy and Climate Seminar, May 2017. Washington, DC. http://eea.epri.com/pdf/epri-energy-and-climate-change-research-seminar/2017/07c%20Electrification%20and%20Decarbonization%20Geoffrey%20Blanford.pdf

[5] Supra note 1 at page 62: *"Based on the analysis, between 50 and 60 percent of these [existing] buildings must pursue strategies that include a transition to efficient electric technologies for heating systems, tapping into a significantly cleaner future grid."*

[6] Mosenthal, Phil & Socks, Matt. (2015). Potential for Energy Savings in Affordable Multifamily Housing. Energy Efficiency for All. http://www.energyefficiencyforall.org/sites/default/files/EEFA%20Potential%20Study.pdf

[7] Regional Energy Efficiency Organizations (REEO). Multifamily Energy Efficiency Retrofits: Barriers and Opportunities for Deep Energy Savings. (December 2016). Page 6 briefly describes nine *"significant hurdles to achieving these levels of energy savings in the multifamily building stock."* https://neep.org/sites/default/files/resources/REEO_MF_Report.pdf

[8] One HVAC professional in the Chicago area confuses a brand for the technology in general (emphasis added): "Mitsubishi makes these incredible units called Hyper Heat. It's basically a typical condenser unit that's located outside and can deliver heat or deliver cool; **it's not like a heat pump**, which won't work in this area. These actually provide 100 percent efficiency up to -5 degrees." https://cooperator.com/article/heating-options-for-multifamily-communities/full The Mitsubishi Hyper Heating hardware is, in fact, a heat pump system: https://www.mitsubishicomfort.com/benefits/hyper-heating

[9] For guidance, see 2017 Renewable Energy Tax Credits. https://www.energystar.gov/about/federal_tax_credits/2017_renewable_energy_tax_credits

[10] Glossary, U.S. Energy Information Agency. https://www.eia.gov/tools/glossary/index.php?id=G

[11] Id.

[12] Hopkins, Takahashi, Glick, Whited. "Decarbonization of Heating Energy Use in California Buildings". October 2018. Synapse Energy Economics, Inc. Pages 10-11. http://www.synapse-energy.com/sites/default/files/Decarbonization-Heating-CA-Buildings-17-092-1.pdf

[13] For this discussion, heat pumps are described as delivering heating, but the same concepts apply if the equipment is in cooling mode.

[14] See this product from Mitsubishi as an example: Mitsubishi R410 HVRF R2

[15] R134a has a 100-year GWP of 1,300. International Panel on Climate Change (IPCC). Page 732. https://ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Chapter08_FINAL.pdf

[16] R410a has a 100-year GWP of 2,088.

[17] Stationary Refrigeration Leak Repair Requirements. Accessed 2018-11-09. https://www.epa.gov/section608/stationary-refrigeration-leak-repair-requirements

[18] 40 CFR Part 82, Subpart F. §82.152, definition of Appliance: "For any system with multiple circuits, each independent circuit is considered a separate appliance. Electronic Code of Federal Regulations (e-CFR). https://www.ecfr.gov/cgi-bin/retrieveECFR?gp=&SID=1a3e7a7905504ef2565b08bb0c7f29c7&mc=true&r=SUBPART&n=sp40.21.82.f

[19] The uncertainty in EPA requirements is summarized in this page summarizing the potential rescission of HFC regulation (accessed 2019-01-17): https://www.epa.gov/section608/revised-section-608-refrigerant-management-regulations

[20] United Nations Treaty Collection, Chapter XXVII – 2.f (2016). https://treaties.un.org/Pages/ViewDetails.aspx?src=TREATY&mtdsg_no=XXVII-2-f&chapter=27&clang=_en

[21] "Big Business Wants to Stop Trump from Leaving this Other Climate Deal". Time.com. Accessed 2018-11-09. http://time.com/5264800/donald-trump-kigali-amendment-hfcs/

[22] United States is implied as an Article 2 country, which is the first group subject to the phaseout. https://www.unenvironment.org/news-and-stories/news/kigali-amendment-montreal-protocol-another-global-commitment-stop-climate

[23] "Update on Kigali Amendment to the Montreal Protocol". Cindy Newberg, U.S.EPA, December 2016. https://www.epa.gov/sites/production/files/2016-11/documents/newberg_kigaliamend_122016.pdf . Slide 4 indicates that HFC use must be reduced by 70% by 2029 for Article 2 countries.

[24] Some U.S. states are contemplating legislation to align with these phase-outs, regardless of federal EPA actions. For example, there is now legislation in WA State to do the same thing. Policy Brief, December 2018: https://www.governor.wa.gov/sites/default/files/hfc-policy-brief.pdf; proposed legislation: https://app.leg.wa.gov/billsummary?BillNumber=1112&Year=2019&Initiative=false

[25] Estimated useful life of heat pump equipment in residential spaces is 15 years for in-unit equipment, 20 years for outdoor equipment. Fannie Mae "Instructions for Performing a Multifamily Property Assessment (Version 2.0), Appendix F". 2014. https://www.fanniemae.com/content/guide_form/4099f.pdf

[26] The amount of refrigerant in a VRF system depends on the total length of piping attached to the central plant. Longer pipe-length systems may have 8-9 lbs refrigerant per 12,000 BTU heating capacity. This number could be significantly higher if there is much more piping for a given space conditioning load.

[27] https://www2.census.gov/geo/pdfs/maps-data/maps/reference/us_regdiv.pdf

[28] EIA. 2015 Consumption and Expenditures Technical Documentation Summary. (2018) https://www.eia.gov/consumption/residential/reports/2015/methodology/pdf/2015C&EMethodology.pdf

[29] Fuel oil has 5,770 kBTU/barrel and emits 426.7 kgCO2e per barrel, so 0.07395 kgCO2e/kBTU. Natural gas has 1.037 kBTU per cubic foot (CF) and emits 0.055 kgCO2e/CF, so 0.057 kgCO2e/kBTU. Coefficients from EPA 1990-2016 National-Level U.S. Greenhouse Gas Inventory. https://www.epa.gov/sites/production/files/2018-04/documents/9509_fastfacts_20180410v2_508.pdf

[30] See the EPA Emissions & Generation Resource Integrated Database (eGRID) for information on region-specific GHG intensities of the electricity grid. https://www.epa.gov/sites/production/files/2018-02/documents/egrid2016_summarytables.pdf

[31] For example, the Spacepak AWHP works in both heating and cooling modes: http://mesteksa.com/fileuploads/Literature/SpacePak/SpacePak/SCM2-01141.pdf

[32] Single-family hydronic retrofit with CO2 heat pump: http://www.ecobuilding.org/code-innovations/case-studies/sanden-co2-refrigerant-heat-pump-water-heater-for-dhw-radiant-heat_-bundle-birch-case-study-house

[33] "Uneven distribution, called imbalance, is the fundamental problem of steam systems." Flothow, J. et al. "Clanging Pipes and Open Windows: Upgrading Steam Systems for the 21st Century". NRDC & EEFA, 2015. Page 7. http://energyefficiencyforall.org/resources/clanging-pipes-and-open-windows-upgrading-nyc-steam-systems-21st-century

[34] Shapiro, Ian. "Water and Energy Use in Steam Heated Buildings." ASHRAE Journal 2010. https://www.taitem.com/wp-content/uploads/SteamBoilerReplacements.pdf

[35] This assumes that while 110V service may be available at the apartment panel, many buildings will not have 230V service, and would need new risers, adding to the cost.

[36] Expected useful life of a "Heat pump condensing component" :20 years; for a "Chilling plant", which has similar compressor components, 15 years. Boilers range from 30-40 years. From Fannie Mae: "Instructions for Performing a Multifamily PCA (Version 2.0) Appendix F – Estimated Useful Life Tables. 2014. https://www.fanniemae.com/content/guide_form/4099f.pdf

[37] Pumping energy costs are not included in the rated efficiency of water source heat pumps, and lower the system coefficient of performance (SCOP): https://buildingscience.com/documents/digests/bsd-113-ground-source-heat-pumps-geothermal-for-residential-heating-and-cooling-carbon-emissions-and-efficiency

[38] Stagner, Joseph. (2016). Stanford University's "fourth generation" district energy system: Combined heat and cooling provides a path to sustainability. Page 23. https://sustainable.stanford.edu/sites/default/files/IDEA_Stagner_Stanford_fourth_Gen_DistrictEnergy.pdf

[39] Kupperman, D.S., Raptis, A.C., & Lanham, R.N.. Detection and location of leaks in district heating steam systems: Survey and review of current technology and practices. (1992). United States. doi:10.2172/5434678. Section 2. https://www.osti.gov/biblio/5434678

[40] Infra note 42

[41] Taitem Engineering, PC for NYSERDA.High-Performance Packaged Terminal Heat Pump Market and Development Research Report. October 2018. Page ES-2 describes the low-cost compromises of PTHPs. https://www.nyserda.ny.gov/-/media/Files/Publications/Research/Other-Technical-Reports/18-27-PTHP-Market-Development.pdf
[42] Next Gen HVAC Innovation Challenges, Attachment E1. Current PTHPs *"… switch from their heat pump mode to an electric resistance heating mode at colder outdoor temperatures to avoid coil defrost requirements. The outdoor temperature at which this switch occurs varies with manufacturers, but 35 to 40°F are common values, with some products going as low as 24°F. Further reducing the outdoor temperature at which this switching occurs could avoid many hours of less efficient electric resistance heating."* New York State Energy Research and Development Authority (NYSERDA). https://portal.nyserda.ny.gov/servlet/servlet.FileDownload?file=00Pt000000BOpXXEA1 (accessed November 2018)
[43] New York State Energy Research and Development Authority (NYSERDA). "Replacing Steam Heat with Variable Refrigerant Flow Heat Pumps (Existing Buildings)". http://www.taitem.com/wp-content/uploads/Steam-to-VRF-Conversions.pdf
[44] Ludwig, Peter & Evens, Anne & Kotewa, Larry. (2018). Cook County Energy Savers: How Energy Efficiency in Chicago's Multi-Family Buildings Has Evolved to Meet New Challenges from the 1980's to the Present Day. https://aceee.org/files/proceedings/2008/data/papers/2_407.pdf
[45] http://www.elevateenergy.org/wp/wp-content/uploads/Chicago-Multifamily-Segmentation.pdf, page 10
[46] Erlich. B. The Cost of Comfort: Climate Change and Refrigerants. Building Green. (2017). https://www.buildinggreen.com/feature/cost-comfort-climate-change-and-refrigerants
[47] https://www.ashrae.org/technical-resources/bookstore/standards-15-34
[48] Chapter 11, Section 1103: "Refrigeration System Classification". https://codes.iccsafe.org/content/yc7355qxk7/chapter-11-refrigeration
[49] The House at Cornell Tech has a condenser on every floor, located inside a louvered area that is outside the thermal envelope of the building but visually "inside" the building. See slide 16: https://www.burohappold.com/wp-content/uploads/2016/05/bhe-cornell-tech-casestudy-web.pdf
[50] Turpin, Joanna. "HVAC Industry Addresses Military Concerns About VRF Systems". May 7, 2018. https://www.achrnews.com/articles/137029-hvac-industry-addresses-military-concerns-about-vrf-systems
While some integration is possible to overlay building automation systems, the components of the VRF systems are only compatible with those from the same manufacturer.
[51] Image source : https://www.trane.com/content/dam/Trane/residential/downloads/brochure/ductless/72-1287-05_HR.pdf
[52] Image source: https://buildingscience.com/documents/digests/bsd-110-hvac-in-multifamily-buildings
[53] CADMUS study on field performance of residential ASHPs. http://ma-eeac.org/wordpress/wp-content/uploads/Ductless-Mini-Split-Heat-Pump-Impact-Evaluation.pdf
[54] Supra 53. Page 89 – "Multi-Head Performance" shows the degradation in efficiency with increased number of connected indoor units.
[55] https://neep.org/initiatives/high-efficiency-products/emerging-technologies/ashp/cold-climate-air-source-heat-pump
[56] Supra 53
[57] Supra note 55.
[58] Supra note 55
[59] Brooks, A. and Dirr, N. "DHW Electrification in Multifamily Buildings". Presentation at ACEEE 2017 Hot Water Forum. https://aceee.org/sites/default/files/pdf/conferences/hwf/2017/Brooks_Session7B_HWF17_2.28.17.pdf
[60] Aldrich, Robb. How to Heat Water in All-Electric Homes & Apartments?. NESEA 2015. Slides 25-33. https://www.energizect.com/sites/default/files/1-0105-Resi-HPWH-MF-Guidelines.pdf
[61] Bush, J. and Davis, T. "CO2 Heat Pump Water Heaters for Commercial & Industrial Applications". ACEEE 2016 Hot Water Forum. https://aceee.org/sites/default/files/files/pdf/conferences/hwf/2016/Davis_Session1B_HWF16_2.22.16.pdf
[62] Third party testing on split HPWHs: Energy Factor = 3.35 in PNW U.S.: https://www.bpa.gov/pages/results.aspx?k=sanden
[63] Delforge, P. and Vukovich, J. "Can Heat Pump Water Heaters Teach the California Duck to Fly?". Section I. B. ACEEE Summer Study on Energy Efficiency in Buildings, 2018. https://aceee.org/files/proceedings/2018/#/paper/event-data/p009
[64] *Supra* note 63, *at Section III. C.*
[65] The Rheem HPWH, as an example, can have ducted exhaust but no less than 37°F allowed inlet temperature: https://s3.amazonaws.com/WebPartners/ProductDocuments/6741707F-9CFE-400D-817B-FEFEB6D3F98A.pdf
[66] Supra note 6